UCF Senior Design II

LEBBVI: Laser Etching Braille Books for Visually Impaired

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1 Executive Summary

Being able to relax and enjoy a book is one of life's greatest pleasures. Yet, it is not one that every person can enjoy. Individuals with visual impairments have to rely on other methods to take in the book medium such as audio transcriptions or through textile understanding using braille. The audio method is often available, as individuals without visual impairments enjoy the medium as well. However, that begs the question on braille books and their availability.

Considering how large the portion of visually impaired people living is, one would imagine the availability of braille books to be large. This is not the case, as the means to do so are not widely available and the desire to serve this population is not present. The Laser Etching Books in Braille for Visually Impaired (LEBBVI) seeks to bridge this gap.

In the current marketplace, commercial solutions cost exorbitant amounts of money. There is no economic choice for writers or students of little means. LEBBVI provides an economically feasible way for writers, students, and ordinary individuals to translate text of different mediums into braille using Laser Etching on paper. The system is simple to use, and can even take in inputs on the fly with a keyboard if a user so desires. The use cases for the LEBBVI are endless, students are able to use it to learn, individuals with visually impaired family members can convert personal libraries into understandable text, and an underserved community can get more support.

The LEBBVI utilizes a Raspberry Pi in conjunction with a MSP board on a custom Printed Circuit Board (PCB) in order to process the information and command the various subsystems such as the laser etcher. The LEBBVI can take in inputs from a USB port, either reading keyboard inputs or reading text files from a USB drive. The input method is read in with the respective method and "understood" by the Raspberry Pi, where instructions will then be sent over via UART to the MSP to command the etching system on how to operate. This system is not expensive at all to make and is incredibly scalable. With tweaks to code and a potential for machine learning implementation, the possibilities are endless.

As for our goals with the system, the intention is to make the LEBBVI correctly read and decipher the input text with incredible accuracy. The LEBBVI needs to output at an acceptable rate and the device needs to be easy to use. Having a screen on the front of the device will allow users to understand what functions are being used and read what is happening. The screen is able to show certain important measures such as desired input method, current input if using a keyboard, and system info. These measures ensure accessibility and usability.

The logic and programming of the device will be finished over the course of SD2, with a goal of finishing by the end of the first quarter of the semester. This code will be tested throughout its development and rigorously tested on development boards until it can be uploaded to the fabricated PCB. Ultimately, the goal is to furnish the PCB in a shell to protect internals and have it properly interact with peripherals as well as the larger etching mechanism. The motors will be controlled and the large components hidden from sight to keep it aesthetically pleasing yet still easy to use.

2 Project Description

2.1 Motivation and Background

Our motivation for developing a machine capable of etching Braille patterns into paper using a laser is rooted in the critical and ongoing need to improve access to written information for individuals with visual impairments. In a world overflowing with printed content—ranging from books and letters to academic materials and official documents—only a small percentage is ever translated into Braille. This lack of accessible formats significantly restricts access to education, employment, and essential information, reinforcing systemic barriers faced by those who are blind or have low vision.

Our project seeks to address this disparity by introducing a novel laser-based Braille etching system that enables rapid, precise, and customizable transcription of text into tactile Braille directly on standard paper. Unlike traditional embossing machines, which tend to be bulky, expensive, and often require specialized materials, our system leverages compact laser technology to create Braille patterns in a streamlined and cost-effective manner. This opens the door to more flexible and scalable Braille production that can be performed on demand, without the logistical burdens of conventional methods.

The core of our system lies in the integration of advanced text recognition and transcription software with finely tuned laser etching hardware. This combination allows our device to process a wide range of printed materials in real time—converting anything from a personal letter or classroom worksheet to a full page from a novel into readable Braille. Users will be empowered to independently produce tactile documents tailored to their immediate needs, supporting both everyday tasks and long-term learning.

Ultimately, our goal is to create more than just a functional machine—we aim to contribute to a broader movement toward inclusivity and equal access to information. By making Braille more readily available and easier to produce, we hope to enhance literacy, independence, and opportunity for visually impaired individuals, helping to ensure they have the same access to communication, education, and empowerment as sighted individuals.

2.2 Goals and Objectives

The goals and objectives of this project are categorized into three different sections: basic, advanced, and stretch goals. Each category will vary in difficulty as you move on to the next category. These goals are instrumental in planning the steps of the project and provide ways of checking on progress as the device is built.

2.2.1 Basic Goals

The basic goals of this project are considered to be non-negotiable to have. Our system must have all of the goals presented below:

1. Laser Ablation
   We must achieve controlled, repeatable holes in standard 24 lb bond paper at 10mW laser power. There must be 2.3-2.5mm between each dot (within a single letter), 6-7mm between each letter (counting from the left-most dot of one letter, and left-most dot of the second letter), around 10mm from line to line, dot size 1.4-1.5mm in diameter with 0.4-0.6mm in height. A detailed spacing diagram is shown below:

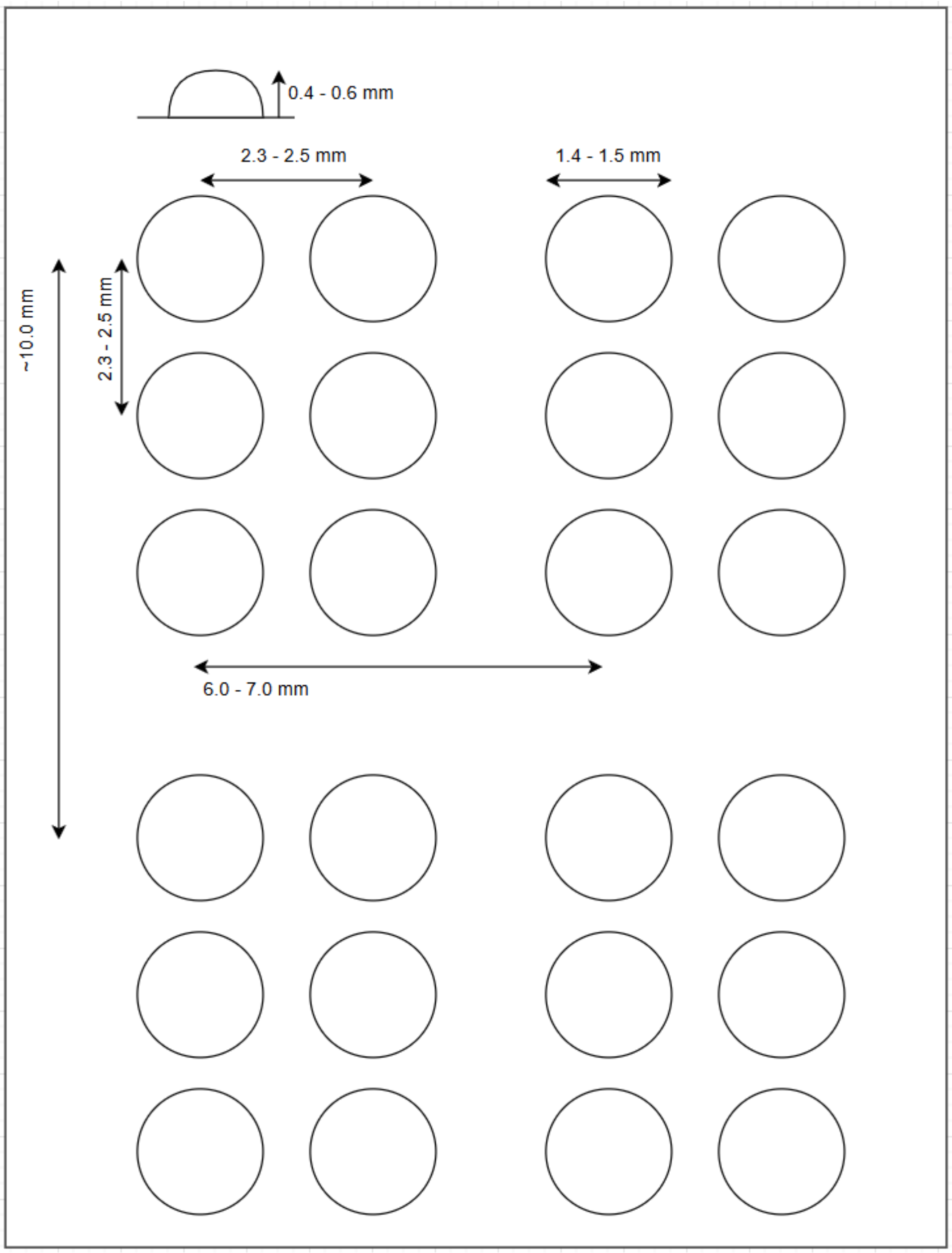


Figure 1: Detailed Braille Spacing Diagram

2. Print Rate
   The print rate for our system shall be at least 10 characters per minute. This is the speed in which the system will print out the entirety of one character (between one to six dots) over a minute.
3. Translation Accuracy
   We shall achieve an accuracy of 95% when taking English text from the text file or keyboard.

2.2.2 Advanced Goals

Our advanced goals of the system are realistic, achievable goals in which the system may have, but is not a must in order to operate. These goals are listed below:

1. Multiple Translated Language Support
   The ability to read multiple languages from text files and then have the software translate it into english, and then into braille.
2. Fine Tuned Laser
   The laser source shall be able to be finely tuned to control the depth of the etching to achieve variable depth on the go, which will enable the user to use various sheets of paper, or raise/lower the height of the bump to their liking.
3. Reduced Vibrations
   The rails with the motors driving them shall be able to move the laser and paper quickly without any sudden movement within the system. With the ability to keep these vibrations to a minimum, we can see a large increase in print speed as we will not have to wait for the laser to stop "vibrating" after each movement.

2.2.3 Stretch Goals

Stretch goals are goals that would be nice to have, but are not essential for this project. These can be worked towards after the entire system is functional. These are listed below:

1. Integration of a Camera
   We can have an external camera that can take a photo of any kind of text and directly translate it into braille. This would include a machine learning aspect as the camera would need to accurately detect what is text, and leave out any unimportant information. This would increase the versatility of our system, but is not needed.
2. Dot Size Variation
   The ability to vary the dot size of the braille by incorporating a system that can increase/decrease the radius of the laser would help the user finely tune the exact dot size to their liking. It can also be used for different use cases.

2.2.4 Objectives for Basic Goals

The way we can achieve our basic goals is by designing a way to utilize the laser in which we can etch bumps into the paper to represent braille. The design is crucial as we do not want to burn holes through the paper, which can induce safety problems (fire, combustion, damaging surrounding components) as well as rendering the system useless since the paper will be unreadable. Laser ablation must be less than the width of the paper, which is to be determined until we can find the correct height of paper that will not burn through when printing out braille. We can also achieve 10 characters per minute by constructing a mechanism that the laser can mount on to and make precise movements to create braille. We can use a system that uses stepper motors, as these shall give us precise movements. For our accuracy goal, our software must be able to read from a thorough library to make accurate translations at a goal of 95% translation accuracy. As well as where to tell the laser to etch into the paper since one wrong bump can create a broken word.

2.2.5 Objectives for Advanced Goals

For the advanced goals, we can create support for multiple languages by adding multiple libraries on the software side that can be used as translation. This can only be achieved by using an alternate language keyboard since our main focus is going from typed English to braille. We can also set up another translator within the software to translate a certain language into English and then into braille. For tunable laser depth, we can utilize Pulse Width Modulation (PWM). And then for a controlled rail system, we must dive deep into fine tuning it so it does not seem out of control. If we can find a good medium, then it can increase print speed by being able to move swiftly to the next position without having to wait for the laser to stop swaying (if it is moved at an uncontrollable speed and improper mounting).

2.2.6 Objectives for Stretch Goals

Utilizing a camera in our design would be great, but implementing it may prove to be too difficult due to timing constraints, hence it being a stretch goal. However, the way we can implement it into our project is by setting up a full machine learning algorithm that can detect text within an image, and throw out all unnecessary details (such as the surrounding area), leaving just the text. This can take numerous test runs to help build its accuracy and teach itself what to keep and throw out. The idea behind dot size variation is to get as close to the standard braille size, which is to the hundredths of an inch. This can prove to be a challenge as the laser will have to be perfectly tuned to provide braille in that standard, so on the go variation would be a useful tool to help tune the dot size to perfection.

2.3 Existing Products

The below existing products are available for public purchase but are not affordable or available for the common person. Students are not able to afford this, and the available printers are not a real option for the everyday individual. The average price is well above $1,000 USD before shipping and taxes. For an item intended to improve quality of life, this high cost fails at being accessible. LEBBVI seeks to remedy this issue by costing below $500 which is well more affordable.

2.3.1 Thermal-Emboss Braille Printers

Most desktop units use a heavy embossing head and motorized platen. They cost $2000–$5000, consume 20 W, and print at around 15 chars/sec. They require special thick paper and frequent maintenance. With a high variable cost and requiring incredible constant maintenance, this device is not good for everyday use and is not accessible for everyone. The desktop unit is large, not portable, and fragile.

2.3.2 Piezo-Actuated Dot-Formers

Emerging designs (e.g. Tactonix BrailleCell) use piezo stacks to push pins through paper. They offer real-time refreshable panels but remain $1000+ per cell and limited to small displays. The small display is counterintuitive for those visually impaired.

2.3.3 Commercial Braille Embosser IRIE

A main braille embosser for “every day users” created by IrieAT, the IRIE Braille Buddy, starts at $1,495 plus tax. This piece of hardware comes without any software options and no warranty. To include a windows or apple software translator along with a 1 year warranty, this total skyrockets to $2,389 plus tax[10]. Without software, the hardware is effectively useless to the common user without extensive research, rendering this common “everyday use” market item impossible to ascertain for lower income individuals.

2.4 Engineering Requirements and Specifications of the System

The engineering requirements and specifications of the system are quantifiable requirements that can be shown when the system is fully assembled. These are listed in the table below.

Specification	Value
Laser Ablation	Less than thickness of paper
Print Rate	≥ 3 char/min
Printed Types of Braille	2 (Uncontracted+Contracted)
Dot Size (Diameter of Base)	≤ 2mm
Custom Battery Pack Life Attachment (Full Load)	≥ 2 hours
Weight of Device	≤ 6800 grams
Translation Accuracy	≥ 95%
Cost	≤ $600

Table 1: Engineering Specifications

The demonstrable specifications for our project are the print rate, dot size, and translation accuracy. The print rate of our laser printer system must be over ten characters per minute, where one character is a full letter of braille. The maximum number of dots needed to create a character in braille is five, so the laser must be at least able to print out fifty dots per minute (will be less than this as there are only two characters that need five dots to read). This can be achieved by optimal software code, optimizing the speed and control of the motors, and minimal input delay when using the keyboard option. We also need to demonstrate that our dot size is less than 2mm. We chose 2mm as this gives us some headroom for the actual dot size the laser can produce onto the paper. The braille standard for the base diameter of a dot is 1.4-1.5mm and achieving a perfect sized dot may pose a challenge. Therefore, leaving around 0.5mm of forgiveness is reasonable, as there will be hardly any noticeable difference in dot size from the standard. Lastly, we must demonstrate the accuracy of translation from another language to braille. We want to achieve an accuracy rating of 95% or higher, meaning our software must be developed with the highest accuracy in mind. The accuracy will be tested per character, meaning if we have printed a sentence with twenty characters (or about four to five words), then we need to show that 17 characters were printed correctly.

The non-demonstrable specifications are the laser ablation, printed types of braille, battery life, weight of the device, and the cost. Laser ablation should be clearly demonstrated when the printing of the dots happens, as we must not pierce (or burn) through the paper. The types of braille printed, both contracted and uncontracted, can also be demonstrated as well, but printing out in uncontracted form will be the most important as “contracted” words can be mistranslated very easily. Battery life is very hard to demonstrate when your demonstration is thirty minutes, and the weight and cost of the device is not a key target of this project, but still important.

2.4.1 PCB Specifications

In the planning phase, our PCB will be a compact, multi-layer board sized to fit inside the handheld enclosure. We anticipate using between two and four copper layers so that power, ground, and signal planes can be separated as the design matures. The board will be partitioned into distinct functional regions: a power-management area housing the battery connector, voltage regulator(s), and bulk decoupling capacitors; a control-logic zone for the microcontroller and its programming/debug header; an isolated section for the laser driver with room for wider high-current traces; and a communications segment with pads or a header for UART, USB, or I^2C connectivity. Early on, we'll designate a "star point" ground region to simplify grounding strategy and reserve trace corridors adjacent to the laser driver for later thermal and noise management. We'll also leave room for SWD/JTAG programming and clustered test points on each power rail, and sketch standoff mounting holes and clearance zones around heat-generating components to ensure mechanical stability and adequate spacing.

In order to utilize external components and peripherals the board must have USB ports integrated. The board will also need to have a high level microprocessor akin to a Raspberry pi and a low level one similar to the MSP or ESP. The high level system will need to be connected to the USB ports in order to utilize keyboard and USB memory functionality. This way, the script will interface with either the USB or keyboard to obtain the inputs and then begin the translation process. Via UART, the information and instructions will be sent to the hardware level system, the MSP in this example, in order to properly display information on the LCD and control the laser system.

2.4.2 Software Requirements

Software must be able to properly interface between the keyboard, USB, LCD, printer, PSU, and main control unit. The software must also have language libraries that can be accessed and used in order to correctly translate the pictured word into both Contracted and Uncontracted Braille. In order to properly complete these functions, there will be two languages used, Python and C. C will be used on the MSP chip in order to handle hardware functions and python will be used for logic handling as well as parsing through the keyboard and USB inputs.

In order for the device to properly translate text and keyboard inputs, code will have to be implemented to read and parse the strings. The user will have to select whether or not the translation is contracted or uncontracted, as that will require two different techniques of translation. The MCU's function as a translator is the step in the chain that does most of the actual work. Contracted Braille will have a library of direct one-to-one translations by word whereas Uncontracted Grade 1 Braille will "translate" letter by letter. The library for each word or letter will most likely contain instructions and commands for how the printer will operate in order to properly mark the paper. The printer will receive the command, then execute the correct actions in order to make each “word” or letter appear.

The development will be done using mutually operated IDEs such as Visual Studio Code to ensure comparability and understanding across the group.

2.5 Block Diagrams

The system block diagrams are key components in the overall scheme of this project. They help visualize how the system works at the hardware level, software level, and the optics level. These diagrams go into detail about how each respective level works and how components will work in the project. We will start with the hardware block diagram and work our way down to the software diagram.

2.5.1 Hardware Block Diagram

The hardware block diagram lays out the major subsystems of our project. The subsystems include the power supply (PSU) section in yellow, the printed circuit board (PCB) in green, and the printer system in blue. The overall design will take an input from a keyboard or a text file and print it out in braille, where each subsystem is important in doing so.

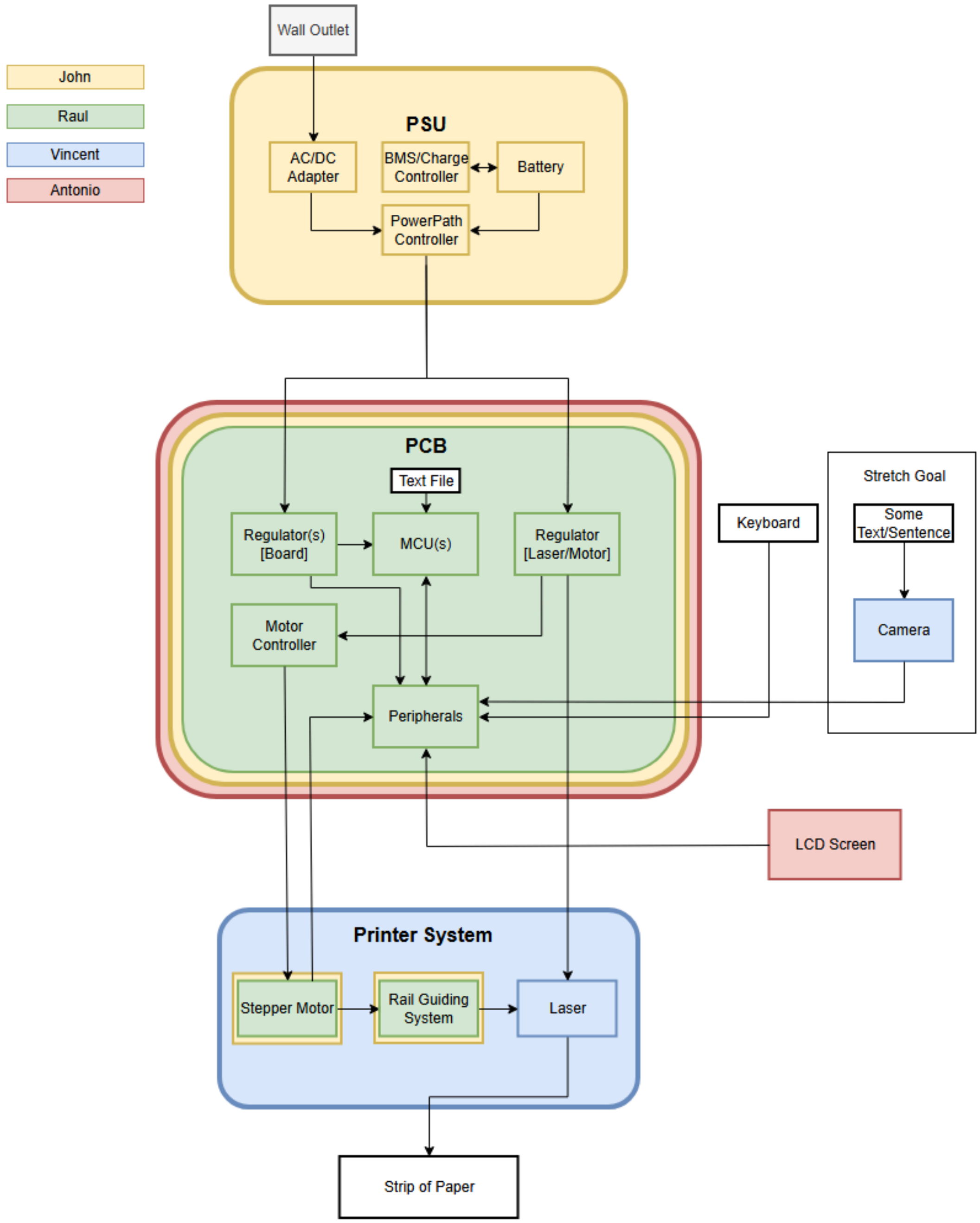


Figure 2: Hardware Block Diagram

The power supply system will be created by designing a battery pack that supplies various levels of constant DC voltages to the system using regulators. We will also utilize wall power when the battery pack needs to charge, or when the user does not want to drain the batteries. This battery pack must be managed by a battery management system (BMS) to protect the pack from overcharging, provide balanced charging to each cell, under and over voltage protection, and short circuit protection.

The PCB must be designed in a way to direct power to where it needs to go, act as a hub for any external peripherals, and incorporate multiple microcontrollers that tell our device what to do. The MCU's will receive the data from the text file or keyboard and tell our motors and laser what to do. It will direct the motors that drive the rail guiding system to accurately print out braille onto a sheet of paper. We also want to utilize an LCD that can tell us multiple types of information.

Then the printer system will consist of two motors, one that drives the paper in one axis and the laser in the other. This is to simplify the coding aspect of leaving the paper stationery and having the laser move in both the 'x' and 'y' axis. We must design some type of rail guiding system which will be challenging as this is typically a mechanical engineering problem, so we must try to keep it as simple as possible but also suit our needs.

2.5.2 Optics Diagram

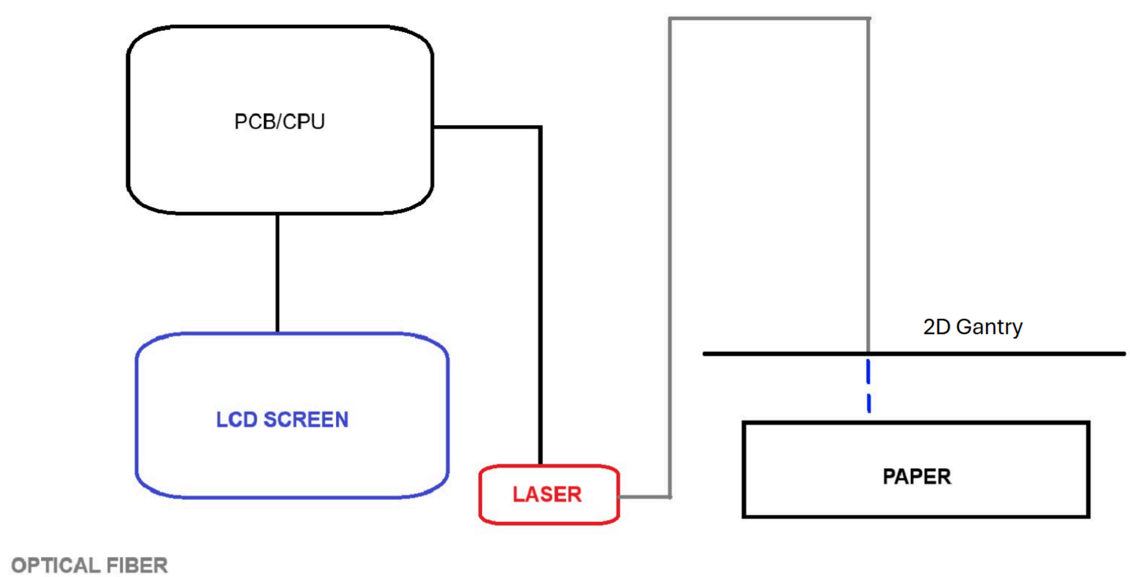


Figure 3: Optics Diagram

2.5.3 Software Diagram

The software diagram displays the various interactions between hardware and software. It also notates the different group members working on the various aspects of software development. Our team consists of three members who are able and willing to code, making the dispersal of work easier on the group. The software diagram begins with the user making a choice on whether or not to take input from a USB or keyboard. An error screen would appear depending on if the selected input method is unavailable or not recognized by the hardware. The user then is prompted for contracted or uncontracted braille.

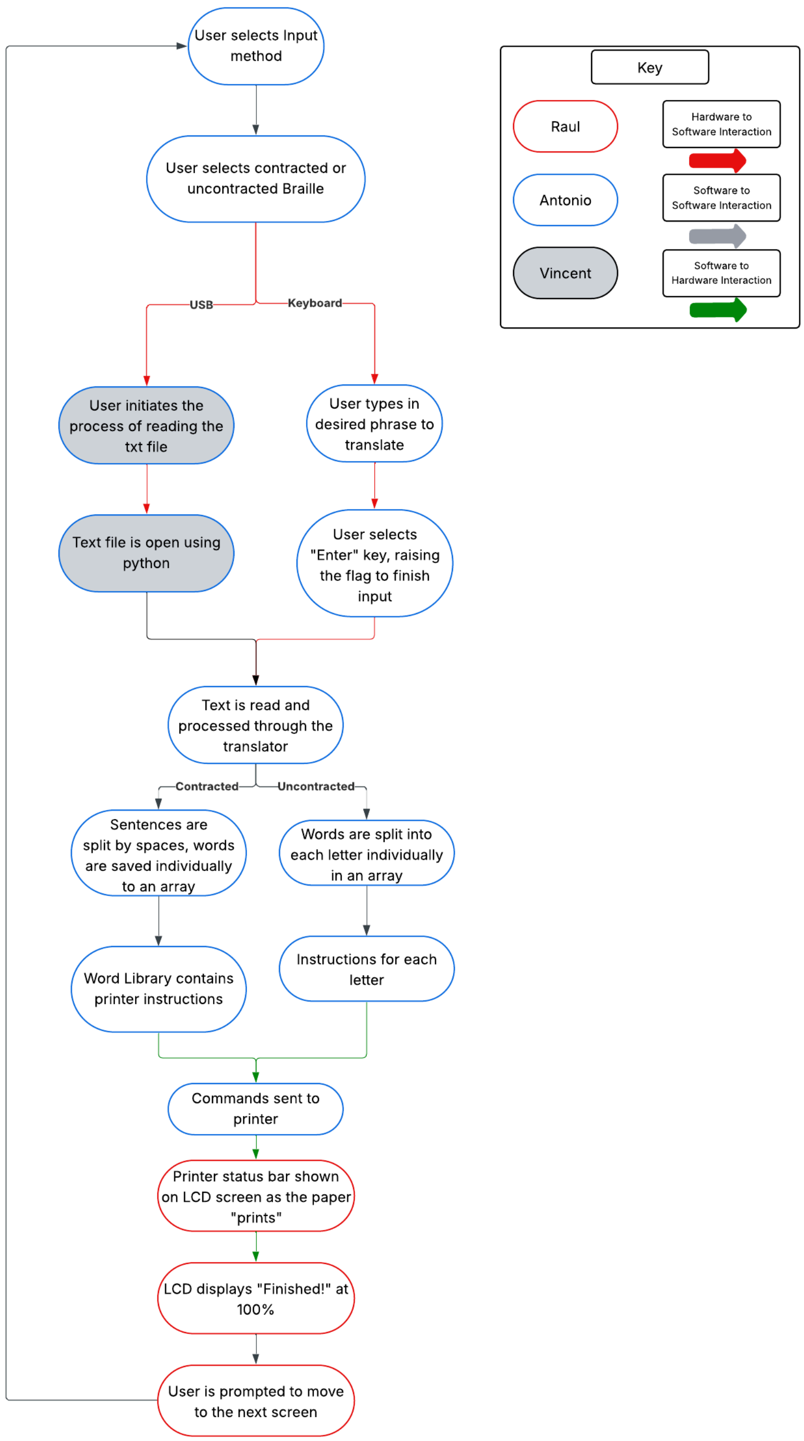


Figure 4: Software Block Diagram

After making the selection the diagram splits depending on the input method, with the user typing in the desired text to translate as compared to parsing through the text file. The “translations” in the desired mode are then placed into an array, similarly to a queue of instructions for the laser apparatus. The program language this is all done in is python. Through UART, the instructions are sent to a separate chip controlling hardware that operates in C code to control the laser apparatus.

The C code also interfaces with the LCD screen, updating with progress as the operation continues. When 100% is reached, a completion message is shown with a prompt to continue to the next option set which includes starting again at the start with the same initial prompts.

The software diagram depicts the interactions as well which detail the scope of work and aid in planning what goes on the PCB. The initial hardware to software interactions are the keyboard and USB interaction with the software. The PCB on the board needs to contain at least one USB port, up to two in order to transcript both. Having multiple USB ports increases functionality as well as operative use with the ease of being able to type or obtain the file from the USB. The next hardware and software interaction is from the C code interacting with the laser apparatus and giving instructions on how to laser the braille. The libraries will have the instructions mapped to each individual word if contracted or each individual letter if uncontracted. The laser apparatus will need to be connected via another medium, most likely a direct connection or via USB. This would move the number of USB ports up to a minimum of 3 unless a sacrifice is made on input functionality.

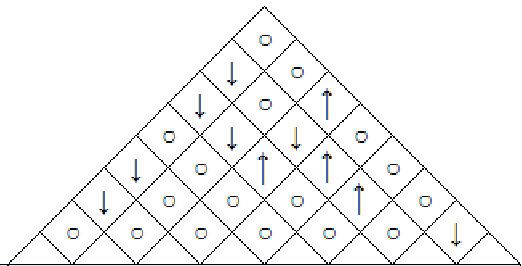
The integration of hardware and software interaction across two separate programming languages is a hefty task, the ability to use python helps leverage this difficulty but requires another powerful chip such as a Raspberry Pi in order to facilitate the translation and UART interaction.

2.6 House of Quality

The house of quality takes the engineering requirements and puts marketing requirements against them (and engineering requirements against themselves) to give a representation of the project’s overall requirements. We have eight engineering and marketing requirements. The engineering requirements consist of print rate, printed types of braille, dot size, battery life (at full load), weight of the device, translation accuracy, cost, and laser ablation. The marketing requirements: the size of the device, affordability, laser accuracy, battery life, ease of use, maintenance, reliability, and safety.

Correlations	
Strongly Positive	↑↑
Positive	↑
No Correlation	○
Negative	↓
Strong Negative	↓↓

Direction of Desirability	
Maximize	+
Minimize	-



Column #		1	2	3	4	5	6	7	8
Engineering Requirements / Marketing Requirements (Explicit and Implicit)	Direction of Desirability	Print Rate	Printed Types of Braille	Dot Size	Battery Life (Full Load)	Weight of Device	Translation Accuracy	Cost	Laser Ablation
Direction of Desirability		+	+	−	+	−	+	−	−
Size of Device	−	○	○	○	↓	↑↑	○	↑	○
Affordability	+	○	○	↓	↓↓	↑	○	↑↑	↓
Laser Accuracy	+	↓	○	↑	○	○	○	↑	↑
Battery Life	+	↓	○	○	↑↑	○	○	↓	○
Ease of Use	+	○	↑	↑	↑	↑↑	↑	○	↑
Maintenance	−	↓	○	↓	↑	○	○	○	↓
Reliability	+	↓	↓	↓	↑	○	↑↑	○	↑
Safety	+	↓	○	↓	↓	○	○	○	↓↓
Target		>= 10 char/min	2 (Uncontracted + Contracted)	<= 2mm	>= 2 hours	<= 6800 grams	>= 85%	< $600	< Thickness of Paper

Figure 5: House of Quality

The goal for the printing rate of our device is for the laser to print at a speed of over ten characters per minute. Where one character is one letter printed in braille. This will have no effect on the size of the device, affordability, ease of use, or the types of braille printed. However, the laser accuracy can decrease when moving the laser at higher speeds to print faster. Battery life will decrease quicker, safety decreases because the laser may move too quickly, and reliability decreases as well.

The printed types of braille are both un-contracted (Grade 1) and contracted (Grade 2). Where un-contracted will spell out each letter of a word and contracted will form contractions of words to shorten the amount of braille needed to read (e.g. “people” in un-contracted takes six characters, but in contracted it takes one character). This will increase the ease of use of our device as it allows for various forms of reading, but reliability will decrease as translation errors can occur, specifically in contracted form where the placement of the dots is critical.

Dot size is also important; the braille standard is 0.48mm in height and 1.44mm in base diameter. We are going to try to achieve a size less than 2mm, as getting a finely tuned laser to print at a size of exactly 1.44mm may be a challenge. If our laser is inaccurate, then we can see variable sized dots which will impact the readability of the braille.

Battery life for our system must last at least two hours. This is achieved by creating a battery pack large enough in capacity to last this long, therefore the affordability, cost, safety, and size of the project will take a hit. This also impacts our print rate, as increasing our print rate will draw more power, decreasing the battery life. However, this will allow the user to use the device without any worry of running out of power.

The weight of the device is important as it will allow the user to freely move the device around the room to help multiple people in succession, or for personal use cases. This heavily increases the ease-of-use factor, but the size of the device will be directly related to the weight as we want it to be no more than 6800 grams.

The ability to accurately translate is super important in a device like this. We aim to have a translation accuracy of 85% or higher, meaning that the ease of our project will increase, but to accurately translate the languages will mean that the print rate must be adjusted to avoid misprints.

Cost is a huge factor in any project, where just about every engineering requirement is impacted by it. If we want longer battery life, faster print rate, and a reasonably weighted device, we must budget and plan accordingly. We do not want to overspend in areas where better, cheaper alternatives are available.

Lastly, laser ablation has many correlations to the marketing requirements of our device. Notably the safety as burning the paper to create the bumps can lead to fires if not properly designed.

3 Research and Part Selection

3.1 Existing Technologies

During the design process of this project, a significant portion of development has been informed by studying existing technologies and previous implementations of related systems. Technologies such as laser printers, CNC engravers, and older laser etching platforms have undergone extensive development over several decades. These systems provide valuable design references, particularly in areas such as motion control, beam delivery, safety protocols, and software integration.

Researching prior work has proven to be an effective method for identifying successful design patterns and avoiding common technical pitfalls. Documentation from earlier iterations of laser-based machines—both in commercial settings and in academic environments—offers insight into system architecture, component selection, and performance benchmarks. These examples allow for a more informed and efficient design process by building on proven methods rather than starting from first principles.

In addition to industry case studies, previous senior design projects and academic prototypes have also served as useful references. These projects often share similar constraints in terms of budget, scale, and available resources, making them particularly relevant to the current design context. Examining their results, challenges, and documented outcomes helps to guide design decisions and improve system reliability.

This section will present a review of selected historical systems and past academic projects that align with the objectives of this braille etching printer. The purpose is to analyze the evolution of related technologies and to identify features or solutions that can be adapted or improved upon in the current project.

3.1.1 Creality Falcon Engraver

In our research we have found many different kinds of laser engravers that each have their own unique characteristics. The creality falcon Engraver is a very similar final product to what we have in mind for this project. This product is your average engraving machine, as it has a 5 watt laser and boasts a 0.1 mm precision and spot size compression to 0.12*0.06 mm from 0.32*0.14 mm. So immediately this is different from what we are aiming for because we actually want to have the largest spot size we can rather than the smallest. Much can still be learned from this product.

Looking at this product we really took notice of how the laser is able to move across the work area. The set up for this product is that there is no z-axis control and the laser is set at a fixed height. The laser is on a rail that uses a helix pattern to rotate and move the laser left and right. The rail is also attached to a gantry that moves the rail back and forwards. This is a different method of moving that we had not previously come up with or seen before. While the final design of the moving mechanism has yet to be decided this will be something we look into.

3.1.2 Subtractive Manufacturing

At its core our project boils down to one thing, subtractive manufacturing. As the name suggests this is the practice of creating something via the process of removing material. This is what we are trying to do with the paper in this project. We have our material, the paper, and remove parts of it to create braille patterns. This process is a long standing practice that dates back to the beginning of man and therefore has been thoroughly studied and understood. This knowledge will prove to be invaluable in the process of this project.
When talking about subtractive manufacturing in the modern era it is impossible to not mention Computer Numerical Control Machines or CNC Machines. These are machines that autonomously use a plethora of different tools such as drills, lathes, saws, and more, to precisely carve out a designed piece from a larger chunk of material. These kinds of systems usually have an arm that can move in all three dimensions to ensure maximum accuracy as the tolerance for these parts can be extremely low. There are three approaches that CNC machines offer as solutions to subtractive manufacturing. First option is to have the material stationary and have the removal technology be able to move in whatever directions necessary. Secondly you could have the removal technology stationary and make the material able to move around, and thirdly a combination of the two where both elements move.

There are pros and cons to these approaches and we should understand them in order to decide what our process of movement is going to be. Firstly, looking at keeping one of the elements stationary and moving the other seems like the most straightforward solution as it would work very similarly to a normal printer as the laser scans across the paper. But after looking into the design of a system like this, it turns out to be much more complicated. Making a moving part work in a custom system is hard enough let alone building a moving part on top of a moving part. So with this in mind we have decided that instead of building one two dimensional gantry we will install two one dimensional rails in which the laser output and etching platform will move on respectively.

3.1.3 Thermal-Emboss Braille Printers

Most commercially available Braille printers, such as those from companies like Index Braille and Enabling Technologies, use thermal embossing to create tactile dots on thick paper. These printers employ a heated embossing head to form raised dots, but they require specialized paper and are costly ($2,000–$5,000).

Additionally, they are bulky, consume significant power (~20 W), and require frequent maintenance. Our laser-based approach aims to eliminate the need for thick paper and reduce costs while maintaining portability.

3.1.4 Piezo-Actuated Dot-Formers

Emerging technologies, like the Tactonix BrailleCell, use piezoelectric actuators to push pins through paper, creating refreshable Braille displays. While innovative, these systems are expensive ($1,000+ per cell) and limited to small-scale applications. Our project diverges by focusing on permanent Braille etching onto standard paper, offering a more scalable and affordable solution.

3.1.5 Laser Engraving Systems

Commercial laser engravers, such as the Creality Falcon, are designed for high-precision etching on materials like wood, acrylic, and metal. These systems use CNC-controlled lasers to remove material, achieving resolutions as fine as 0.1 mm. However, they are overqualified for Braille production, as our project requires larger dot sizes (~1.5 mm) and lower power (10 mW). By adapting laser engraving principles, we can achieve precise Braille dots without the complexity or cost of industrial systems.

3.1.6 CNC Machines

Computer Numerical Control (CNC) machines, which automate tool movement along multiple axes, provide a framework for our laser positioning system. Unlike industrial CNC cutters, our design simplifies motion to two axes (X-Y), similar to consumer-grade devices like Cricut cutters. This approach balances precision with cost-effectiveness, ensuring smooth laser movement for Braille dot placement.

3.1.7 Past Projects

Over the years, there have been several senior design projects that closely parallel the goals and structure of our current endeavor. These past projects serve as invaluable references, offering a wealth of insight, practical lessons, and design strategies that can significantly benefit our own development process. It is essential to approach these works with both appreciation and respect for the original teams, recognizing the time, effort, and innovation that went into their creation. By carefully studying their documented challenges, breakthroughs, and decision-making processes, we can anticipate potential obstacles in our own project and discover effective solutions that might not have been immediately apparent to us.

While many of these earlier projects shared a common foundation—namely, using a laser-based system for engraving or marking surfaces—they often pursued slightly different objectives. For example, a majority of them aimed to engrave various materials at the highest possible resolution, pushing the limits of detail and image fidelity. In contrast, our project is more specialized in scope: we are focused on interacting with a single substrate—paper—and our output is not limited by visual resolution but instead by the tactile legibility of Braille patterns. This key distinction redefines many of the technical requirements and design priorities of our system.

Among the historical approaches, two common strategies have emerged. One involved constructing a mechanism that printed text by depositing small laser-etched dots to form individual characters. Another advanced further, enabling the system to replicate full digital images, effectively turning the laser into a high-resolution printer. Our project diverges even more from these examples—not by increasing complexity, but by shifting focus entirely. Rather than aiming to print images or conventional text, our system is designed to create raised, tactile Braille symbols readable by touch, prioritizing accessibility over visual aesthetics.

Given how closely related these prior efforts are to our own, it would be a disservice to the dedicated students who came before us not to acknowledge their contributions. Their work forms a foundation upon which we can build, refine, and innovate. By drawing on their experiences, we not only pay homage to their achievements but also strengthen the foundation of our own project through informed, respectful iteration.

3.1.8 Pre Existing Software

Our Braille laser etching system requires specialized software to handle text translation, laser control, and motion coordination. Several existing software solutions provide partial functionality that could be adapted for our project, but none offer a complete, Braille-optimized solution. Below, we analyze these tools and explain why a custom software approach is necessary.

3.1.8.1 Braille Translation Software

LibLouis is one of the most widely used open-source Braille translation libraries, supporting multiple languages and Braille grades (contracted and uncontracted). It is highly accurate and integrated into many accessibility tools, making it a strong candidate for our translation needs. However, it lacks direct hardware control capabilities, requiring additional programming to interface with our laser and motion systems. BrailleBlaster, another Braille transcription tool, offers a user-friendly interface but is designed for desktop use rather than embedded systems, limiting its real-time applicability for our device.

3.1.8.2 Laser Control & CNC Software

LaserGRBL and Universal G-Code Sender (UGS) are popular for controlling laser engravers via G-code commands. While these tools excel in general CNC applications, they are not optimized for Braille, as they treat text as rasterized images rather than structured dot patterns. RasterCarve, a Python-based script, converts images into G-code but similarly lacks Braille-specific features. These tools could theoretically be adapted, but their reliance on manual G-code generation would add unnecessary complexity to our system.

3.1.8.3 Image Processing Tools

For our stretch goal involving camera-based text input, OpenCV provides robust optical character recognition (OCR) capabilities. It can extract text from images or scanned documents, which could then be fed into our Braille translator. ImageMagick, a command-line image processor, offers PDF-to-image conversion but does not directly assist with Braille generation. While useful for preprocessing documents, these tools would require significant integration effort to work seamlessly with our hardware.

3.1.8.4 Proposed Custom Software Solution

After evaluating existing software options, we realized none perfectly matched our needs for a complete Braille printing system. While tools like LibLouis handle translation well and LaserGRBL controls laser movement, we needed a more integrated solution. Our team decided to develop custom software that combines the best features of these programs while adding our own innovations.

The heart of our system uses LibLouis, an open-source Braille translation library, because it's reliable and already supports multiple languages and Braille standards. We're building a Python-based interface that will let users input text either by typing, uploading files, or eventually through a camera (our stretch goal). Python works well here because it's great for handling text processing and has good USB/serial communication libraries.

For the actual printing, we're taking the translated Braille and converting it into precise laser positioning commands. These commands get sent through a UART serial connection to our MSP430 microcontroller, which runs custom C code to control the stepper motors and laser. We chose this two-language approach because Python makes the high-level processing easier, while C gives us the low-level control we need for timing-critical motor movements.

Instead of using generic G-code like some laser engravers, we're creating a more efficient command format specifically for Braille dots. This should make the printing faster and more reliable. We're also including real-time feedback through an LCD screen so users can see the printing progress.

The software is being designed with future upgrades in mind. The modular structure means we can easily add support for more languages later, or improve the camera OCR functionality if we get to that stretch goal. We're also making sure all the components communicate clearly, with good error handling so the system can recover gracefully if something goes wrong.

Feature	**LibLouis**	**LaserGRBL**	**OpenCV**	**Custom Software**
Input Types	Text	Images (JPG/PNG)	Images/PDF	Text/USB
Output Format	Braille Unicode	G-Code	Rasterized Text	Custom Braille Commands
Braille Support	Full	None	None	Full
License	GNU LGPL	GNU GPL 3.0	Apache 2.0	Custom
GUI	No	Yes	No	Yes
Real-Time Processing	No	Yes	No	Yes
CLI	Yes	No	Yes	Yes

Table 2: Software Comparison Chart

3.2 PCB

A review of current PCB design practices for compact, power-intensive handheld devices shows that a 2–4 layer FR-4 board is the de facto standard: two inner planes for ground and power ensure low impedance return paths, while external signal layers simplify layout and routing. Industry guidance emphasizes partitioning high-current domains—such as a laser driver’s switching elements—into isolated copper pours with wide traces (≥2 mm) and thermal relief pads to manage heat dissipation [1]. Studies of portable electronics recommend placing bulk decoupling (10 μF) and high-frequency (0.1 μF) capacitors within 5 mm of each regulator pin to suppress switching noise effectively [2].

Furthermore, a “star ground” topology, where all ground pours converge at a single chassis-bonded via, minimizes ground loops and crosstalk between digital logic and analog or power sections. For mechanical stability and EMC, designers often include distributed test-point clusters on each supply rail and a standardized programming header (SWD/JTAG), allowing in-system validation without reworking the board. Finally, a thermal-conscious layout,reserving clearance zones around MOSFETs and keeping heat-generating components near board edges or dedicated heatsinks, has been shown to extend component lifetime in battery-powered systems by up to 30% [3]. This body of research underpins our decision to adopt a multi-layer FR-4 PCB with clear functional segmentation, robust decoupling strategies, and careful grounding to balance performance, reliability, and manufacturability.

When selecting a PCB manufacturer for our laser braille etching system, we conducted a thorough evaluation of four primary options: JLCPCB [1], PCBWay [2], and OSH Park [3]. Each vendor offers distinct advantages and tradeoffs that must be carefully considered for our specific application requirements [4].

JLCPCB [1] represents the most cost-effective solution for our needs, providing 4-layer boards at just $54 for a set of five boards with a reasonably fast 5-day production time plus shipping. This is approximately 40% less expensive than PCBWay's comparable 4-layer service [2] while still meeting our essential IPC Class 2 quality standards [5]. The ability to obtain five fully fabricated boards at this price point gives us ample units for prototyping, testing, and potential design iterations. JLCPCB's capabilities include 6 mil trace/space tolerances, 1oz copper layers, and lead-free HASL surface finish - all of which satisfy our design requirements without unnecessary premium features that would increase costs. They also offer student discounts that can further reduce expenses, making this an academically budget-friendly choice.

PCBWay [2] positions itself as a higher-end alternative, with IPC Class 3 certification [5] and optional Electroless Nickel Immersion Gold surface finish available for an additional $45. While the Electroless Nickel Immersion Gold finish provides superior surface planarity and oxidation resistance compared to HASL [9], this premium feature is not essential for our prototype development phase. The IPC Class 3 rating offers marginally better reliability than JLCPCB's Class 2 boards [5], but our application does not demand the extreme longevity that would justify this upgrade. PCBWay's typical 7-day turnaround is slightly slower than JLCPCB [1], and their base pricing starts at $68 for five 4-layer boards - a significant premium without providing critical benefits for our use case.

OSH Park [3] occupies the niche of low-volume, high-quality fabrication with their distinctive purple solder mask and reputation for excellent quality control. However, their pricing structure makes them less practical for our needs - charging $105 for just three boards with a longer 10-14 day lead time. While their boards are beautifully fabricated and include 100% electrical testing, we would sacrifice both quantity and timeliness without gaining meaningful technical advantages for our project. The aesthetic appeal of their purple boards does not justify the nearly double per-unit cost compared to JLCPCB.

After careful evaluation, JLCPCB [1] stands out as the optimal balance of cost, capability, and turnaround time. Their 4-layer process provides the necessary power and ground planes for clean power distribution, while their 6 mil trace/space capabilities accommodate our component density requirements. The $54 base price for five boards fits comfortably within our budget, allowing room for optional expedited shipping while still staying under our $90 PCB allocation. We should specify FR-4 Tg130 material with 1oz outer and 0.5oz inner copper weights when submitting our Gerber RS-274X and Excellon drill files [30]. Importantly, we can avoid unnecessary costs by skipping premium features like blind/buried vias (which would add $120+) and impedance control (unneeded for our low-frequency signals). With student discounts potentially available [8] and the ability to receive production-quality boards within a week using expedited shipping, JLCPCB provides the best combination of affordability, capability, and speed for our braille laser project's PCB needs.

Our PCB design adheres to critical industry standards to ensure reliability, safety, and manufacturability. The foundation of our design follows the IPC-2221 Generic Standard on Printed Board Design, which governs essential requirements for materials, conductor spacing, hole sizing, and manufacturing processes. This standard is particularly crucial for our mixed-signal design, where high-power laser driver circuits coexist with sensitive microcontroller components. Complementing this, we apply the IPC-7351 Land Pattern Standards to optimize component footprints and pad sizes, ensuring proper solder joints while maximizing space efficiency in our compact layout. For quality assurance, we reference the IPC-A-600 standard, which defines acceptability criteria for finished boards, focusing on aspects like plating quality and solder mask coverage that directly impact long-term reliability. Given the laser operation in our system, we prioritize safety by selecting PCB substrate materials that meet UL 94 flammability ratings, preventing potential fire hazards.

Several project-specific constraints shape our PCB implementation. Size limitations demand careful component placement to fit within our handheld enclosure while maintaining the target weight of ≤6800 grams. To achieve this, we employ a 4-layer board stackup with dedicated power and ground planes, balancing routing density against manufacturing complexity. Power handling presents another critical constraint, particularly for the laser driver circuit, which must deliver up to 500mW efficiently while minimizing voltage drops and heat buildup. Signal integrity considerations require strategic partitioning of the board layout, physically separating high-current laser and motor circuits from low-voltage control signals to prevent noise coupling. Thermal management challenges emerge from heat-generating components like the laser driver and motor controllers, necessitating thoughtful placement near board edges, thermal vias, and adequate copper pours for heat dissipation. All these design decisions must align with our $500 budget, favoring standard FR-4 materials and conventional manufacturing processes over specialized alternatives.

Material selection reflects a careful balance between performance and cost. Standard FR-4 emerges as the optimal choice, offering sufficient thermal performance (with a glass transition temperature of 130-140°C) at the most economical price point. While high-Tg FR-4 variants provide enhanced thermal resistance (Tg >170°C), their additional cost proves unnecessary for our application's power profile. More exotic materials like polyimide or Rogers substrates, despite their superior thermal and high-frequency characteristics, would strain our budget without providing meaningful benefits for our primarily DC and low-frequency design. By adhering to these standards and constraints, our PCB design achieves the necessary performance and reliability while remaining feasible for prototyping and future production.

3.2.1 SPI

SPI (Serial Peripheral Interface) is a synchronous, full-duplex communication protocol widely adopted in embedded systems for its simplicity and high throughput. At its core, SPI uses a master/slave architecture in which the master generates a clock (SCLK) to synchronize data transfers, and each slave is selected via an individual chip-select (CS) line. Because MOSI (Master Out, Slave In) and MISO (Master In, Slave Out) are separate data lanes, SPI can transmit and receive data simultaneously—ideal for applications where speed and deterministic timing are critical.

Data exchange over SPI occurs one bit per clock edge, with the master toggling SCLK to “clock out” MOSI data while “clocking in” MISO data from the addressed slave. The CS signal frames each transaction, ensuring that only the targeted device responds. In practice, pull-up or pull-down resistors on CS lines maintain defined idle states, preventing spurious selections. The absence of start/stop bits and parity overhead means raw data rates can reach multiple megabits per second, limited only by signal integrity and trace length.

However, SPI’s advantages come with trade-offs. Each additional slave requires its own CS line, consuming GPIO resources. There is no built-in arbitration or acknowledgment, so higher-level protocols must handle error detection and device coordination. For our Braille printer prototype, SPI makes sense if we need fast external flash or high-speed display updates, but we’ll balance pin usage carefully—reserving MOSI, MISO, SCLK, and a minimal number of CS lines to keep the MCU’s GPIO footprint under control.

3.2.2 UART

UART (Universal Asynchronous Receiver/Transmitter) is a point-to-point, asynchronous serial protocol that requires no shared clock line—only TX (transmit), RX (receive), and a common ground. Before communication begins, both devices agree on a baud rate. Data is packaged with start and stop bits (and optionally a parity bit) to delineate each byte, allowing the receiver to synchronize on the falling edge of the start bit and sample the data line at predetermined intervals.

Because UART's framing overhead is minimal and its implementation widespread in MCUs, it's the go-to interface for debug consoles, external sensors, and PC-to-device communication. Its simplicity comes at the cost of half-duplex timing ambiguity; if clock drift causes misalignment, framing errors or garbled bytes result. Parity or checksums can mitigate occasional errors, but UART lacks hardware flow control unless additional lines (RTS/CTS) are added.

In our design, UART will serve as the primary text-in and status-out console. By dedicating a 4-pin header (TX, RX, VCC, GND), we can feed ASCII strings from a PC or companion microprocessor and receive real-time logs (e.g., "Cell 12 embossed," "Battery low"). This debug channel accelerates early firmware development and diagnostic testing without consuming high-speed protocol resources.

Specifically, UART facilitates the interactions required between Python and C. Python needs to send commands to the MSP via C to have printer and LCD functionality as well as to handle all high level logic. This includes handling the hardware-software interaction on iterating through either the text file or keyboard entry. After the python script translates each word, the command for how to print each letter or word is sent via UART to the MSP where C will be used to operate the functionality behind the printer.

3.2.3 I²C

I²C (Inter-Integrated Circuit) is a two-wire, multi-master, half-duplex bus that combines a data line (SDA) and a clock line (SCL), both open-drain with pull-up resistors. Devices are identified by 7- or 10-bit addresses, allowing dozens of peripherals on the same bus. During each transaction, the master generates clock pulses on SCL and toggles SDA to transmit address, read/write bits, and payload bytes, while slaves pull SDA low to acknowledge (ACK) each byte.

Because I²C supports bidirectional data and clock stretching, it's well suited for mixed-speed peripherals like temperature sensors, EEPROMs, and simple character displays. Its built-in ACK/NACK mechanism provides basic error signaling. However, bus capacitance limits total line length and practical speed (usually 100–400 kHz for standard and fast modes, up to 1 MHz for fast-mode plus), and the open-drain design means each bit transfer takes two clock phases.

In our planning, I²C is perfect for low-bandwidth, on-board peripherals: a fuel-gauge IC to monitor battery state, an ambient-temperature sensor for thermal safety, or an optional I²C-driven OLED for status readout. By grouping these devices on one bus, we minimize pin usage and simplify schematic complexity, reserving SPI and UART for functions that demand full-duplex or high-speed transfers.

3.2.4 LCD

Character LCDs (e.g., 16×2 or 20×4 modules) remain popular in hobby and industrial designs for their low cost, ease of use, and readability in a variety of lighting conditions. They typically use HD44780-compatible controllers, which can operate over an 8- or 4-bit parallel interface—allowing text to be written directly to DDRAM addresses. Backlight LEDs ensure contrast, and adjustable contrast pins let you dial in visibility.

While parallel interfaces consume many MCU pins, many modules now include I²C adaptor boards that convert I²C commands into parallel writes, reducing control lines to two. This adapter also handles backlight control, enabling simple commands like “write character” or “move cursor” over a two-wire bus. Character LCDs are ideal for displaying simple status messages (“Ready,” “Line 3/10”) without framebuffer complexity.

Graphical LCDs and small OLEDs offer pixel-level control (allowing custom fonts and simple graphics), but they demand SPI or parallel bandwidth and more RAM for framebuffer storage. For our initial prototype, a basic I²C-adapted character LCD strikes the best balance: it uses minimal pins, integrates seamlessly with our I²C bus, and provides immediate visual feedback during embossing tests—without the cost and code overhead of a full graphics solution.

Feature	**Character LCD HD44780**	**Graphical LCD**	**OLED**
Interface	Parallel or I2C	Parallel/SPI	I2C/SPI
Pins Required	6–11 (parallel) or 2 (I2C)	5–9 (SPI) or 7+ (parallel)	2 (I2C) or 4+ (SPI)
Speed	Slow (I2C) to moderate (parallel)	Moderate (SPI)	Fast (SPI), Slow (I2C)
Flexibility	Text-only	Custom graphics	Custom graphics/text
Cost	$2-$5	$5-$15	$8-$20

Table 3: Display Comparison Chart

3.3 Microcontroller System

The microcontroller serves as the central nervous system of our Braille etching device, orchestrating all critical operations from laser control to user interface management. Given its pivotal role, selecting the right microcontroller requires balancing computational capabilities, peripheral support, power efficiency, and development accessibility. Our system demands an MCU capable of precise stepper motor control for laser positioning, real-time Braille translation, communication with multiple peripherals including cameras and displays, and robust safety monitoring. These requirements guided our evaluation of available microcontroller options.

Among the considered options, the MSP430 family from Texas Instruments emerged as a strong candidate due to our team's prior experience with these chips in embedded systems coursework. We currently have access to two MSP430 models: the MSP430FR6989 and MSP430G2553. The MSP430FR6989 operates at 16 MHz with 128 kB of flash memory and 2 kB RAM, offering 83 GPIO pins and supporting UART, SPI, and I2C communication protocols. By comparison, the MSP430G2553 shares the same clock speed but provides only 16 kB flash, 0.5 kB RAM, and 24 GPIO pins, while supporting the same communication standards. A third option, the MSP430F56, offers improved specifications with 20 MHz operation, 256 kB flash, and 16 kB RAM, but is not currently available to our team.

The MSP430 family's key advantages include exceptional power efficiency with six low-power modes, which aligns perfectly with our portable device's battery life requirements. The availability of Code Composer Studio as a mature development environment with robust debugging tools further strengthens the case for these microcontrollers. Our existing inventory of MSP430FR6989 units provides additional practical benefits, eliminating procurement delays and costs while allowing us to leverage our team's familiarity with the platform.

However, we must acknowledge certain limitations. The 16-bit architecture, while sufficient for our basic requirements, may present challenges if our Braille translation algorithms grow in complexity. The limited RAM, particularly in the MSP430G2553 variant, could constrain buffer sizes for text processing. We also considered alternative microcontroller families, including 8-bit ATmega chips and 32-bit STM32 ARM processors. While the ATmega series offers cost advantages, its lack of native USB support and limited processing power made it less suitable. The STM32 family, particularly models like the STM32F407VET6, provides superior performance with 32-bit processing and larger memory, but would require our team to adopt new development tools and workflows.

The microcontroller is a central component of our Braille etching system, responsible for coordinating motion control, signal timing, and user input processing. During the selection process, our team evaluated several potential candidates, including Arduino-based AVR microcontrollers, the ESP32 platform, and members of Texas Instruments' MSP430 family. After careful consideration of our system requirements—such as power efficiency, peripheral support, memory capacity, and development familiarity—we determined that the MSP430FR6989 was the most suitable choice for our design.

One of the primary reasons for selecting the MSP430FR6989 is its extremely low power consumption. The microcontroller is designed to support various low-power operational modes, making it well-suited for applications that require efficient energy use, particularly when operating in thermally sensitive or battery-powered environments. It also incorporates ferroelectric RAM (FRAM), which not only provides fast read/write access but also offers significantly higher endurance compared to traditional flash memory. This allows us to store and update temporary buffers or etch data during operation without concern for memory wear.

In addition to power efficiency, the MSP430FR6989 provides a rich suite of built-in peripherals that are directly aligned with our project's needs. It features multiple 12-bit ADC channels, three timers capable of PWM generation, and support for essential communication protocols including UART, SPI, and I2C. These peripherals are necessary to handle tasks such as sending control pulses to the DRV8825 stepper motor drivers, reading input from push buttons, controlling a laser firing signal via PWM, and potentially communicating with a display or external storage device. The abundance of peripherals allows us to implement these features without relying on external hardware extensions or complex multiplexing schemes.

Another key advantage of the FR6989 is its large number of general-purpose I/O pins—up to 83—enabling us to make clean, isolated connections to each subsystem. This simplifies PCB routing and improves signal integrity across the design. In contrast, other microcontrollers we considered, such as the MSP430G2553, offered far fewer GPIO pins, and their reduced peripheral sets would have significantly limited the scalability and modularity of our system. The G2553 also contains only 16 kilobytes of flash and 512 bytes of RAM, which would not be sufficient for storing firmware, runtime buffers, and future feature expansions.

Finally, our team's prior experience with the MSP430 ecosystem played a role in the selection. We are already familiar with TI's Code Composer Studio and associated driver libraries, which reduces the onboarding time required to develop, debug, and deploy firmware. The MSP430 LaunchPad development kits are also readily available and relatively inexpensive, minimizing budget strain and avoiding potential delays caused by supply chain issues. Altogether, the MSP430FR6989's balance of energy efficiency, peripheral support, memory architecture, GPIO availability, and ease of development makes it the optimal microcontroller choice for our Braille etching device.

Device Name	**MSP430FR6989**	**MSP430G2553**	**MSP430F56**

Frequency (MHz)	16	16	20
Flash Memory (kB)	128	16	256
RAM (kB)	2	0.5	16
GPIO Pins (#)	83	24	74
Supported Protocols	UART, SPI, I2C	UART, SPI, I2C	UART, I2C, USB 2.0
Power Efficiency	Excellent	Excellent	Good
USB Support	No	No	Yes
Ease of Development	High	High	Medium

Table 4: Microcontroller Comparison Chart

Beyond microcontroller selection, the successful deployment of the MSP430FR6989 in our system requires strategic integration with the hardware and firmware layers of the device. The microcontroller's architecture and pin layout significantly influence our PCB design and subsystem communication. For instance, the control signals for our stepper motors—STEP and DIR lines—are routed through GPIO pins on Port 2 of the MSP430 to take advantage of contiguous pin groupings and reduce trace complexity on the board. This enables synchronized timing control and minimizes signal interference. Pulse generation for motor control is handled using the onboard Timer_A module, which supports precise PWM output and is configured to deliver clock-accurate pulse trains to the DRV8825 drivers.

The laser control mechanism is similarly routed through a PWM-capable output pin, allowing us to modulate burn duration through duty cycle adjustment. This approach gives us fine-grained control over the laser's exposure time per etched dot, a critical factor for ensuring clean and legible Braille cell patterns. Additionally, user interface components such as physical push buttons are assigned to GPIO pins equipped with internal pull-up resistor capabilities, reducing the need for external circuitry and simplifying the BOM. These buttons can be configured with edge-triggered interrupts to reduce polling overhead and improve firmware responsiveness.

In terms of communication, the UART interface on Port 4 is reserved for serial debugging and may later support Bluetooth module integration for wireless data transfer. We have also allocated unused SPI and I2C pins on Port 3 for future peripherals, such as an LCD display for user feedback or an SD card module for non-volatile storage of translated Braille content. Keeping these interfaces reserved during SD1 provides headroom for expansion in SD2, ensuring that the design remains modular and scalable.

The FRAM memory architecture of the MSP430FR6989 plays a crucial role in system resilience and flexibility. Runtime buffers, character maps, and translation state data can be dynamically written to non-volatile memory without degrading the hardware over time. This allows the device to maintain session continuity in the event of a power interruption. A designated memory region is reserved for storing custom character sets or configuration parameters that may be programmed in the field, adding adaptability to the final implementation.

From a power perspective, the microcontroller and all logic-level components operate from a regulated 3.3V supply derived from an LDO linear regulator. The entire logic side draws less than 25 mA during typical operation, with the MSP430 contributing only around 2.5 mA at 16 MHz. During idle intervals between etching cycles, the system enters Low-Power Mode 3 (LPM3), reducing current draw to under 5 µA. This efficiency is critical for thermal management and energy budgeting, particularly if the device is later transitioned to a battery-powered form factor.

The integration strategy for the MSP430FR6989 not only supports the technical requirements of the Braille etching process but also informs several layers of the system architecture—from schematic design to firmware flow. The peripheral mapping, signal timing, and memory access patterns implemented in SD1 provide the foundation for a robust, scalable, and efficient embedded system that will be fully realized and tested during the SD2 phase of development.

3.4 Power

The way power should be distributed for this project should be able to power the microcontroller(s), peripherals (keyboard, LCD screen, motor, camera [stretch]) and the laser. There are many options to achieve this goal, such as using wall power, designing a battery pack/battery system, or even using solar. We can also use a combination of the options, such as wall power and a battery system. It would be a benefit to have rechargeable/replaceable batteries as well as a system that can run on pure wall power without needing to worry about the system running out of charge. Using a configuration that utilizes solar power would not make as much sense as we would like it to be used indoors. So that makes a wall power system paired with a battery pack the ideal choice.

We can utilize an on-board power path circuit that can choose which input power is in use. For example, when the system is plugged into the wall, it will turn off the supply from the batteries. When it is unplugged from the wall, it can run off the battery pack. This makes our system more usable in the real world as it does not have to be permanently plugged into the wall. In our scenario, it can be moved anywhere in a classroom or around the house.

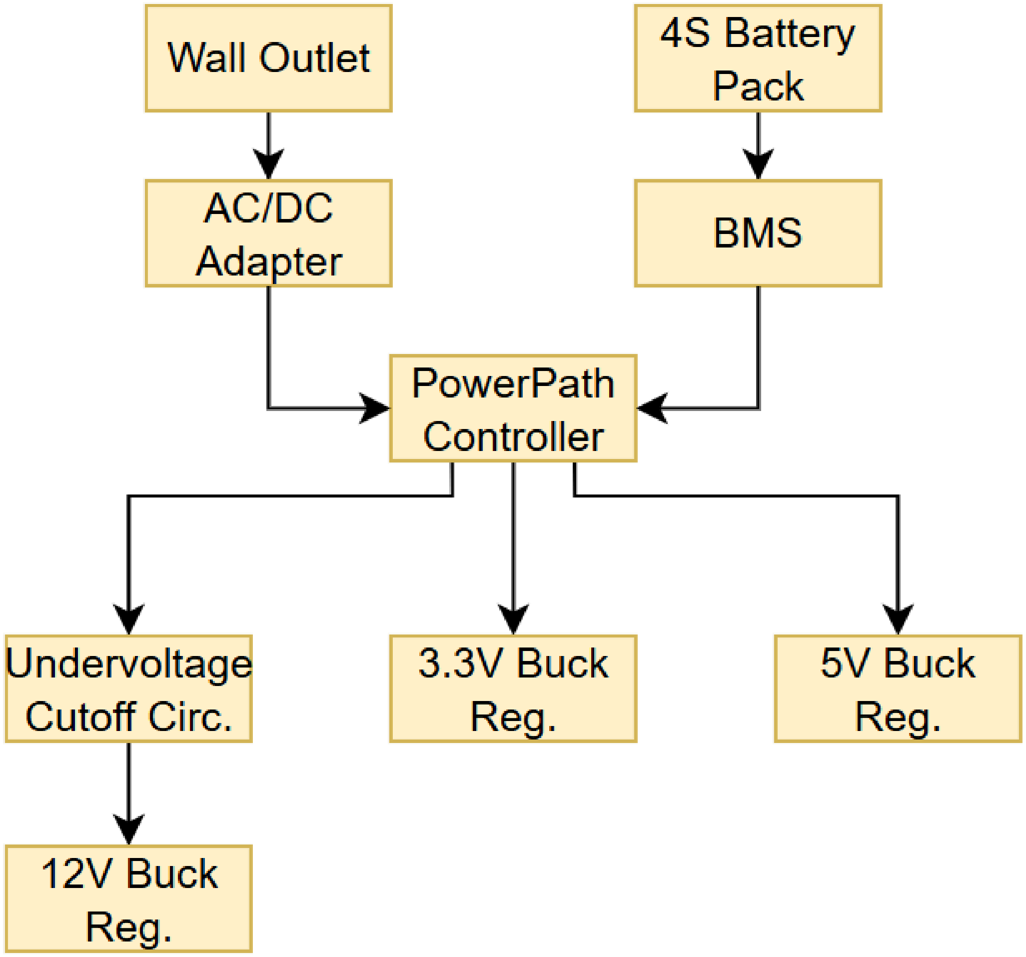


Figure 6: Detailed Power Supply Block Diagram

The PSU block diagram simplifies the way the power supply system will operate. We will have two input voltages, either using wall power or a 4S battery pack. The wall power will be supplied by an AC/DC wall adapter that is larger than 16.8-volts as the PowerPath controller will decide which input will be used by choosing the one currently supplying the highest input voltage. Since our battery pack will supply around 16.8-volts at maximum charge, we must use an AC/DC wall adapter that supplies more than this, so the PowerPath controller knows when to prioritize wall power over the battery. Then the PowerPath controller will go to various buck regulators, noting that the 12-volt buck regulator must be equipped with an undervoltage cutoff circuit. This is because the battery pack will have a minimum voltage of 10-volts (when almost fully depleted), so we want to ensure that we do not damage our system by supplying an input to the 12-volt buck regulator that is less than 12-volts. Then each regulator will supply power to all the peripherals to fully operate our system.

3.4.1 PSU Goals

The goal is to create a rechargeable/replaceable battery system and wall power capability, ideally ~15 volts, that will use buck/boost converters to regulate voltage for the peripherals, laser, and motor. We will then take the voltage our PSU outputs and utilize linear regulators, buck/boost regulators to either step down or step up the voltage. We can step up our voltage to power the laser, and step down our voltage for the peripherals. Utilizing either a voltage rail or multiple regulators will help achieve a constant voltage going to our peripherals and laser, ensuring no voltage drops or loss of power. We also want the system to last around two hours at full utilization/load. Since this system would not be constantly running, it should ideally last the user a full day (or session) of taking text and printing it in braille.

3.4.2 Battery Pack Design Options

The battery pack can be designed in a couple of ways, notably using Lithium Polymer (LiPo) batteries, lithium-ion batteries, or alkaline batteries. We want to achieve a nominal voltage of 12-16 volts as this is a common standard, so we want to have 3-4 series of batteries to get around 11-15 volts, with varying voltage at fully charged and fully discharged, depending on the battery. We also want to increase our mAh so we have no issues powering our device for extended periods of time, meaning we want to connect batteries in parallel. Ideally, we want to have 2 batteries in parallel and have 3-4 series of them. Totaling 6 to 8 batteries at 11-15 volts and around 6000-7000 mAh. This should have no issues powering our system when we start to utilize buck converters as well as no issues staying ‘alive’ before running out of charge.

3.4.3 Alkaline vs. Lithium Polymer vs. Lithium-Ion Batteries

There are key differences between lithium polymer, lithium-ion, and alkaline batteries such as their chemistry makeup, packaging, *safety*, cycle life, etc. Due to these differences, we must take into consideration what each type of battery has to offer and how it will benefit us the most.

Battery Type	**Alkaline**	**Li-Po**	**Li-Ion**
Nominal Voltage [V]	1.5	3.6 – 3.7	3.6 – 3.7
Operating Range [V]	0.9 – 1.6	2.75 – 4.2	2.5 – 4.2
Capacity [mAh]	500 – 3000	500 – 3000	800 – 5000
Cycle Life [Cycles]	N/A	200 – 500	300 – 500

Rechargeable	No	Yes	Yes

Table 5: Battery Type Comparisons

3.4.3.1 Alkaline

Alkaline batteries are typically what the average person would imagine when they hear the word battery. These are your AAA, AA, C, and D batteries that you would typically buy off the shelf for common household appliances, toys, etc. Alkaline batteries are composed of zinc and manganese dioxide as electrodes. They are typically used in low and high drain applications and low voltage applications, (e.g. alarm clocks, remotes, computer mice). They also offer an extremely low discharge rate allowing them to sit around on the shelf without losing their charge. One of their biggest flaws is their inability to recharge unlike their other lithium-ion/polymer competitors. Combined with their low voltage usage, using lithium battery counterparts makes more sense to use.

3.4.3.2 Lithium Polymer

Lithium polymer batteries are far newer than lithium-ion batteries (introduced in the late 1900s), and are seen in a various range of RC vehicles, hobbyist's projects, and DIY projects. These batteries are very portable as they have a small form factor and can squeeze into small housings. This is due to a key factor: they use a gel-like or a solid substance. In order to make lithium polymer batteries "conductive at room temperature, gelled electrolyte has been added" [10]. This allows these cells to be made much thinner than a traditional lithium-ion battery, hence the reason they are found in many devices today.

However, there are safety risks when using lithium polymer batteries. Making the cells thinner and putting them in a pouch casing makes them susceptible to puncturing or swelling, which is extremely dangerous. And you will only find them in pouch form. They are also prone to overcharge and catch on fire when they become overheated. This is why if we are to use lithium polymer batteries, we are not allowed to use them inside of the Senior Design laboratory as they are deemed unsafe.

3.4.3.3 Lithium-Ion

Lithium-Ion batteries are also batteries used in everyday electronics such as smartphones, laptops, power banks, vehicles, you name it. These batteries are also very portable and can be housed in a pouch similar to lithium polymer or in the form of 18650/21700 battery cylinders. These cylinders are very common and inexpensive as well and are what you think of when you think of a battery. These batteries are also very low maintenance [11], recyclable, and will be relatively safe when they have built-in circuit protection. They come in two forms, protected and unprotected.

Protected cells will come with a protection circuit that will prevent short-circuiting, overcharging, and over-discharging. This built-in circuit monitors temperature, voltage, and current to prevent these common failing points. However, the downside to a protected cell is from the protection circuit itself. It will typically limit the maximum output current, which is not ideal in applications where we need a lot of power. Unprotected cells lack the usage of protection circuits, which is a positive in this case as they will be able to output more current. They are also a bit cheaper than protected cells. Since they are unprotected, we must utilize a battery management system (BMS) when using multiple cells in parallel and in series. They offer higher energy density than lithium polymer batteries too. We are also allowed to use them inside the Senior Design laboratory, so that is a huge plus when it comes to using these batteries.

3.4.3.4 Battery Selection

After comparing the three battery options: lithium-ion, lithium-polymer, and alkaline, we are deciding to move forward with unprotected lithium-ion batteries. They offer a high maximum output current when paired with a battery management system and will satisfy our power needs. Alkaline batteries prove to be very lackluster when it comes to a project like this, so the main decision came from weighing the options of lithium-polymer and lithium-ion. Lithium-polymer batteries are only found in pouch form, and despite their smaller form factor, putting them in a confined space packed together will be too dangerous and unsafe. Lithium-ion batteries are easier to handle and typically safer when using them in a controlled environment. Due to their ease of use, flexibility, positives, and a high nominal voltage, they will be a good fit for our project.

3.4.4 Lithium-Ion Battery Options

There are various options to consider when choosing which lithium-ion batteries will work best for our device. Choosing the size of the battery will be the main object for this custom battery pack. Lithium-ion batteries come in many sizes, most notably, the 14500,18650, 21700, 26650, etc. The way they are classified is the dimensions, where the number is the diameter and the length of the battery. For example, an 18650 battery is 18 mm in diameter and 65 mm in length. Each size of battery has its own capabilities, specifically their mAh capacities and maximum discharge current. These batteries come in three forms, an energy cell, power cell, or a hybrid cell. Each type of cell has its own characteristics and is better suited for different applications. Two key components are their capacity and their maximum discharge current, or continuous discharge rating (CDR). CDR is the maximum amount of current a battery cell can supply nonstop until it is discharged. If you go beyond the rated CDR, then you can experience overheating, damage, or a decrease in lifespan.

3.4.4.1 Energy Cells

High energy cells “will have better…energy density at the expense of the ability to deliver a high current” [12]. The electrodes have medium to large particle sizes, low conductive carbon content, high coat weights, and low coating porosity. This enables them to have a much higher capacity at the cost of being able to deliver high current. The energy cell has “thicker layers of active material, thinner current collectors and less of them” [12]. Due to this, it will have a much higher electrical internal resistance, resulting in more heat generation. It has poor thermal conductivity in-plane and through-plane, needing a higher temperature gradient to reject this heat.

Battery (Energy Cell)	**14500**	**18650**	**21700**
Nominal Voltage [V]	3.6 – 3.7	3.6 – 3.7	3.6 – 3.7
Operating Range [V]	2.5 – 4.2	2.5 – 4.2	2.5 – 4.2
Capacity [mAh]	900 – 1000	3000 – 3500	4800 – 5000
CDR [A]	2 – 3	10 – 12	10 – 15
Cost/Cell [$]	4 – 6	6 – 9	7 – 12

Table 6: Energy Cell Comparisons by Size

3.4.4.2 Power Cells

Power cells will have a lower internal resistance and “will be optimized to deliver current over energy density” [12]. These cells’ electrodes are direct opposites of energy cells, where they have low coat weights, higher conductive carbon content, small and medium particle sizes, and a higher coating porosity. Their current collectors are also much thicker than energy cells, which is why their ability to deliver more current along with the other characteristics listed prior.

Battery (Power Cell)	**14500**	**18650**	**21700**
Nominal Voltage [V]	3.6 – 3.7	3.6 – 3.7	3.6 – 3.7
Operating Range [V]	2.5 – 4.2	2.5 – 4.2	2.5 – 4.2

Capacity [mAh]	600 – 700	2000 – 3000	3700 – 4200
CDR [A]	6 – 10	20 – 35	30 – 45
Cost/Cell [$]	5 – 8	6 – 10	8 – 15

Table 7: Power Cell Comparisons by Size

3.4.4.3 Hybrid Cells

Hybrid cells fall in between the characteristics of energy and power cells. They have both moderate capacity and moderate delivery of current. They are the middle ground of power and energy cells where their porosity, particle sizes, carbon content, and coat weights are modified in a way to grant the best of both worlds, where certain characteristics are achieved without sacrificing other key factors. Such as capacity and their CDR. One thing to note about the table below is 14500 battery cells not being available in hybrid form due to the lack of size. Due to its smaller form factor, it is more beneficial to either make it have higher capacity or higher CDR.

Battery (Hybrid Cell)	**18650**	**21700**
Nominal Voltage [V]	3.6 – 3.7	3.6 – 3.7
Operating Range [V]	2.5 – 4.2	2.5 – 4.2
Capacity [mAh]	2800 – 3100	4000 – 4500
CDR [A]	15 – 20	15 – 25
Cost/Cell [$]	6 – 10	8 – 14

Table 8: Hybrid Cell Comparisons by Size

3.4.4.4 Battery Dimension Selection

Each size of battery has its own positives and negatives. Power cells offer a high CDR but have smaller capacities, energy cells have high capacities but lower CDR, and hybrid cells have the “average” of both. Using a hybrid cell for this system should provide us with the best of both worlds of high CDR and high capacity. This allows our system to stay on for longer periods of time when using the battery system as well as providing enough current to all our peripherals. The reason we chose an 18650 cell over a 21700 cell is because they are cheaper and a bit overkill for our project. We are going to use 8 batteries.

Since we are now combining multiple cells of batteries together, we have to orient them correctly. Connecting batteries in series will increase the voltage by addition but will have no increase/decrease on the mAh value. Connecting them in parallel will increase the mAh value by addition with no effect on the voltage. This results in a 4S2P battery pack, four cells in series and two in parallel. This will give us a nominal voltage of 14.4 to 14.8 volts and a capacity of 5,600 to 6200 mAh. This will be sufficient enough to power our system for a long time. Below is a simple 4S2P battery configuration using eight 3.6 volt batteries, showing that they output 14.4 volts (3.6*4 = 14.4 V). This can be shown in a simple simulation inside of LTSpice:

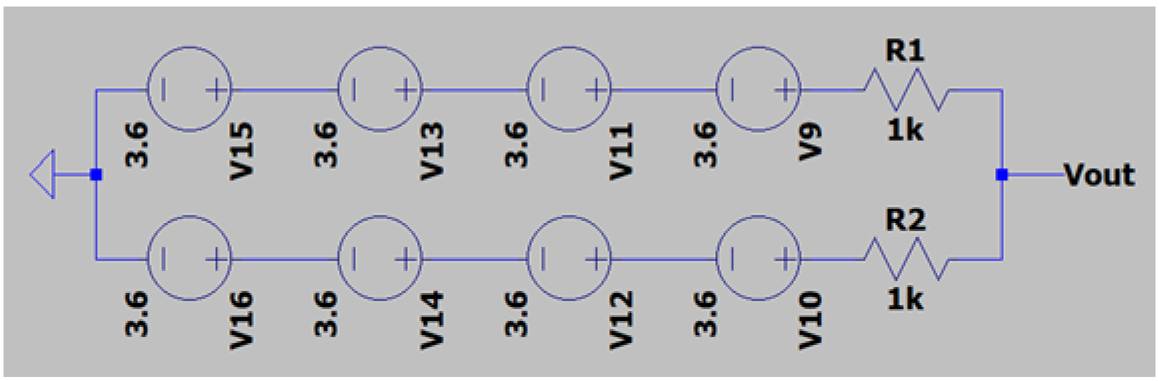


Figure 7: Simple 4S2P battery pack design in LTSpice

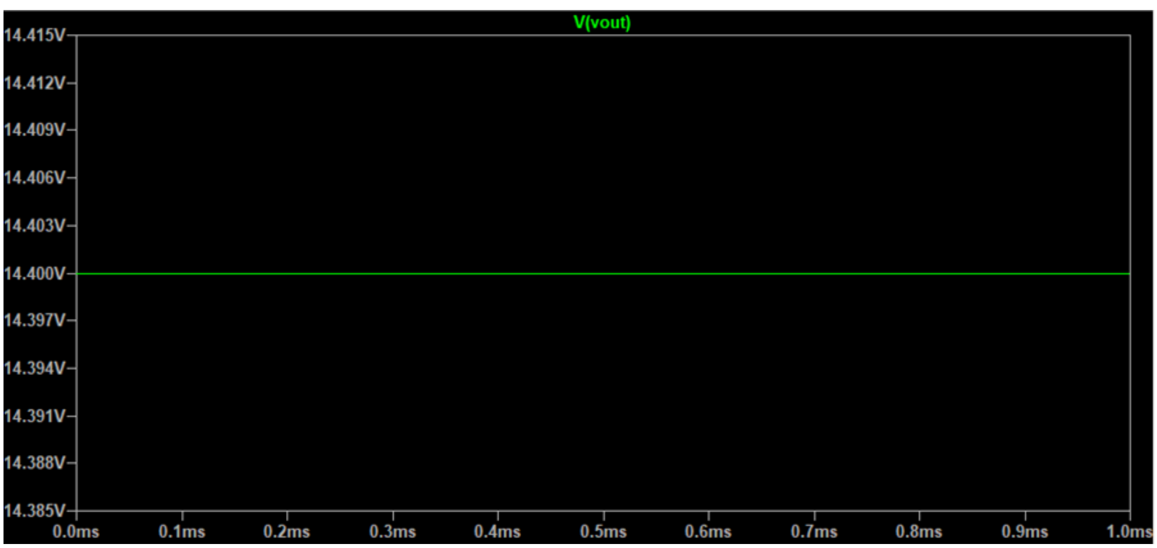


Figure 8: Output waveform of Vout showing 14.4-volts DC in LTSpice

3.4.5 Battery Management System

The battery management system is a vital piece of the battery pack, specifically, for unprotected cells. The BMS has a lot of key functions that make it so crucial to have for the battery pack. It will monitor the battery, provide battery protection (undervoltage, overvoltage), will optimize the battery performance, and can provide balance charging (important). The important function that a BMS must have for a battery pack is the ability to keep the cells balanced when charging. When battery cells are not balanced, i.e., one cell is overcharged and one is undercharged, it can create a fire hazard. Imbalanced cells are something that we must avoid no matter what as just a singular cell can limit our back, or much worse, malfunction and start a fire. When choosing a BMS, we must look for a balancing header that connects to a balance harness that then connects to the battery pack, keeping the battery cells balanced when charging.

There are a lot of benefits when using battery management systems. They will increase the life span, reliability, performance, range, and safety of battery packs that they connect to. Being able to protect the battery pack gives us the confidence we need when using a custom battery powered supply, making it essential to have for our unprotected battery cells as these do not have any built in circuit protection. The reason for choosing unprotected cells is explained in *3.4.3.3 Lithium-Ion*, which is the reason for needing a BMS.

Battery management systems come in many forms, specifically related to the number of batteries that are in series. This can be a 2S, 3S, 4S, up to around 16S. They are typically equipped with pads labeled “B-, B+, B1-Bx (‘x’ is the number of batteries in series minus 1), P-, and P+.” “B+/-“ are the pads connect to the beginning off the battery pack and the end, creating the combined output voltage of the cells. The “P+/-“ pads are the pads that we connect to when we want to use the battery pack, as well as charge it. And “B1-Bx” connect to the groups of batteries in series. Since we want to design a 4S battery pack, we will choose a 4S BMS. A simple model of what a 4S BMS with a balancing header looks like is below:

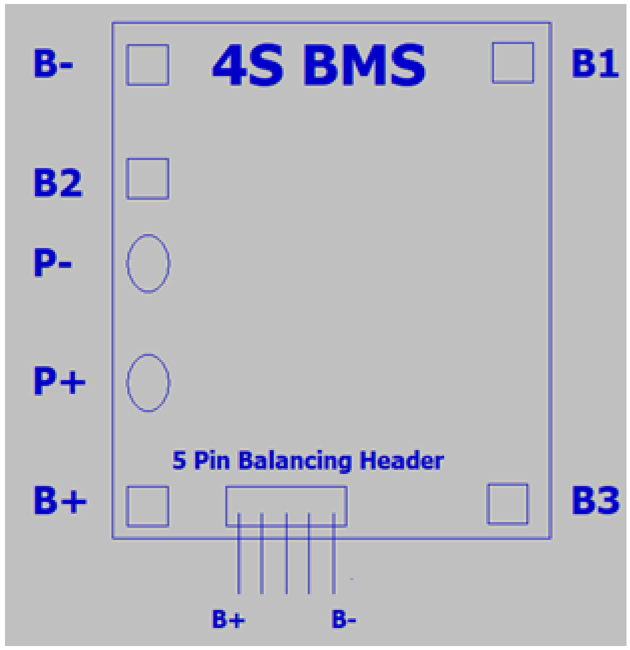


Figure 9: Typical 4S BMS layout with a balancing header

3.4.6 Linear Regulators (LDO) vs. Switching Regulators (Buck/Boost)

Choosing between an LDO or a switching regulator is very important, where each has their own advantages and disadvantages. Linear regulators are very simple and work best when the input voltage is slightly greater than the output voltage required. However, their thermal performance and efficiency are severely lacking in comparison to switching regulators. “With a large difference between the input and output voltages, the switching regulator…excels in efficiency compared to either linear circuit” [13]. Using this reference, we can look at the tables comparing switching regulators to integrated/discrete linear regulators. These are based on a 5-V output from a 24-V bus. The linear regulators take a major hit on efficiency (boasting an underwhelming 20% efficiency based on Texas Instruments tests) and power loss versus switching regulators due to the large difference in input and output voltage (switching regulator at 84.5% efficiency). We can also note the difference in complexity as well, where the linear regulators need a larger board area but fewer components, and the switching regulator utilizes the board area more efficiently but uses more components.

With our system, we will choose to use switching regulators due to their extremely high efficiency and low power loss when operating with a larger difference in input and output voltage, despite their complexity over LDOs. We should see even higher efficiency numbers as our input voltage will be close to 12-V and our output voltages will be 3.3-V, 5-V, and possibly 12-V for the laser.

3.4.7 Voltage Regulator Options

There are many switching regulators that we can utilize to either “step-up” or “step-down” our input voltage. The most common options are the buck, boost, and buck-boost (or inverting) regulators. Other less notable options include the flyback, push-pull, half-bridge, and full-bridge regulators. We will be going in depth about each of the common options listed above in depth where we will go over reasons why each option can be of benefit to our project.

Switching Regulator	**Buck**	**Boost**	**Buck-Boost**
Input Voltage [V]	1 – 100	0.5 – 40	2 – 40
Polarity	Positive	Positive	Negative
Output Voltage [V]	0.8 – Vin	Vin – 100+	-(0.8 – 100)
Efficiency [%]	85 – 95	75 – 90	70 – 85
Ripple Voltage [mV]	< 50	50 – 100	50 - 200

Table 9: Regulator Comparisons

3.4.7.1 Buck Regulator

The buck regulator “steps-down” the input DC voltage to a lower, constant DC voltage of the same polarity. Buck regulators are a key component in a system where we want to create multiple “voltage suppliers” to other peripherals/components. We know that we cannot simply give an MSP430 12 volts to power it on as this will destroy the chip, so we must utilize a buck regulator to step this voltage down to the 3.3 volts it needs. This example can be used for any peripheral or component. Buck converters can step this voltage down with very little power loss. They use a “transistor as a switch that alternately connects and disconnects the input voltage to an inductor” [14]. This switch is actively being turned on and off at a high frequency controlled by a PWM and the output capacitor and inductor will smooth out these switching pulses, resulting in a constant DC voltage that is lower than the input voltage used. It can do this with very high efficiency, making buck converters essential in any circuit.
The reason for choosing only buck regulators in our system is due to using a 4S2P battery system and a wall adapter with a larger input voltage than our battery pack (to make the PowerPath integration easier). Stepping down our voltage for the laser will be more reliable as boost converters have higher

switching losses and may drop in efficiency when or if the laser draws a lot of current.

3.4.7.2 Boost Regulator

Boost regulators will “step-up” the input DC voltage and output a constant higher DC voltage of the same polarity. These are also key components in the same way buck regulators are. Say we only have a 8–10-volt input voltage and want to power a laser that needs 12 volts. We must utilize a boost converter to step this voltage up to the laser so we can meet its power needs. Boost converters work in a very similar way to buck converters, they use a nearly identical circuit but swap the diode, transistor, and inductor to achieve a constant DC voltage higher than the input voltage. The switching mechanism works the same as the buck regulator, but produces an average DC voltage higher than the input voltage at a very high efficiency.

3.4.7.3 Buck-Boost/Inverting Regulator

A buck-boost regulator will take a DC input voltage and produce a DC output voltage in the opposite polarity of the input, hence the name inverting regulator. This negative output voltage can either be larger or smaller than the input voltage, also where the “buck-boost” name comes from. This circuit also swaps a couple components (in this case, the diode and inductor from the buck regulator), resulting in all three options having very similar footprints. The way we can determine whether the output voltage is higher or lower than the input voltage is the duty cycle, which translates to the time the MOSFET is on and off. This will generate various magnitudes of output voltage depending on the duty cycle.

3.4.7.4 Buck Regulator Part Selection

We will be moving along with the buck regulator; we must select the right component for our system. There are various types of buck regulators out there that are able to accomplish what we want. We need to design three types of step-down regulators: a 3.3-volt, 5-volt, and a 12-volt regulator. These regulators are essential in stepping down our input voltage to a useable, constant input voltage that can power various components in our system. These components include the motors, motor controller, MSP430, and the Raspberry Pi. The difference between each buck regulator comes down to the technique they use for switching (going from high voltage to low voltage). We also want to take note of their maximum output current. The three regulators we will take a look at are the LM2596, TPS5430, and the LT8609.

Buck Converter	**LM2596**	**TPS5430**	**LT8609**
Input Voltage [V]	4.5 – 40	5.5 – 36	3 – 42

Output Load Current [A]	3	3 (4 peak)	3
Efficiency [%]	Up to 73	Up to 95	Up to 95+
Switching Frequency [Hz]	150k	500k	200k – 2.2M
Operating Junction Temperature [C]	-65 – 150	-40 – 125	-40 – 125

Table 10: Buck Converter Comparison Table

The reason we will be choosing the LM2596 buck converter over the other options is because of its simplicity, familiar use (from previous classes), its cost, purpose, and availability. For our project, we will be utilizing five of these, each for one major component in the system. The 3.3V regulator will provide power to the MSP430 which will only require a minimum amount current, then the 5V will go to the Raspberry Pi and since we will only be utilizing it for text translation and taking input from a keyboard (versus using its HDMI, Wi-Fi, or other high-tech features), we expect the current draw to be low as well. Then one 12V regulator will power each of the DRV8825s and the laser, which will not draw close to the maximum output current.

3.4.8 PowerPath Controller

A PowerPath controller is used when a system has multiple power supplies. In our case, we will have a battery pack to power the system when the user wants to use it away from a wall outlet, or they can use wall power to power the system. It essentially manages the flow of power between multiple PSUs. They also have the capability to keep the system powered on when unplugging from the wall and switching to the battery power simultaneously. They achieve this by “minimizing reverse currents back into the supply and shoot-through currents between supplies” [15]. The two ways to determine which power supply supplies power are either by the highest voltage or highest priority. Implementing a PowerPath controller that decides which power supply is the highest priority is difficult, whereas using a design that chooses the supply based on which one is supplying a higher voltage is easier. Therefore, it can easily decide which power supply is running. If we are using a wall adapter that is supplying a larger voltage than our battery pack voltage, then it will choose the wall power. Vice versa if the wall power is disconnected. There are various types of PowerPath controllers, such as ideal diode-based power path control, power multiplexers, and dedicated PowerPath ICs. Each comes with their own benefits and disadvantages.

PowerPath Type	**Ideal Diode-Based**	**Power Mux**	**Dedicated ICs**
PowerPath Eff.	High	High	Moderate

Control Method	Voltage Difference	Comparator	Internal Logic
Voltage [V]	< +/- 100	0.7 – 22	3 – 70
Batt. Charging	No	No	Yes
Regulation Control	No	No	IC Dependent

Table 11: PowerPath Comparisons

3.4.8.1 Ideal Diode-Based PowerPath Controller

A typical ideal diode is a MOSFET with a control circuit surrounding them. They turn on when the input voltage is greater than the output voltage (forward biased) with a voltage drop below 50mV. They turn off when the input voltage is less than the output voltage (reverse biased). Ideal diodes also minimize heat sinking requirements, increase voltage headroom for low voltage applications (below 5V), and includes additional protection features/monitoring. It combines supplies together using a diode-OR to provide “redundancy in the event of input failure or short-circuit” [16]. You can also implement a prioritization system using a diode-OR circuit that monitors the highest priority source with a resistive divider that disables the lower priority supply, given that the highest supply is available (typically above a 9V threshold). Then an extra MOSFET will be needed as well. This is a complicated process compared to using a simple diode-OR for selecting between the highest voltage supply.

3.4.8.2 Power Multiplexer PowerPath Controller

The power multiplexer uses electronic switches to select and transition between multiple (two or more) power paths to a singular output. They can be integrated in either a priority power supply system or based on the highest input voltage. The way they can control which input power supply should be active is based on three ways: manual, automatic, or both. Manual control is as it sounds, you use a manual switch/external signal to switch between input supplies. Automatic control does not need an external signal to switch between input supplies. You can either incorporate a priority system where the user chooses which supply should be prioritized or go based on the highest input voltage as stated before. Then the combination of both has an external signal that can choose the input power supply as well as an automatic switching design.

3.4.8.3 Dedicated PowerPath ICs

Dedicated PowerPath ICs will also manage multiple power supplies by switching them however the user needs. But they go beyond an ideal-diode or a multiplexer. They can also monitor voltages, provide status signals, have an integrated battery charger, multiple safety features, and offer high efficiency. However, integration can be complex as they have a larger footprint on the PCB, various external components to the IC itself, difficulty in charging batteries, difficult routing, etc. The integration of a dedicated PowerPath IC is very complex and will most definitely take a lot of time learning about them as well as integrating it into a PCB design. Overall, dedicated PowerPath ICs are the most complex way to create a system that utilizes switching power supplies such as ours.

3.4.8.4 PowerPath Controller Part Selection

Choosing the right ideal-diode PowerPath controller for the main PCB is critical to ensuring that the board is powered correctly from either the wall power or battery power. The company that makes these types of PowerPath controllers is Analog Devices, so we will look over three of their ideal diode controllers: the LTC4412, LTC4413, and LTC4416. Each ideal diode controller features an external P-channel MOSFET that will act as the ideal diode.

Part Number	**LTC4412**	**LTC4413**	**LTC4416**
Input Voltage from AC/DC Adapter [V]	3 – 28	0 – 5.5	3.6 – 36
Input Voltage from Battery [V]	2.5 – 28	2.5 – 5.5	3.6 – 36
Channels	1	2	2
Max Output Current [A]	Limited by FET	2.6 per channel	Limited by FET
Max Quiescent Current [uA] (High Supply)	26	40	130
Operating Temperature [C]	-55 – 150	-40 – 85	-40 – 125

Table 12: Ideal Diode PowerPath Part Comparison Table

We are going to choose the LTC4412 for our main PCB because of its simplicity, high input voltage range, and its usability in our system. The main factor considered for choosing which ideal diode controller was the input voltage range and the number of channels it uses. Having more channels adds unnecessary complexity to our main board design as it is essentially two ideal diode controllers in one chip. Each ideal diode controller will choose between the two inputs and output them into two separate channels, such as load 1 and load 2. In our case, we only want the input of either power supply we choose, not the input of both. This makes the single channel LTC4412 the best choice, especially since it is tailored to use an AC/DC wall adapter and a battery, which is exactly what we are using.

3.4.9 Undervoltage Cutoff Circuit

The undervoltage cutoff circuit is critical for our design as the LM2596 regulators must maintain an input voltage of 1.5 volts above the rated output voltage. This means that our 12V buck converter can run into regulation issues if our battery starts to run out of voltage, specifically, near 13.5 volts. This means that our system could run into errors, or potentially an accident if the laser and motors start to malfunction due to the 12-volt regulators not being supplied enough input voltage. This is why we will connect an undervoltage cutoff circuit to the output of the PowerPath controller to ensure that the system will not run when it detects that the battery or AC/DC power supply drops below 13.5 volts. Instead of just connecting the battery pack to the undervoltage cutoff circuit since we know it can drop below that threshold, we connect it for the entire system. This is to protect the overall system just in case the AC/DC power supply somehow rapidly degrades, or any internal issues arise from it. We can achieve this by using a TPS3808G01 supervisory circuit, which monitors the system voltage and compares it to an adjustable internal reference voltage. This threshold voltage can be chosen by this equation:

$$V_{Threshold} = 0.405(1 + \frac{R1}{R2})$$

This equation will tell us what resistor values we need to choose as well, where Vsupply is what we want the cutoff voltage to be: 13.5V. Choosing R2 to be 10k ohms, we can calculate that R1 will be 323.3k ohms. When the input voltage, VSupply, falls below the threshold voltage (13.5V), it will then make the reset pin on the TPS3808G01 low which can drive to the gate of a P-channel MOSFET. This FET will take the output of the PowerPath controller as the source, and then the drain of the FET will be the voltage source for all components in the system. An example of this is shown below.

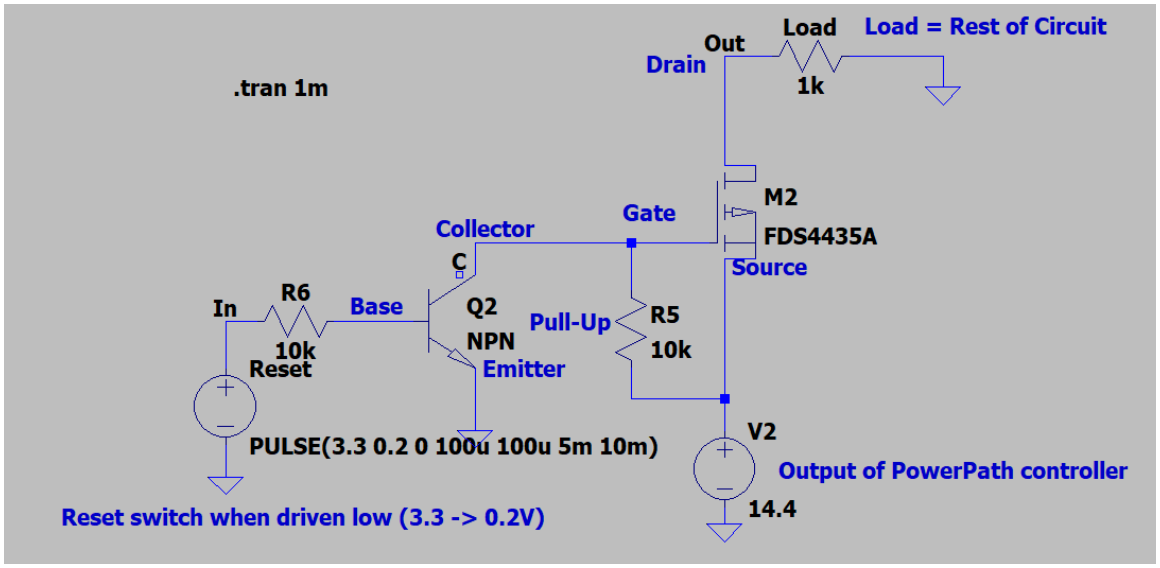


Figure 10: Example circuit using TPS3808G01 RESET Pin

The SENSE pin will use the input from the output of the PowerPath controller and run it through the voltage divider. VDD is the pin that is powered by the always-on 3.3V regulator that ensures that the internal logic is always running. Then if it detects that Vsupply falls below 13.5V, the reset pin will be pulled low, turning off the MOSFET, preventing any power flow to the main circuit. The LTSpice simulation uses a pulse voltage source, starting at 3.3V and ending at 0.2V. This is to simulate the RESET pin going from HIGH to LOW. This then goes into an NPN transistor that is being utilized to drive the P-Channel MOSFET low, to disable any current flow into the main system. When the RESET is driven low at 0.2V, the NPN turns on and drives the PMOS low via the pull-up resistor. When RESET is high (the output of the PowerPath controller is above 13.5V), the NPN stays off and will not drive the PMOS low, allowing current to flow from the PowerPath controller to the rest of the circuit. Here is the simulation showing this scenario:

Figure 11: Output Waveform of Example TPS3808 Circuit

Here we can see our V(In) starting at 3.3 volts (RESET signal high), our V(Out) starting at 14.4 volts (output from PowerPath controller), and our V(c) (the voltage at the collector of the NPN) at 0 volts. When the RESET pin is driven low to 0.2 volts, we see our V(out) and I(Load) drop to ~0 volts and ~0 amps, while our V(c) rises to 14.4 volts through the pull-up resistor. This successfully demonstrates how the RESET pin will disable any current flowing into our system when the TPS3808 senses that our battery drops below 13.5 volts.

3.5 Camera (Stretch)

The camera is not the focus of the optical design and will therefore not be discussed at length. The camera we have chosen to use in the system is a 1080p, 42 degree FOV, USB connected, CMOS camera. This will give us the resolution needed to accurately read and translate the text into braille. We did have to make sure that the resolution could be able to distinguish text at a reasonable distance so this is a solid option for this function. The USB connection also makes it very simple to connect to the other systems the camera will have to work with. It is also important to note that the camera does not have to have color capabilities and we would rather trade that for higher resolution.

3.6 Laser System

This section provides a comparison of various laser sources to determine which type is most suitable for the requirements of the braille etching system. The selected laser must be capable of producing sufficient power density to ablate the surface of the target material without causing excessive damage or compromising safety. Laser characteristics such as wavelength, power output, beam quality, and compatibility with available optics are key factors in this evaluation.

The method used for material ablation will depend on both the laser's properties and the thermal or photomechanical response of the paper. Shorter wavelengths are typically absorbed more effectively by organic materials like paper, while higher power levels can lead to deeper or more aggressive ablation. Therefore, the interaction between the laser beam and the chosen substrate must be matched to achieve controlled surface modification without perforation or unwanted burning.

The type of paper used will further define the constraints and possibilities of the system. Thicker, darker papers may allow for better absorption and more tactile results, while thinner or lighter papers may impose limitations on depth and contrast. The combination of paper characteristics and laser parameters will directly influence the effectiveness of the braille formation. The absorbance spectrum of whatever paper we end up using will be documented and used to do more analytical calculations at a later part.

In the latter part of this section, the optical configuration used to focus the laser will be analyzed. This includes the selection and arrangement of lenses or fiber optics to achieve the desired spot size and output power at the surface of the material. Factors such as focal length, beam divergence, and alignment stability will be considered. Since the braille character set consists of fixed dot patterns, the system does not require variable image resolution. As a result, the analysis will prioritize power delivery and spot size uniformity over resolution flexibility.

3.6.1 Laser source

We're currently evaluating several laser options for our project. The previous team utilized a 1W, 405-450nm laser diode and controller. Their experience highlighted a key challenge: they struggled significantly to find a compatible laser diode, often purchasing multiple units before finding one that worked with their controller. This valuable insight is heavily influencing our current selection process, as we're committed to avoiding similar compatibility issues. Based on the previous group's spectral range and our goal of working with wavelengths close to ultraviolet, we're focusing on three primary laser types: diode-based lasers, gas lasers, and fiber lasers. Each of these technologies comes with its own unique operating requirements, advantages, and disadvantages, all of which we're carefully considering. All lasers at their core come down to the laser resonator of the laser. The shape, material, and position of every element of the resonator changes the characteristics of the laser in some way. One of the most common lasers you will see in the world is the Neodymium YAG (Nd:YAG) Laser. Resonators have three main elements to consider, the rear mirror, the front mirror, and the gain medium. The rear mirror is usually close to 100% reflective to the wavelength of light that is being generated. The front mirror is usually only about 80% reflective so as to let some of the light out to be used but to send more to cause additional optical gain. The optical gain occurs in the gain media when the photons in the resonator interact with the electrons in the upper lasing band and then release an identical photon. This is the basis of the process of stimulated emission.

Figure #12: Neodymium YAG Laser example

3.6.1.1 Gas Lasers

In evaluating potential laser sources for use in the braille etching system, one of the first categories considered was gas lasers. Gas lasers operate by using an electric current to excite a gas medium enclosed within an optical cavity and are the poster child of lasers in the world of optics. There are many different shapes and sizes of gas lasers that can all be used for different purposes meaning it is a great place to start looking for a laser for almost any occasion.

One common example is the helium-neon (HeNe) laser. HeNe lasers typically emit red light at a wavelength of 632 nm and are known for their low power consumption, high beam quality, and long-term stability. These features make them useful for alignment tasks, optical experiments, and barcode scanning. However, their output power usually ranges from 0.5 to 10 milliwatts, which is insufficient for material ablation. As a result, HeNe lasers do not meet the power requirements necessary for producing tactile braille features and are not suitable for this application.

Another widely used gas laser is the carbon dioxide (CO_2) laser. CO_2 lasers emit infrared light at approximately 10.6 μm and are capable of delivering high power outputs, often in the range of 30 watts to several kilowatts. These lasers are frequently employed in industrial settings for cutting and engraving a variety of materials, including wood, plastic, and metal. While CO_2 lasers are effective for high-energy applications, their power levels are excessive for the controlled ablation required in braille printing. In addition, CO_2 laser systems tend to be physically large, require complex cooling systems, and have a relatively high cost of ownership.

Due to their high power output, large form factor, and cost, CO_2 lasers are not well suited for compact, low-power applications such as laser braille etching. Based on these factors, both HeNe and CO_2 gas lasers were evaluated and determined to be unsuitable for this specific project.

3.6.1.2 Fiber Lasers

Another type of laser source we considered was the fiber laser. At first glance, fiber lasers appeared to be a highly promising option due to their unique architecture and performance advantages. Conceptually, a fiber laser can be thought of as a traditional laser diode system that has been integrated with an optical fiber, typically one that has been doped with rare-earth elements such as ytterbium, erbium, or neodymium. These doped fibers serve not just as light guides but also as gain media, amplifying the light as it travels through the fiber. This configuration allows for significant increases in output power and beam quality compared to standalone laser diodes.

One of the most appealing aspects of fiber lasers is their mechanical flexibility. Because the lasing medium is built into the fiber itself, the bulky and often heavy laser pumping hardware can remain stationary while the lightweight fiber output can be routed to the desired location. This greatly reduces the mechanical complexity of a moving system and minimizes potential issues related to vibration, misalignment, or instability during operation—making fiber lasers especially attractive for setups that require precision and robustness.

Fiber lasers are widely used in demanding industrial applications such as metal welding, cutting, and 3D printing, where extremely high power levels and long-term reliability are critical. Their ability to maintain excellent beam quality even at high powers makes them a go-to solution in manufacturing and materials processing environments. However, this level of performance comes at a cost: commercially available fiber laser systems are typically priced in the hundreds to thousands of dollars, which puts them well beyond the budgetary limits of many academic or prototype-scale projects.

Given their high cost and complexity, purchasing a commercial fiber laser may not be practical for our current needs. However, the concept of constructing a custom fiber laser from more affordable components remains an intriguing possibility. This would involve integrating a laser diode with a doped fiber segment and coupling optics, potentially giving us a scalable and cost-effective solution—if we can successfully manage the alignment and gain conditions required for lasing. We plan to explore this DIY approach further as we refine our system design.

3.6.1.3 Laser Diodes

The last laser source we examined was the tried and true laser diode, a staple in modern photonics and optical systems. Laser diodes are among the most versatile types of lasers available today, capable of operating effectively across a wide range of power levels. Their adaptability allows them to be used in both compact, low-power applications—such as barcode scanners, laser pointers, and optical drives—and in high-power systems used for industrial cutting, medical treatments, and advanced research. This flexibility stems from the wide variety of diode designs and materials available, each tailored for specific wavelengths and power outputs.

Laser diodes are an excellent choice for nearly any project thanks to their widespread availability, cost-effectiveness, and compatibility with compact electronic systems. Their small size and efficiency make them ideal for integration into custom setups, and the fact that they're mass-produced contributes to a large supply chain, reducing both cost and lead times for procurement.

In our case, we are particularly interested in high-powered laser diodes that emit light in the ultraviolet (UV) region of the electromagnetic spectrum. These UV-emitting diodes are especially valuable in applications that require high beam intensity and precise energy delivery. One key advantage of UV lasers is their strong interaction with materials like paper, which readily absorb UV light due to their molecular composition. This high absorption rate makes UV laser diodes ideal for processes such as etching, printing, or marking paper surfaces, as the energy is efficiently transferred to the target material.

Another significant benefit of using laser diodes is the ease with which their output power can be modulated. By simply adjusting the current supplied to the diode, users can fine-tune the intensity of the emitted laser beam in real-time. This level of control is particularly useful in dynamic systems where precision is critical, and it simplifies both hardware design and software integration for power regulation.

3.6.1.4 Our Own Fiber Laser

In the past projects like this have usually used a diode laser and achieved great success in their results so we are going to use something similar. Instead of paying the thousands of dollars to obtain a fiber laser that would fit our requirements in this project we are going to build our own. Gas lasers are still not a viable option for the same reason, the price just doesn't make sense for the scope of this project. Specifically CO_2 lasers would do the job great but are simply overqualified when it comes to etching paper. To build our own fiber laser we are still going to use a laser diode but then couple it into an optical fiber. While this does add a noticeable amount of financial strain on the project I think the functionality outweighs it. The laser diode we chose is a 405nm 500mW laser. The source we specifically got already has a focusing lens on it which will make the coupling of the laser and fiber even simpler.

To ensure stability, precision, and safety in our optical system, the laser source will be housed in a custom-designed 3D-printed enclosure. This housing is specifically engineered to maintain the precise alignment between the laser diode and the coupled optical fiber, preventing any unwanted movement or misalignment that could compromise system performance. Given that the resolution of most standard 3D printers is not fine enough to guarantee micron-level precision by default, the housing design will incorporate mechanical adjustment features—such as small set screws or threaded mounts—on one or both ends of the assembly. These allow for fine-tuning of the fiber's position after printing, enabling us to achieve the necessary alignment accuracy manually.

A similar 3D-printed enclosure will be used at the output end of the fiber, where the laser light exits and enters the free-space optical path. This housing will securely hold the fiber tip in place and ensure proper alignment with the first lens in our beam expander system. Maintaining the spatial relationship between the fiber output and the optical components is critical, as even minor misalignments can drastically alter the beam profile, direction, or focus.

The beam expander itself—comprising two carefully selected lenses—will also be integrated into this housing system. The lenses will be mounted at a fixed distance from each other, corresponding to the optical design parameters needed to expand the beam to our desired diameter. The use of custom enclosures allows us to rigidly fix the lenses in place while also simplifying the overall alignment process during assembly.

Beyond alignment and stability, one of the most important benefits of using 3D-printed housings is the ability to incorporate safety features directly into the design. Because we are working with a high-powered laser, minimizing the exposure of free-space beam paths is essential for protecting both the user and the surrounding environment. By enclosing as much of the beam path as possible within printed housings, we significantly reduce the risk of accidental exposure to stray or reflected laser light. These enclosures can also be designed with additional features such as ventilation, interlock mounts, or shielding for further safety enhancements.

In summary, designing and printing custom housings provides us with a flexible, cost-effective way to address multiple engineering challenges simultaneously: ensuring precise alignment, enabling fine adjustments, maintaining mechanical stability, and enhancing the overall safety of our high-power laser system.

3.6.2 Optical Fiber

Selecting the appropriate optical fiber for our system is a critical decision that will significantly influence the overall performance and reliability of the project. Our challenge lies in striking the right balance between optical performance—specifically minimizing dispersion at our operating wavelength of 405 nm—and staying within the constraints of our project budget. Dispersion, which causes broadening of the laser pulse or beam as it travels through the fiber, can reduce the spatial resolution and efficiency of the etching process if not properly managed. Therefore, the choice of fiber must ensure that signal integrity is preserved over the length of the transmission.

The primary function of the fiber in our setup is to serve as a flexible conduit for delivering the laser light from a fixed, stationary laser source to the working end of the etching system. At that end, the beam will enter an optical focusing assembly designed to concentrate the light onto the target surface with high precision. Using a fiber-based delivery system allows for mechanical flexibility in the design and layout of the machine, enabling us to keep the laser source in a safe or optimized location while still reaching the intended workspace.

To make the most informed choice, we will explore various types of optical fibers—including single-mode and multi-mode options, as well as fibers made from different core materials optimized for UV transmission. Some fibers may offer superior transmission efficiency or lower loss at 405 nm but come at a higher cost, while others might be more economical yet introduce greater dispersion or attenuation. Understanding the trade-offs between these different characteristics will help us identify the fiber type that best supports our project’s technical requirements without exceeding budgetary limits. Ultimately, this analysis will guide us toward a solution that ensures stable light delivery and high-quality etching performance.

3.6.2.1 Single-Mode (SM) vs. Multi-Mode (MM)

As light travels through a fiber the light will travel in certain “shapes”, these are called modes. The mode of the laser light is important to keep in mind due to the effect it can have on the ablation pattern on the paper. There are pros and cons to using SM and MM fibers. As the name entails a SM fiber only allows one mode to propagate through the fiber. This is called the fundamental mode and has a gaussian shape. Due to SM fibers only having one more available the dispersion is minimalized allowing for long distance transport of information. However due to the smaller core size of SM fibers the laser light must be very precise to ensure effective coupling. With the MM fibers there are multiple modes allowed to propagate through the fiber, these modes can interfere with each other and can cause modal dispersion and interference. This interference is why MM fibers are not a good option. We want the mode profile to be as uniform and predictable as possible to ensure accurate etching.

Using a single mode fiber ensures that only the fundamental mode is allowed to propagate through the fiber and reach the optical system. The fundamental mode is perfectly fine for etching but requires precise alignment between the laser source and the fiber core. The specific fiber we chose is SM300 which is a commonly used fiber when dealing with UV range light. It is mass produced so it is affordable and can easily be used in conjunction with other standard equipment. There is little to no dispersion especially since we are only traveling about a meter through the fiber before the output.

3.6.3 Beam Profile

We have chosen to use a gaussian mode profile but there are others that could be useful in this situation. In this section we will be exploring the pros and cons of using a gaussian mode profile and comparing it to other possible beam profiles. Really the only other beam shape we should be considering is the top hat beam. This beam could be useful due to the lack of superfluous energy that is seen when using a gaussian beam. In theory you could precisely and uniformly change the depth of ablation if you use a top hat beam while creating clear and defined edges. This however creates many more optical challenges. In order to create a top hat beam you must introduce other optical components such as diffractive elements or refractive beam shapers. This adds complexity and cost to this project and simply does not add enough functionality to rationalize using a top hat beam.

It is much easier to create and manipulate a gaussian beam as most laser sources do emit a gaussian beam already so there is no need to add any optical elements to change the profile of the beam. Using a gaussian beam does also have its uses due to the gradual decline of the intensity. This gradual decline can be used to create smooth gradients not just hard edges like a top hat beam would. The narrow peak also allows for the possibility of ultra precise etching as decreasing the power would decrease the dot size.

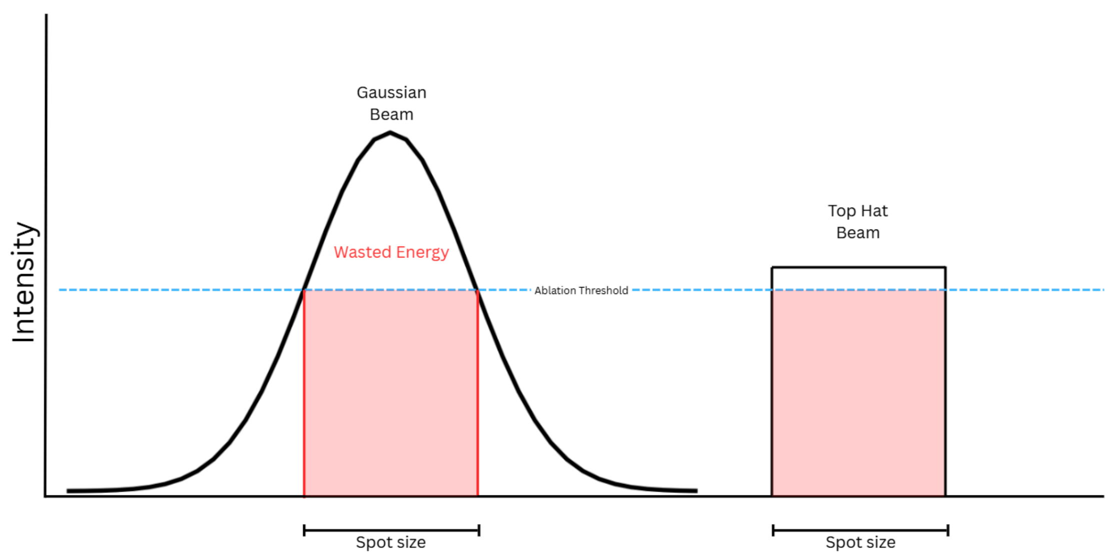


Figure 13: Beam Intensity vs. Spot Size Comparison

3.6.4 Optical System

After the laser source has been coupled with the fiber and the fiber output has been set up the next step in the process is to collimate and focus the laser light. Since the divergence of fiber output is quite high we need to use lenses with high power to ensure we keep the optical path length as short as possible. The next step in the process is to find the maximum spot size we can have while still achieving ablation. Once that spot size has been determined we will use a collimating lens in combination with a beam expander or shrinker To achieve that spot size. Since the braille markings we are making are going to be much larger than our spot size we want our spot size to be as large as possible. This does mean that our system is not restricted by resolution.

Luckily a system like this is very easy to make with readily available parts. This means that adding this subsystem is low cost and low complexity. Because of the lack of stress this subsystem adds there is no reason to not implement it. In the figure below there is a Zemax simulation of what our beam expander could look like.

	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia
0	OBJECT	Standard		Infinity	Infinity			Infinity
1	STOP	Standard	LC1975	-12.400	2.000	BK7		0.400
2		Standard		Infinity	15.500			0.445
3		Standard	LA1560	13.000	3.500	BK7		0.976
4	IMAGE	Standard		Infinity	-			0.965

Figure #14: Example Zemax Beam Expander Simulation

3.7 Software

For the bulk of the software operations, C will be used. C is able to properly control hardware devices and other peripherals with ease, as well as being a language most of the team has extensive experience with. Specifically, C will be on a version of MSP that will control several key elements including the LCD display, controlling the laser, and the overall system. Pulse duration and PWM will also be done using C on the MSP. C is the foundation of our device's hardware. Considering most of the team has extensive experience relating to C and C++, this is also a benefit to using it as the basis of our hardware. C also has a large amount of libraries available for reference and sources in case any problems arise in the software-software or software-hardware interactions.

Python will handle the input taken from the USB or keyboard. Python will then handle the logic behind translating the text into the braille output. The translation logic will be handled by first identifying if the user desires contracted or uncontracted braille. After selecting the type, the input will be taken by the device and processed by the python code.

In case one, the text is from a keyboard peripheral and is read using python. The code then parses the code depending on the previously mentioned contracted or uncontracted braille. With contracted, the words are separated and the words are then placed into an array in order to search the library for a match. The “match” will be instructions for how to print the desired translation. The instructions are placed into a queue and the command is relayed to the MSP via UART. In the event the mode is uncontracted, the logic is the same but the printer instructions are per letter instead of per word.

For case two, the text file is opened and “read” by the python script. The words/letters will be saved in an array, depending on the selected mode as in case one, and the formula will follow the same logic as case one. The only difference is the method in which the text arrives at the main translating python script. The python code will then, via UART, relay that the translation is complete to the main device where the C code will be used, once again, to display a message on the LCD depicting the progress of the printing as well as any potential errors.

Using two different languages that interact with one another depends on serial communication in order to send data and have components interact with one another. If a Raspberry Pi is the second chip used, the pyserial will be used in order to facilitate the UART serial data transmission. The C language on the MSP will parse the commands and then operate the printer system that will work under order of the python commands whilst updating the LCD with the progress.

3.7.1 Software Constraints

The main constraints of using python and C is the potential lack of use and experience relating to complex systems. Another constraint is the potential dependence on onboard memory in order to have multiple languages and braille libraries. The difficulty in mapping the braille word or letter to commands for the laser apparatus does not appear too difficult but that can easily become a more difficult task all things considered. The sections, as of now, are split based off interest and where each individual’s relative skills are. Some of the software sections have multiple people assigned as a way to spread the workload and continue to build up system integrity.

Another software constraint can be seen as the limitations of each individual language. Although powerful, the languages can only do so much without proper implementation. To beat this, the team must continue to refine programming skills and continue to innovate in the function events. The internal code must handle and only use the UART when absolutely necessary, being careful as to not continue sending frivolous information. This makes sure that overload issues are avoided.

3.7.2 Potential Errors and Error Handling

The main error that comes up is the idea of a word not being translated or not being included in the dictionary library saved to the files on the PCB. If a word is spelled incorrectly and the mode is contracted braille, the system will be unable to find a word to use. This would break the software and there needs to be a critical fail safe in case this happens.

There are two realistic approaches to this scenario consisting of utilizing an autocorrect feature or a brute force approach. Putting an auto correct feature would have to trigger if the word failed any translation checks. This would require a check against the words saved that have similar letters and lengths, then systematically selecting the one most likely to be used. From a developer standpoint, this is a difficult task but there is a pyspellchecker feature that can be installed, this would use pythons integrated spell checker that does the work for us. It utilizes edit-distance lookups with little downtime in order to quickly “autocorrect” the word.

The second approach is much easier. The second approach is to, when an error flag is raised, to translate the word as uncontracted, having every letter be abased on the paper as opposed to the word. This would be easier to implement and will most likely be the first option coded in as a fail safe and a basis for error handling. As the project continues and time to develop additional functions grows, this will be one of the sections expanded upon.

Another error would originate in the LCD display and the complex interactions between all of the systems. The percentage bar and interactions over UART are not something the entire group has extensive experience with. The LCD functionality, user inputs, laser interactions, as well as functionality are difficult, getting the UART to work perfectly with this many moving parts would require a decently powerful system. The answer to this dilemma rests in the hardware-software considerations of the system. Using a Raspberry Pi and having onboard memory will increase cost but will ensure that the system can properly interact within itself and have the logic or dictionaries easily accessible for translation.

3.7.3 Two Language System

Using the two language system, the device is able to properly handle the translation, display, and laser functions. One language will interface with system memory and translate while the second, lower level language handles hardware operations. There are several options we can use for the high level language such as Python, Java, Javascript, and other compounded options such as Go. For low level hardware languages C and C++ are the main options.

When comparing JS, Java, and Python to one another, the group preferred Python for its immense libraries and ease of use. Python has libraries and programs that are easily installed and allow for niche use-case functions such as a word checker and autocorrect. The ease in using a built in auto correct, especially when not having this function would brick our system, puts Python ahead of the other languages. Python also has direct support for using a USB and reading its contents. This use is extended to the keyboard, it is a low skill floor language with a large skill curve that allows all of our team to contribute if necessary.

For low level programming, the choices are C++ and C. Both languages are excellent but the main choice for us is C. C is flexible and the team has knowledge of it. It may be seen as difficult to use and lacks some safety and error checking systems as Micropython. In the event the MSP is changed to a ESP, Micropython will be substituted in as it keeps with language continuity. Experience with C enables the developers to focus on using a known language as opposed to learning an entirely new one.

Having a two language system around Python and C is beneficial to ensuring project success and smooth development. Python and C can be run and developed on every system OS and using common IDEs. Having these two languages allows programming on a high and low level to ensure success. Using an ESP may be a good alternative depending on the budget and desired outcomes.

3.8 Motors

There are a lot of options when it comes to using motors for a design like this. We want to be able to make an “open enclosure,” similar to a 3D printer, that uses motors to drive both the motor and the paper tray. The motor will be moving along the x-axis and the paper tray along the y-axis. We need to use a motor that will be able to move in precise millimeter increments. This means our motors must have consistent micro steps/adjustments to get the result we want. There are three readily available motors that we could use: brushless DC motor, stepper motor, and the servo motor. Below, you will find a description of each motor and how they could function in our project.

3.8.1 Brushless DC Motor

Brushless DC motors function without the use of a brush, where typically brushes will send current to the coils on the rotor. But without the brush, we can arrange the coils in a way where they are not on the rotor and instead, the rotor is a magnet, eliminating the need for brushes. This increases efficiency, control, power output, and can operate at a higher speed than a brushed DC motor. They are so efficient because that can operate at maximum torque continuously as the brushed DC motors can only reach maximum torque at different points in their rotation. Also, since there are permanent magnets on the rotor, there is no rotor loss due to not having a need for electrical windings inside the motor. They also offer a high level of controllability as they use feedback mechanisms that can deliver precise torque and speed via current regulation and electronic speed controllers. A drawback from using brushless DC motors is that they are very good at spinning continuously but need a lot of work to operate them in millimeter steps in our case. They are also prone to vibrations during low-speed operations, which is not ideal for the system we want to build.

3.8.2 Servo Motors

Servo motors is not just a motor, but a complex system using motors that can offer a lot of features. They are closed-loop systems that use feedback to control how the motor functions (the position and speed). What makes up a servo motor is an AC or DC motor, control circuit, servo drive, servo amplifiers, and encoders. Servo motors can deliver very high precision and torque control with all the components that make up one. It takes a PWM control signal and then the internal controller will compare the desired position (from the PWM signal) to the current position via the feedback system. AC motors use three-phase AC power and are typically used in higher power/speed applications. A DC motor is used when you want to achieve finer control over the motors, which would be useful in our case. Due to their complexity, they are on the expensive side and more difficult to incorporate into a system.

3.8.3 Stepper Motors

The stepper motor is another type of motor in which the shaft rotates in steps, typically a fixed number of degrees. It has a central rotor surrounded by a stationary stator with coils, and energizing the stator phases will create a magnetic field in which the rotor aligns with. This results in very precise “steps” enabling the user to have fine control of the motors. These motors are also driven by a STEP signal and a DIR (direction) signal from the microcontroller. A common step per revolution is 200, which means that the step angle of any given motor (in this case, Steps/Revolution is 200) can be found using this equation:

$$Step\ Angle = \frac{360°}{Steps/Revolution} = \frac{360°}{200} = 1.8°$$

As seen by the equation, the higher the steps/revolution means the higher the resolution as the motor can rotate in less degrees, resulting in more precise control. Having a step angle of 1.8 degrees is very acceptable, as in our project the smallest distance either motor must travel is 2.3 to 2.5 millimeters, which is the space between each dot within a character. The translation of step angle to distance travelled depends on the timing belt and the pulley it is attached to, but no matter what combination you choose you will always end up with a distance/step to be less than 1 mm, which is perfect in our case. One of the drawbacks to stepper motors is their low efficiency and low torque, but this is made up significantly by the precision they offer. This makes the trade-off worth it.

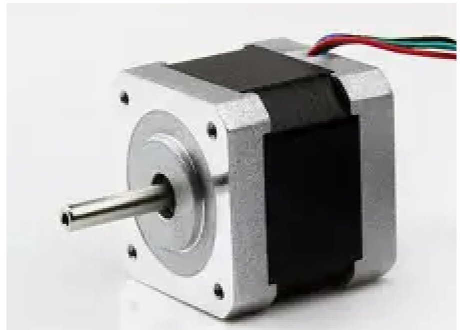


Figure 15: Standard NEMA 17 Stepper Motor

3.8.4 Motor Choice

The decision of which motor is best for our project comes down to cost, ease of use, and suitability. Brushless motors and servo motors are both equipped with AC or DC motors (servo motors build off brushless motors) which increases complexity within our design. This is because they are designed to move continuously rather than a certain degree of rotation every second. This means that stepper motors are the obvious choice as they excel in moving in increments, or tiny steps, hence the name. We can accurately control and tune the distance per step of the motors using a motor controller interfaced by our MSP430 via STEP and DIR signals.

Motor	**Brushless**	**Servo**	**Stepper**
Step Angle	Continuous	Continuous	0.9° - 1.8°
Speed [RPM]	< 10,000+	< 5000+	< 1000
Efficiency [%]	85 – 95	80 – 90	20 – 40
Torque [Nm]	0.1 – 5+	0.5 – 10+	0.2 – 3
Ease of Use	Medium	Complex	Simple

Table 13: Motor Comparisons

3.8.5 Motor Part Selection

Since we have chosen to go with the stepper motor due to its high control due to it moving in steps, we must choose the appropriate motor that will be used for both our x and y-axis. I would say that the NEMA motor is by far the most used and popular form factor of stepper motor inside personal projects, hobbyist projects, as well as student projects. A NEMA motor is classified by its mounting face size by using a number following the word NEMA, where the number is the faceplate size in 1/10 inches. They are also widely used in 3D printers, laser engravers, robotics, etc. and will be no stranger to our project either. The most common sized NEMA motor will be the NEMA 17 stepper motor, which is widely used and recommended online. They are readily available, affordable, have 1.8 degrees of step angle, compatible with multiple motor drivers, and will fit our form factor. Listed in the table below are some specifications of the NEMA 17 motor.

Motor	**NEMA 17**
Steps/Revolution	200
Step Accuracy [%]	+/- 5
Rated Current [A]	2
Operating Temperature [C]	-20 – 40
Shaft Load (at 1000 RPM)	20k Hours
Phases	2

Table 14: NEMA 17 Specifications Table

Due to the NEMA 17 being rated for 2 amps, has 200 steps per revolution (or 1.8 degrees per step) with an accuracy of plus or minus 5 percent, this motor will work extremely well for our system.

3.8.6 Stepper Motor Controller

Now that we have selected our stepper motor, we need a way to interface it with the MSP430 so it can actually function. The motor itself comes with a female header which corresponds to AOUT1, AOUT2, BOUT1, BOUT2 which drives the two phases of our stepper motor. These will plug into our motor controller so it can drive the motor. The most important pins of the motor controller are the STEP and DIR pins which will be delivered by the MSP430 to the motor controller which tells the motor how many steps it must move and the direction. We can also control the mode via MODE0, MODE1, or MODE2 which will set the micro stepping mode if we need even more precise steps. The motor controllers that we will be comparing to use for our project will be presented in the table below.

Motor Controller	**TMC2209**	**TMC2225**	**DRV8825**
Voltage Range [V]	4.75 – 29	4.75 – 36	8.2 – 45

Maximum Drive Current [A]	2.8	2	2.5
Microstepping	Up to 1/256	Up to 1/256	Up to 1/32
Interface Type	STEP, DIR, UART	STEP, DIR, UART	STEP, DIR
Operating Temperature [C]	-50 – 150	-50 – 150	-40 – 150

Table 15: Stepper Motor Controller Part Comparison

The DRV8825 is the best option for our project as we do not need the high-tech features inside the two TMC motor controllers. They offer UART capability and increased microstepping allowing for finer precision, which is not needed for this system. Also, the DRV8825 is very common and widely used along with the NEMA 17 motor. It allows for a maximum drive current of 2.5 amps which works perfectly with the NEMA 17 as it is rated for 2 amps of current. We only need the STEP and DIR pins as well since we will be directly communicating with the MSP430, eliminating the need for UART communication.

3.9 Material Selection

An important controllable factor in the performance of the laser etching braille system is the choice of etched material. The material properties directly influence the quality, clarity, and durability of the resulting braille dots. Initially, standard printer paper was considered due to its low cost and widespread availability. However, further testing revealed that this material has limitations when used for tactile etching.

Several alternative paper types have been evaluated to identify a substrate that better supports the formation of braille dots. The biggest challenge has been related to thickness. Standard braille dots require a tactile height of approximately 0.4 mm to be legible by touch, while common paper stocks typically have a thickness of 0.1 to 0.3 mm. This discrepancy limits the ability to create dots with sufficient elevation using only laser ablation on standard paper.

Testing has also revealed that the optical properties of the paper significantly impact the laser-material interaction. Specifically, black or dark-colored paper absorbs more laser energy than white or lighter-colored paper due to reduced reflectivity. As a result, using black paper has been shown to improve etching efficiency, requiring less exposure time or power to achieve visible and tactile marks. This increased absorption can aid in producing higher contrast and potentially more pronounced indentations or raised features.

Despite ongoing testing, an ideal material has not yet been identified. However, the process has provided useful insights into how factors such as color, thickness, and material composition influence the final output. Continued material testing will be necessary to find a substrate that balances accessibility, cost, tactile clarity, and safety for laser etching of braille.

4 Related Standards and Realistic Design Constraints

Our objective in this project can be split into two aspects, hardware and software. It is important to break down these aspects into goals that can be tracked and organized to ensure the highest probability of success. These key aspects include how the laser source would move, the power requirements of the system, and safety features to align with engineering safety standards. After careful consideration, we selected the components and software we believed would be most effective for achieving our goals.

4.1 Laser Safety Standards

Laser safety standards have been in effect for a long time due to the dangerous nature of even low power lasers. Even a small laser can cause permanent damage to someone's eye. These regulations are governed by the ANSI-US Laser Safety Standards and enforced by the FDA. Lasers are labeled using a four tier system using Roman numerals and English letters.

Class 1 lasers: This is the safest level of laser due to its very low operating power. These can be easily purchased and can be found in almost any store. These lasers are safe to be observed by both the naked eye and through magnifying optics.

Class 1M laser: The class 1M lasers have the same operating power as class 1 lasers but for one reason or another become dangerous when used with magnifying optics. The light can still safely be observed with the naked eye but can cause damage once magnified.

Class 2 Lasers: Class two lasers can be used in mostly the same way a class 1 laser can as the blink reaction is fast enough to stop a dangerous amount of light entering the eye. As such they can function exactly how a class 1 laser would as long as any direct exposure to the eye is less than a quarter of a second. The human blink happens in about a tenth of a second meaning that the bodily reaction to blink is enough protection for these lasers. These lasers only operate with no more than 1mW of power.

Class 2M Lasers: Just like with the class 1M lasers, class 2M lasers can be used and meet the same requirements as class 2 lasers as long as no magnifying elements are used.
Class 3R Lasers: Following suite class 3 lasers operate at a higher output power than the class 2 lasers. Class 3R lasers are considered safe only when the viewing of the beam is restricted. The maximum operating power of the class 3R lasers is 5mW.

Class 3B Lasers: The laser we are using in this project is classified as a 3B laser. A class 3B laser is defined by a maximum operating power of 0.5W and is hazardous to the eye if there is direct exposure. Light that hits the eye after reflecting off a mundane or low-reflectance media is also considered non-hazardous.

Class 4 Lasers: Class 4 is the highest level of classification that can be given to a laser source. Class 4 lasers exceed the specifications seen in a class 3B laser. These lasers operate with an output power greater than 0.5W and can even have outputs of multiple kilowatts. The FDA has made it illegal to have these lasers on the market place without a key switch and safety interlock.

As stated above the laser in our project is classified as a class 3B laser. This means that there are only a few precautions we need to take to ensure we align with the national safety standards. Since reflected and ambient light of the laser is non-hazardous there is no reason to keep the entire system enclosed which will help with ventilation. Ventilation is important to keep in mind when building this system as for when the ablation occurs gases are released into the air which could itself become a hazard if kept in a confined space.

While reflected light is not a large safety concern, direct exposure is still absolutely a concern, especially while testing. To limit the risk of direct exposure any time the laser is being tested the personnel must be wearing safety goggles rated to block out 405 nm light. Due to the high power of the laser skin exposure is also something to be taken into consideration as prolonged exposure can cause burns. To combat this risk the laser beam path will also be contained in an area in which no body part should enter. By keeping the beam contained ig. Pointed down or at a screen, we drastically reduce the chance of someone getting burned.

Another risk that should be measured is the risk of combustion of the paper. Fire as we know is detrimental to the health of both people and electronics so we want to decrease the risk of combustion and have a response in case one does occur. In response to this risk we will have a manual kill switch that will disconnect all power to the system therefore reducing the risk of an electrical fire in combination with a paper fire. While testing is occurring there will also be an inert non-reactive gas such as CO_2 on hand to use to suffocate the fire while protecting the electrical components. To protect both the people around the system and the optical elements in the system the output of the etcher should be covered when not in use.

With these acknowledgments our group accepts the responsibility that comes with using a high powered laser such as the one we have. In taking on this responsibility we are going to be strictly following the ANSI and FDA standards that are in place.

4.2 Material Hazards

When working with high-powered lasers—especially those capable of ionizing molecules and triggering chemical reactions—it is essential to understand how high-intensity laser light interacts with various materials. These interactions can lead to significant physical and chemical changes, some of which may pose safety risks. In the context of our project, we are specifically aiming to induce a thermochemical reaction at the material surface. While this process is fundamental to our goal of creating tactile patterns, it also carries the potential to release harmful or toxic byproducts depending on the composition of the material being etched.

Because of these concerns, a thorough understanding of material behavior under laser exposure is critical. During the research phase of this project, I reviewed relevant scientific literature and analyzed several previous senior design efforts with similar objectives. From this work, I have compiled a list of materials that are commonly used in laser etching applications, along with documentation of how the etching process can transform these otherwise stable materials into potential hazards. This list will serve as a valuable reference for both material selection and risk assessment as we move forward with the design and testing phases of our system.

PVS: A commonly used silicone impression material. When etched using a laser pure chlorine gas is released.Chlorine gas can cause skin, eye, and lung irritation. If the gas gets into your lungs it could cause internal burns leading to respiratory issues.

Plastics: Plastics like polycarbonate, polyethylene, polystyrene, and polypropylene, will all catch fire if exposed to the laser light we are using. As stated before a fire would be disastrous so these materials must stay clear of the beam at all times.

ABS: ABS is specifically dangerous due to when it interacts with the laser light with this intensity the material will release Cyanide gas. This is an extremely toxic gas and should not be ingested in any amount.

To ensure the highest level of safety when working with high-powered lasers, one of the most important best practices is to avoid exposing unknown materials to the laser beam. If the behavior of a material under intense laser irradiation is not well understood, directing the beam at it can introduce unpredictable and potentially hazardous outcomes—including the release of toxic fumes, combustion, or harmful chemical reactions. By following the principle of “if you don’t know how it will react, don’t expose it,” we eliminate the uncertainty and risk associated with unknown material interactions.

With this precaution in mind, our project will exclusively utilize paper as the substrate for laser etching. Paper is a well-characterized and commonly used material in laser applications, and its response to laser energy—particularly in terms of charring, burning, or ablation—is relatively predictable and manageable when proper safety measures are followed. Limiting our material choice to paper not only simplifies the safety considerations but also ensures consistency in the results, allowing us to focus on optimizing the laser parameters and system design without introducing unnecessary risks.

4.3 IPC PCB Design Standards

In 1957, several circuit board manufacturing companies came together to establish the Institute for Printed Circuits (IPC), an organization that developed comprehensive standards for printed circuit board (PCB) design, manufacturing, and production. While the IPC has since evolved, its standards remain foundational in the electronics industry. Although the complete IPC documentation is proprietary and cost-prohibitive for our budget, we have extracted key design principles from publicly available summaries and technical resources to guide our PCB development process.

The IPC classifies electronic products into three categories based on reliability and expected lifespan. Class 1 encompasses general consumer electronics with short lifespans, such as disposable gadgets. Class 2 includes dedicated service products like printers and desktop computers, which require moderate reliability and consistent performance. Class 3 covers high-reliability applications, such as medical and aerospace systems, where failure is not an option. Given that our Braille etching device is intended for regular use with an expected lifespan of several years, we are designing our PCB to meet Class 2 standards, ensuring durability and dependable operation.

The IPC-2221 standard serves as the cornerstone for generic PCB design, addressing materials, layout, electrical properties, and thermal management. Our design follows these guidelines by implementing a 4-layer FR-4 board with dedicated power and ground planes to enhance signal integrity and reduce electromagnetic interference. High-current paths, particularly those supplying the laser driver, will utilize traces at least 2 mm wide with thermal relief pads to mitigate heat buildup. Decoupling strategies include placing bulk (10 μF) and high-frequency (0.1 μF) capacitors within 5 mm of integrated circuits to suppress switching noise, as recommended by industry research. Additionally, we are employing a star-point grounding topology to consolidate ground returns, minimizing ground loops and crosstalk between digital and analog sections.

To ensure manufacturability, we are adhering to Design for Manufacturability (DFM) principles. Heat-generating components, such as voltage regulators, are positioned near board edges with sufficient clearance for thermal dissipation. Debugging and testing are facilitated by clustered test points on power rails and an integrated SWD/JTAG header for in-system programming. The PCB is partitioned into distinct functional zones—power management, control logic, laser driver, and communications—to simplify routing and reduce interference between subsystems.

4.4 UL1642 Certification of Lithium-ion Battery

UL1642 covers many aspects of using rechargeable lithium-ion batteries as a power supply, from safety, material use, battery protection, etc. The certification becomes active when a user uses at least one electrochemical cell or two or more cells connected in either series, parallel, or both while converting “chemical energy into electrical energy by an irreversible or reversible chemical reaction” [17]. This is what defines a lithium-ion battery. The certification requirements also cover any lithium-ion batteries that are being used in user-replaceable applications (such as this project) or technician-replaceable applications. Since we are using unprotected battery cells, we must follow this certification very carefully to avoid any safety risks. Each section mentioned below will be related to the UL1642 Certification, not the sections in this paper.

The first certification requirement we will be discussing is the housing of the battery pack (section 4.1.1 and 4.1.2). The lithium-ion battery pack must be able to withstand the abuse or environment in which it may be subjected to. Also, it shall be in a casing that prevents flexing of the batteries or battery pack. We achieve this by using 18650 battery brackets (or holders) that are plastic, rigid, and shockproof. This will provide the battery pack enough “rigidity” to withstand the environment ours will be put in. In this case, our battery pack will simply be sitting alongside the main PCB and will not be used in any moving object. The only movement the battery pack will go through is moving the device to a different area.

The next requirement we will be focusing on is the lithium-ion battery pack shall be protected from any abnormal charging currents as stated in section 4.3.1. This section states that the battery must be protected from high charging currents and must be protected using blocking parts (such as diodes). Our battery management system (BMS) addresses this section as it has overcurrent protection built onto the board. When this board detects too much current, it will cut off the supply of the battery pack.

The next set of requirements that will be discussed are part of the test considerations portion of the UL1642 Certification. When using lithium-ion batteries, all users must be protected from any sort of fault that may come from the batteries, such as an explosion, sudden release of heat, or flying fragments (section 8.1). The way we address this is by putting our fully assembled battery pack into an explosionproof and fireproof pouch. This will protect the surrounding area from any accident that may occur when the batteries are in use. We will also have a fire extinguisher on hand for any emergency that goes beyond the protective bag.

Many sections within the UL1642 Certification are related to stress testing the batteries. This includes a crush test, impact test, shock test, vibration test, low pressure test, heating test, abnormal charging test, and a short-circuit test. These tests will test the battery pack until the batteries fail (explode, crack, leak, light on fire, etc.) and will not be considered for our project as this requires a closed lab environment, very high budget, and expensive equipment. The best we can do is mitigate any risks that can arise from the use of lithium-ion batteries through taking careful precautions.

4.5 IEC 62368-1 Standard

The IEC 62368-1 standard has been created by a technical committee of Safety of electronics equipment within the field of information and communication technology and audio/video in which the machine does not exceed a rated voltage of 600V. It describes the safeguards that one must take to reduce injury, pain, damage, fires, or even death. There are three classifications of people: ordinary, instructed, and skilled (section 0.2). The ordinary person is applied to those that could operate any energy equipment that could cause potential injury. The instructed person is applied to anyone who has been trained, or instructed, by a skilled person to identify any energy related equipment that can cause injury. Then the skilled person is applied to those who have received professional training or have prior experience with energy equipment. They are expected to use their knowledge to identify energy sources/equipment that can cause injury and tell other “persons” to be cautious. The way we can abide by these specific standards is in the senior design where there are skilled and instructed users that we can communicate with about using the proper equipment.

The definitions that describe the word energy come in these forms: electrical, thermal, chemical, kinetic, and radiated energy (section 0.4). For our project, we face all of these forms from the PCBs, the heat from the power supplies, chemical reactions from lithium-ion batteries, radiation from the laser, and kinetic energy from the motor system that moves the laser. We must follow general safeguards to keep us and others around us safe.

A safeguard is any device, system, or scheme that can reduce the likelihood of any form of energy causing harm/injury and is interposed between any type of energy source that can cause injury (section 0.5). There are various forms of safeguards, such as equipment safeguards, installation safeguards, personal protection equipment (PPE), behavioral safeguards, instructional safeguards, skill safeguards, and precautionary safeguards. We can follow these safeguards by making sure we keep ourselves safe when operating with any form of energy, such as using safety glasses, keeping fire extinguishers nearby, verifying what we are operating on is safe, etc.

There are two key injuries that concern us, which are thermal and electrical fires (sections 0.7 and 0.10). The main thermally caused injury is skin burn where thermal energy that is capable of causing injury comes into contact with a body part. These burns vary based on how long you were in contact with said energy, the materials, and the temperature. The way we can protect against thermal energy is by using basic safeguards such as heat sinking, thermostats, fire protection gloves, fire extinguishers, fire blankets, and overall control of the electrical energy being converted to thermal energy. This is highly important as our project deals with high power lasers and custom lithium-ion battery packs. The next main injury is electrical fires. This is where electrical energy converts to thermal energy and heats some fuel material that is followed by an explosion or combustion. This can be caused by arcing, overloading components, poor heat management, etc. The way we can protect ourselves from electrical fires is to ensure that the temperature of any material does not cause that material to ignite. We can also incorporate the same basic safeguards used for protection against thermal energy.

4.6 IEEE 802.3 standard

One of the most relevant standards to our Braille etching system is IEEE 802.3, which defines the physical layer and data link layer's media access control (MAC) for wired Ethernet. While this standard is traditionally associated with networked Ethernet systems, portions of it have influenced the development and regulation of USB communication protocols as well, particularly regarding signaling, data transmission integrity, and electrical characteristics. In our project, the Raspberry Pi Zero WH communicates with a USB keyboard to receive text input that is ultimately translated into Braille. The connection between the Pi and USB devices must adhere to USB specifications derived in part from IEEE standards, including those governing voltage levels, device enumeration, and data packet structure.

Although our system does not use Ethernet directly, compliance with standards like IEEE 802.3 helps ensure that the USB interface we rely on is electrically safe, interoperable, and functionally stable. For example, USB 2.0 devices are required to negotiate current draw and signal speed with the host system, which is vital in our low-power setup. This is especially important when using a 5V regulator to power both the Raspberry Pi and USB devices from a shared power source, as improper negotiation or deviation from standard current levels could result in system instability or device failure.

By designing with consideration to these standards, our system maintains compatibility with common USB peripherals while minimizing risk of hardware conflict or electrical damage. Moreover, adherence to established communication protocols simplifies debugging, reduces the likelihood of data corruption, and ensures that any future updates to the input interface (e.g., switching to a wireless or full-size keyboard) remain plug-and-play. Integrating devices that operate under well-documented and standardized communication frameworks like those guided by IEEE 802.3 ultimately enhances the reliability and maintainability of our overall design.

4.7 Realistic Design Constraints

Our project operates within a strict $500 budget, which necessitates careful component selection and cost-effective fabrication methods. To stay within financial limits, we are prioritizing off-the-shelf microcontrollers and modular power supplies over custom ASICs. The PCB itself will use standard 2 oz copper layers for high-current traces and economical FR-4 substrate material. While higher-density interconnect (HDI) technology could reduce board size, the added expense is unjustified given our component count and design complexity.

Safety and compliance are critical considerations, particularly given the high-power laser subsystem. Thermal management strategies include heat sinks and strategically placed thermal vias to dissipate excess heat from the laser driver, aligning with IPC-2221's thermal derating guidelines. Electromagnetic interference (EMI) is mitigated through proper trace routing, shielded enclosures, and grounding best practices, ensuring stable operation in portable applications.

Several project-specific challenges influence our PCB design. The laser driver requires isolation from sensitive control circuitry, achieved through wide copper pours and guard rings to prevent noise coupling. Portability constraints demand careful consideration of component density and weight distribution to meet our target device weight of ≤6800 grams. Mechanical stability is further ensured by reserving mounting holes and clearance zones around high-mass components.

By integrating these IPC standards and practical constraints, our PCB design balances reliability, manufacturability, and cost-effectiveness, laying a strong foundation for prototyping and future refinement.

Other design constraints exist in getting the code to operate as intended and create a functioning laser etching apparatus. Getting the UART to properly interface Python and C code can be a difficult task that requires effort, trial, and error. Working to source the correct peripherals, processors, and library dependencies act as design constraints as not every piece will fit this specialized puzzle.

One of the biggest realistic constraints is time. When presented with a project that spans over the course of months, it is hard to keep track of time and also very easy to fall behind. This is why it is very important to stay on top of your work so you do not have to do complicated work (such as design, part selection, schematic capture, etc.) at the last minute. This constraint is applied to everyone and everywhere on this planet. We are all human, and we love to procrastinate. However, avoiding procrastination will lead to a significant boost in productivity and can help with your mental fortitude as you will feel less stressed when you know you are not cramming. Staying on top of your individual tasks and meeting deadlines is crucial to flow as one solid team.

Memory management is another critical design restraint. The storing of libraries large enough to store Contracted Braille will be inevitably large. Uncontracted Braille is an easier task as the letters to number translations are one to one, whereas Contracted Braille depends on saving an entire dictionary of language stored in memory on the device. There is a method to overcome this issue by using compression as well as external memory sources on the device.

Constraint	Mitigation Strategy
Limited RAM	Optimize C code; buffer management
Thermal management	Heat sinks on laser driver; PCB thermal vias
Budget ($500)	Off-the-shelf components; JLCPCB for PCB fabrication
Laser safety (Class 3B)	Hardware interlocks + goggles during testing

Table 16: Key Constraints Chart

4.8 Thermal Constraints

Thermal management is a critical consideration in the design of the Braille etching system, primarily due to the heat generated by key components such as the laser module, stepper motors, and voltage regulators. These elements, when operating simultaneously within a compact enclosure, can result in localized hotspots that degrade performance, reduce component lifespan, or introduce safety hazards. Effective thermal constraint mitigation strategies must therefore be integrated into both the electrical and mechanical aspects of the design.

Laser Module Heat Dissipation

The laser etching module is one of the primary heat-generating components in the system. During prolonged etching operations, the laser diode experiences significant power dissipation, particularly if driven at high currents to achieve efficient paper ablation. Excessive heat buildup in the laser housing can cause wavelength drift, reduced output power, or premature diode failure. To address this, a passive aluminum heatsink will be mounted directly onto the laser housing to increase surface area for convective heat transfer. Should testing reveal inadequacies in passive cooling alone, an active solution—such as a small 5V brushless fan—may be implemented to force airflow across the diode housing and maintain a safe thermal envelope.

Stepper Motor Thermal Profile

The two stepper motors responsible for X-Y gantry movement also contribute to the system's thermal load. Stepper motors inherently dissipate heat due to continuous current draw, even when holding position. The DRV8825 motor drivers used in our design allow for current limiting via adjustable potentiometers, enabling us to reduce unnecessary thermal dissipation by tuning motor current to the minimum value required for reliable torque. Additionally, motor driver PCBs will be placed away from heat-sensitive components, and the main PCB layout will include thermal vias beneath the driver ICs to help spread and dissipate heat through the copper planes.

Voltage Regulator Heating

The onboard LM2596 buck converter used to step down from a higher input voltage (e.g., 12V DC) to 5V for USB devices and logic circuits also generates heat under load. The LM2596 is known to run warm when stepping down from high voltage under moderate current loads, particularly when powering USB peripherals such as a keyboard. To prevent thermal runaway or voltage dropout, the LM2596 will be mounted with ample copper pour around the IC for heatsinking. Additionally, thermal relief cuts will be avoided in these areas to maximize conductive heat transfer to the PCB. If heat dissipation remains a concern during full-load testing, a heatsink may be added to the LM2596 chip itself, or airflow routing may be adjusted within the enclosure to promote cooling.

Passive cooling methods are preferred to keep the system compact, silent, and energy-efficient. These include heatsinks, thermal vias, copper pours, and strategic PCB/component placement. However, should thermal tests during prototype validation reveal hotspots or thermal thresholds being exceeded—especially near the laser driver circuitry—then active cooling will be introduced. This could take the form of low-profile fans mounted to the enclosure, powered through the 5V rail, and thermally triggered via GPIO or external temperature sensors for intelligent fan control.

4.9 Cost Constraints

One of the guiding principles behind the design and implementation of the Braille etching system is affordability. Tools and devices created for accessibility—particularly those intended for individuals with visual impairments—are often priced well beyond the reach of many users due to proprietary hardware, specialized software, and low-volume production. Our team recognized early on that keeping our system affordable would not only meet the practical budget limitations of a student project, but also align with the broader mission of developing accessible assistive technology for underserved communities. As such, we set an internal goal to design a fully functional prototype with a total bill of materials (BOM) not exceeding $200.

To achieve this, we made careful component selections and prioritized low-cost, high-impact design decisions. For instance, the Raspberry Pi Zero WH was selected for its low cost, built-in Wi-Fi capability, and GPIO expandability. It provided sufficient computing power to manage Braille translation tasks and user interface operations while remaining under the $15 price point. The MSP430FR6989 LaunchPad was chosen to serve as the real-time hardware controller for the motors and laser due to its excellent power efficiency and our team's prior experience with it in coursework, which also reduced development time and risk. For motor control, we selected DRV8825 stepper motor drivers, which are not only affordable but also include advanced features such as current limiting and thermal shutdown—critical for maintaining safety in a tightly constrained enclosure.

Throughout the design phase, we relied on academic discounts and low-cost bulk component suppliers such as Digikey, Amazon, and the Texas Instruments University Program to minimize expenses. Rather than investing in expensive mechanical components or aesthetic features, we concentrated our budget on hardware necessary for core functionality. This meant intentionally postponing nonessential features like a user-facing display or a finalized enclosure in favor of more pressing components such as the laser diode module and power management circuitry. Additionally, to minimize software expenses, we used open-source libraries such as Liblouis for Braille translation, avoiding the need to purchase proprietary software or develop complex translation logic from scratch.

Maintaining affordability did not mean sacrificing functionality. Strategic trade-offs ensured that essential features—precise motor control, reliable laser etching, and real-time Braille conversion—remained uncompromised. We also designed the system with modularity in mind, allowing for scalability in future iterations. For example, users who require a more rugged or polished product in the future can add a 3D-printed or laser-cut enclosure without redesigning the electronics. Likewise, the laser module or motor assembly can be upgraded independently if greater performance is needed. This forward-thinking design strategy ensures that the initial system remains low-cost, while future versions can scale in capability and expense as needed.

4.10 Power Constraints

Power management plays a central role in the overall design of the Braille etching system, as it directly influences reliability, portability, and safety. One of the earliest decisions our team made was to support both AC power input and battery-based operation, enabling the device to function in a variety of settings, including classrooms, homes, and mobile outreach environments. This dual-source capability introduced several engineering challenges related to voltage regulation, current distribution, and overall power efficiency, which needed to be addressed early in the design process to prevent instability or component failure.

When powered through a wall outlet, the system receives a regulated 12V DC supply via an external AC/DC adapter. This 12V line is then distributed to the main power path, where it feeds subsystems like the stepper motors and voltage regulators. To make the system portable, we also incorporated the ability to run on a lithium-ion battery pack with equivalent 12V output. To ensure a smooth transition between these two power sources, we implemented a power path controller circuit in conjunction with an undervoltage cutoff mechanism. This design not only allows the system to switch between battery and wall power without interruption but also protects critical components by disconnecting the load if the battery voltage drops below a safe threshold.

Power regulation within the system is handled using both switching and linear regulators. A buck converter (specifically the LM2596) is used to step the 12V input down to 5V, which powers the Raspberry Pi Zero WH and provides USB voltage for peripherals like a keyboard. The MSP430FR6989 microcontroller, which handles motor control and communication, operates at 3.3V and is supplied by a low-dropout linear regulator downstream of the 5V rail. This multi-stage regulation scheme was chosen to isolate noise-sensitive components from power-hungry subsystems, while also maintaining good thermal performance and efficiency.

5 ChatGPT and other LLMs

In the current age of AI and access to information it brings we must talk about the effect AI has on a project like this. AI is a powerful tool that when used correctly, and in unison with a sharp mind, can achieve great things.

5.1 ChatGPT

When using AI it is important to not blindly trust it as it can be inaccurate especially when the question becomes more complicated. Take the beam collimator at the output of the fiber. When I asked ChatGPT “Can you help me design an optical system that collimates light coming from an optical fiber into a beam size around 1mm?” The LLM broke it down into 3 steps as follows.

Step 1: Key Information needed
In this part ChatGPT lays out the variables it is about to use to calculate the required values for the system I specified. It states it needs to know the fiber core size and assumes we are using a single-mode fiber that has a core size of around 5 µm. It then states that the numerical aperture for these fibers is usually 0.12 which is a very common value seen in standard fibers. It then asks for the wavelength of the light and the beam shape preference. Initially I thought those last two values were unnecessary as they would not have large effects on the system design. But these values become very relevant as the LLM delves deeper into the design process than expected.

Step 2: Basic Principles and Step 3: Sample Design

These last two steps are simply the LLM explaining the equations needed to find what focal length of lens it suggests we use and then taking some arbitrary numbers to give an example answer.

Beam Diameter $= 2f * NA \Rightarrow f = \frac{1mm}{2 * 0.12} = 4.17mm$

Using this equation, ChatGPT suggests we use a lens with a 4.2mm focal length. Again as you can see both the wavelength of the light and the beam shape preference do not play a role in these calculations and the beam shape still does not but the wavelength does. ChatGPT proceeds to give part numbers for real lenses that could fit these parameters. It suggests we use a “Thorlabs A390TM-A” lens, which is a real lens and ChatGPT gave fairly accurate information on it. The ChatGPT says the focal length of the lens is 4.5mm while it is 4.6 and also states the numerical aperture is 0.55 while it is 0.53. The reason it wanted to know what wavelength we are using is because this lens has an AR coating for wavelengths 350 - 700 nm which ChatGPT correctly states as well.

ChatGPT can also excel at giving usable part numbers when prompted a question about “what would the best part for this application be?” When researching about regulators, PowerPath designs, motor controllers, etc., it gave insight into what parts can be used to achieve a desired result. Not only would it suggest a part number, but it would suggest multiple part numbers and give examples of each of their own capabilities. Of course, you would have to go to the datasheet and verify everything it told you (and to make sure it would work in your project), but it was very accurate when it came to discussing broad details about each part.

For example, when asking about what battery (brand/part) would be ideal for what we wanted to accomplish in the battery pack design, it listed out multiple brands of batteries. The batteries we went with were one of the suggestions ChatGPT said, the Sony Murata VTC6s. These batteries are highly recommended and used across many personal projects or hobbyists. They offer a high energy capacity and a high continuous discharge rate, which fit perfectly in our project.

It also excels in giving surface level information about any topic you wanted to research about. Since we are branching out of our engineering disciplines a little bit and incorporating motors, ChatGPT gave multiple suggestions on how we can achieve a mechanical system that will help us achieve our goals. These goals being a precise printing mechanism using a motor for each axis (x and y-axis). It went into detail about various types of motors we can use and their advantages, disadvantages, popularity for specific applications, and much more. It also suggested a motor controller that can interface with our microcontroller and the motors themselves, and after researching the part number and verifying that it can certainly work in our project and decided it was a good fit (the DRV8825) for this system. Overall, it significantly increased our knowledge about the mechanical side of this project.

5.2 Google Gemini

Here in this section we will be giving the Google Gemini AI the same prompt and analyzing its response to compare it to the ChatGPT model. Immediately the response looks vastly different from the response from the ChatGPT model. It gives longer, more drawn out explanations of the properties of optical fiber and collimation. Its first large difference from the other model is that it gives two different methods to find the divergence angle of the fiber. It states that for SM fibers the half-angle divergence can be approximated as $\lambda/(\pi * w_0)$ and for MM fibers the half angle is given by arcsin(NA). After this the AI starts to spew paragraphs of information that is cluttered and hard to sift through but eventually ends up with a familiar equation.

$$f = \frac{D_{beam}}{2 * NA}$$

This is exactly the same equation that the ChatGPT model gave us to find the focal length of the lens we want to use. This equation showing up twice in two different models is already a good sign that we are being given accurate information.
Next the AI also gives us an example solution using arbitrary values as the ChatGPT model did but also offered possible optimization methods. It started to explain the different kinds of lenses that could be used to help collimate and focus the light such as aspheric lenses and GRIN lenses. It also talks about the diffraction limit and how it affects collimation amongst other related topics that I did not request. This is very impressive because it shows that these LLMs are able to emulate a true understanding of whatever topic one might throw at them.

5.3 AI and Code

AI is an incredibly powerful tool that can also be used to aid in coding the main system of the device. ChatGPT o4-mini-high is specialized for programming and does an excellent job in finding the cause of errors as well as laying out skeletons and lines of thought when programming code this complex.

AI websites such as programs such as DeepAI are excellent at debugging and acting as a space to test theoretical input/outputs, allowing code to be “tested” in an environment that does not have the physical components. Debugging with AI presents an interesting dilemma on what is made by hand and what is simply taken from a model, it is up to the user to tow the line of adopting for slight gain and strengthening existing code and outright plagiarism. In the modern world, jobs encourage the use of AI or have their own molded AI models that are secure to handle the businesses source code.

Our group is dedicated to maintaining our integrity on our code but having the ability to leverage our own intelligence with the power of AI is an incredible feat that will better not only our skills but the project itself. Utilizing AI, our group has the ability to scour resources across a wide range of texts and trusted organizations to solidify knowledge on the various complex moving parts involved in this design. ChatGPT, when handed prompts on the design and logic behind the project, suggests UART communication between the MSP and a potential Raspberry Pi.

Using a language model such as DeepAI, when asked “Info on device that uses a keyboard or usb to enter text then prints a braille translation that uses uart or spi and how does an interaction happen between a raspberry pi and msp?” the model broke it down into input, processing, interactions, and output sections. The DeepAI model confirmed our approach by noting the user input, processing, and translations all being handled by Python. The information on printing data would be sent by UART to the MSP. The next language controlling the printer hardware functionality would be C. The language model gave rather weak and undeveloped code as a “skeleton”.

With the same prompt, ChatGPT o4-mini-high gave more in depth explanation. The model first notates the differences between SPI and UART. The model argues that SPI is not really needed as the data transfer is simple and the hardware is connected mainly to the Raspberry Pi’s ports. The code then goes through a simplified list of Python steps. This consists of detecting the USB or keyboard’s presence as well as obtaining user choice for the input method. The code parses the info in the desired contracted or uncontracted pattern and sends instructions for UART.

The C steps have initializing the laser, UART connection, power, and clocks. The MSP will await signals that will dictate the commands executed by the C code, sending acknowledgements and controlling printer functions. The C code will also update the LCD with any pertinent information.

The differences in the analysis by the models is interesting, DeepAI did not give SPI insight as it was “deemed” unnecessary. ChatGPT’s model was relatively detailed, but the skeleton given by the model was very incomplete. All in all, the models confirmed the ideas and thought processes held by the team in the approach to the braille laser etcher.

6 Hardware Design

The hardware design section is to present all hardware aspects of the system and how they are integrated with each other to form a complete, functional system. This will include a high-level subsystem block diagram that will illustrate the system's architecture in detail. This will highlight how each connection is made at the hardware level. This section will also have all the schematics of the PCBs that we will be designing for this project. This includes the main PCB with the MSP430, regulators, PowerPath controller, stepper motor driver controller, battery management system, etc.

6.1 High-Level Design Block Diagram

The high-level design flowchart depicts our entire system and how everything connects to each other at the top level. It shows how external components will be connected to the main PCB and then how they are connected on board, as well as where power/signals are being sent to.

We can see our two main power sources; the custom battery pack and the AC/DC power supply that will plug into the wall. These will both be fed into female barrel jacks that will be operated via on board switches. If both switches are turned on, then our on-board PowerPath circuit will determine which of the two input voltages are higher and choose the highest. This means that our system will prioritize the AC/DC power supply over the battery pack so there is no wasted energy from the battery pack, maintaining its charge. Once the PowerPath controller chooses our power supply, we then feed this through the undervoltage protection circuit. However, it must be powered on by an always-on 3.3V regulator so it can always compare the voltage. Then, this circuit will cut off the input voltage when it detects that our voltage goes below 13.5-volts. This is because we want our 12V regulators to operate as efficiently as possible, and when we drop below +1.5V over the rated regulated voltage, we will start to see it fail. Our input voltage then goes into all our regulators, where our 12V regulators will power the motors and lasers, 5V for the Raspberry Pi, and 3.3V for the MSP430. The MSP430 will be designed on board, while the Raspberry Pi will be connected to the main board by USB. We chose this because the Raspberry Pi is essentially a mini-computer, and designing one is extremely difficult.

The Raspberry Pi will take input from a keyboard or a text file and translate the text into braille. It will then send this information over to the MSP430 via UART for it to communicate with the motor controllers, which will then drive the motors. These motors will drive the 'x' and 'y' axis of our system, where the laser is on the x-axis and the paper tray is on the y-axis.

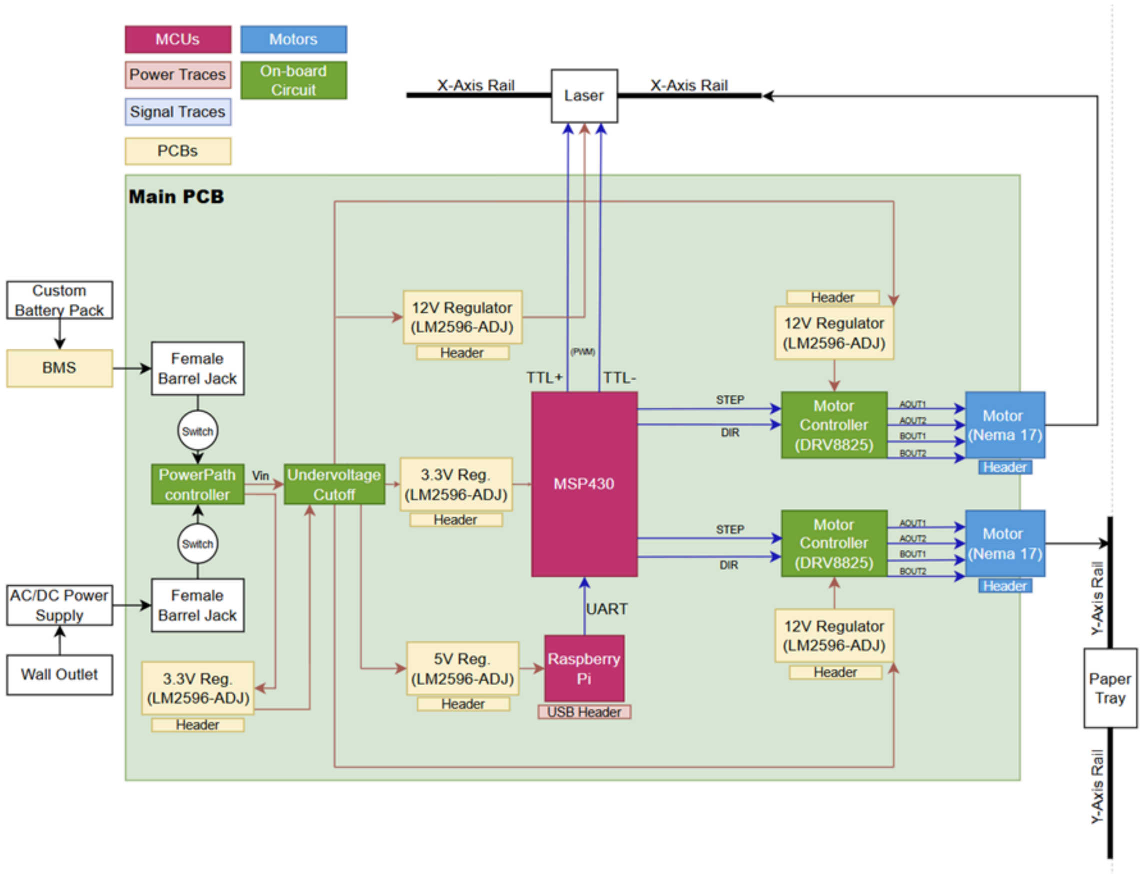


Figure 16: High-Level Design Block Diagram

6.1.1 Overall Schematic

The overall schematic of the main PCB contains the MSP430, each motor controller and their respective headers to the motors, the undervoltage protection circuit, PowerPath controller circuit, and the headers that will connect all of the regulators to the board. Each respective circuit will be found below in "**6.2.X Schematics**."

6.2 Schematics

The schematics of our system will include all PCB designs that are within our system. These were all created inside AutoDesk Fusion.

6.2.1 Voltage Regulators

Our device will be utilizing three buck regulators: 3.3V, 5V, and 12V. Each of these regulators will be using the adjustable LM2596 buck regulator (LM2596T-ADJ/NOPB) where the main component changes happen at CF, RFB2, COUT, and D1. Using an adjustable LM2596 buck regulator will help save costs, as we only need to design one PCB and solder on the different components to assemble the correct buck regulator. These designs were created using WEBENCH® POWER DESIGNER by Texas Instruments. We wanted to have an input voltage of 11-16.8 volts because this will be the operating range of the battery pack when at maximum charge to nearly discharged. However, the 12V regulator will have an input voltage of 13.5-16.8V because the regulator's input voltage must be 1.5V higher than the regulated voltage. Therefore, we will implement a voltage detection circuit on the main PCB for this regulator to guarantee that the voltage going into the 12V regulator will be above 13.5V and will "deactivate" when below 13.5V. Below, you will find each regulator design.

The 3.3V regulator will be placed onto two different headers. One header for the MSP430FR6989 and one header for our "always-on" header that will provide power for the internal logic of the PowerPath controller (LTC4412) and the voltage detection chip (TPS3808G01) that drives our undervoltage protection system.

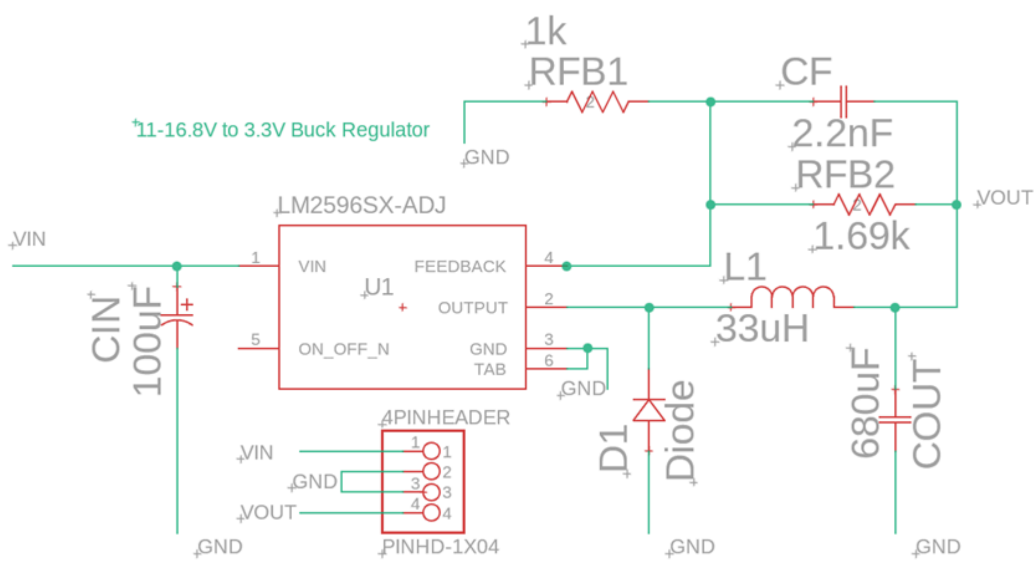


Figure 17: LM2596-ADJ 3.3-volt Buck Regulator Schematic

The 5.5V regulator will strictly be used for the Rapsberry Pi Zero, as this is the only component in our circuit that needs 5 volts. The Raspberry Pi will take the regulated 5 volts and power the entire board, enabling us to plug in various USB devices to the board, such as the keyboard. It will also enable the Raspberry Pi to communicate with the MSP430FR6989 via UART which is crucial for our project.

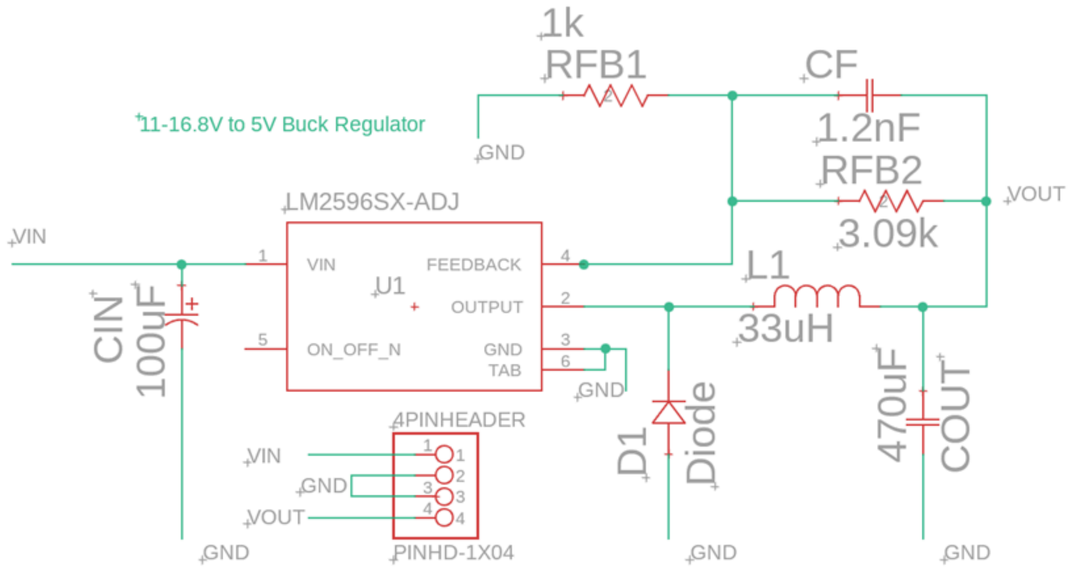


Figure 18: LM2596-ADJ 5-volt Buck Regulator Schematic

Last but not least, the 12V regulator will be used to drive the laser and the motors. We will use three 12V regulators on our board, where one will power a female barrel jack that can connect the laser to power. Then the other two 12V regulators will be used to drive the DRV8825 motor controllers which also drive the two stepper motors. The reason we want to use a separate regulator for each component is because they can each potentially draw large amounts of current, and the LM2596 regulator is only rated for 3 amps continuously. Therefore, if we divide them up to have three separate regulators, we can distribute the current so there is no overload on a single regulator.

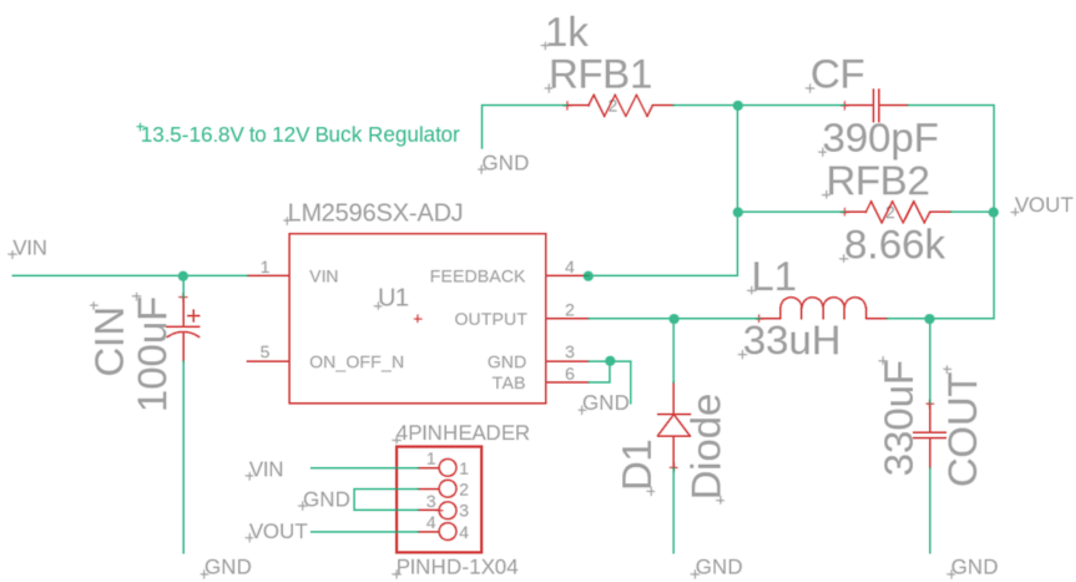


Figure 19: LM2596-ADJ 12-volt Buck Regulator Schematic

6.2.2 Stepper Motor Controller

The motor controller that will be designed onto the main PCB is the DRV8825. The DRV8825 is what communicates with the motors and the MSP430. The STEP and DIR pins instruct the motors where to move our laser and paper tray to correctly etch into the paper. We will be using two motor controllers on the main PCB, one for each motor. This is essential because a single motor controller will not be able to control two motors at the same time as they would both function off the same STEP and DIR pins. The input for the motor controller will come from the 12V regulators to provide power to the motor controller and motors. AOUT1/2 and BOUT1/2 will connect to a header in which the motors will be plugged into so they can interface each other. The DRV8825 datasheet had a useful “typical application” figure in which it detailed the overall circuit for this motor controller, which was very helpful.

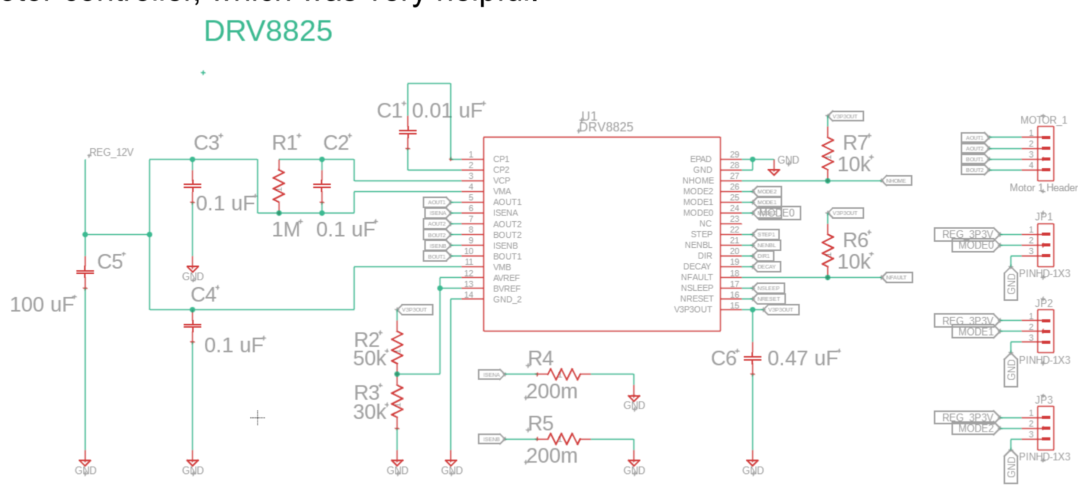


Figure 20: DRV8825 Motor Controller Schematic

6.2.3 Gantry Design

A critical component of the system involves determining the method for controlling mechanical movement. For this project, a pre-existing motion control approach was selected rather than designing a new one. The design is based on a gantry-style motion system, which is commonly used in 3D printers. These systems typically allow for precise, two-dimensional movement of a tool head or platform.

The selected gantry mechanism operates using stepper motors, timing belts, and linear rails to enable movement along the X and Y axes. These components are widely available, well-documented, and have established performance characteristics. The configuration allows for consistent positioning and repeatability, which are necessary for laser etching applications.

The gantry system supports scalable design modifications, allowing adjustments to travel distance, resolution, and speed. Integration with microcontroller-based motion drivers and open-source control software is also supported, enabling automated control and path planning. This setup aligns with the system requirements of directing a laser beam or moving a material substrate with high spatial accuracy.

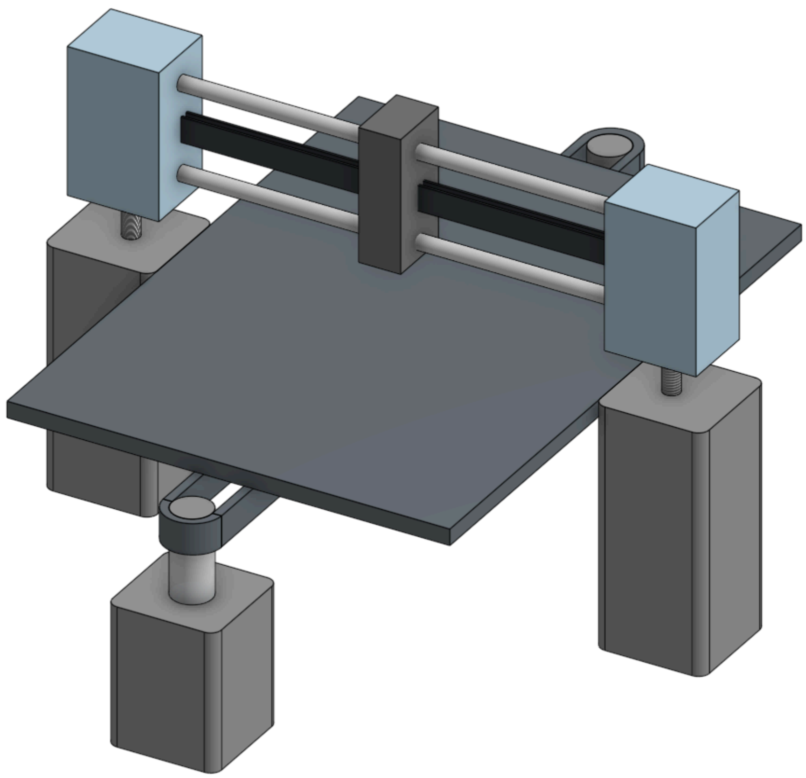


Figure 21: 3D Rendering of Gantry

The selected gantry system for the braille etching printer allows for a degree of mechanical customization beyond the basic capabilities of the stepper motors. To control movement in both the X and Y directions, the design incorporates timing belts as the primary transmission mechanism. Timing belts are commonly used in two-dimensional motion systems due to their ability to provide reliable, synchronized linear motion with minimal backlash.

The use of timing belts enables the application of gear ratio principles to adjust mechanical resolution and precision. By selecting appropriate pulley sizes and belt pitches, the system can be fine-tuned to achieve the desired level of motion accuracy. This is particularly important in applications where consistent step size and repeatable positioning are required, such as laser etching of tactile braille dots.

In addition to improving resolution control, the timing belt system assists in maintaining synchronization between the two axes. Proper synchronization is critical to prevent mechanical misalignment during motion. If either the X- or Y-axis motor loses steps or fails to maintain position, the resulting offset can lead to positional errors, distorted outputs, or potential collisions within the system. Maintaining tension in the belts and ensuring stable motor control helps to reduce the risk of such failures.

Timing belts are a standard solution in many commercial and DIY gantry systems. Their widespread use is due to advantages such as low cost, ease of integration, and smooth motion transmission. In this project, the choice to implement timing belts aligns with industry practices and offers a practical solution to the mechanical challenges associated with coordinated two-dimensional motion.

6.2.4 Battery Management System (BMS)

The battery management system is crucial for the custom battery pack, specifically one that uses unprotected cells. Finding a design of a 4S BMS is very difficult online as there are no results that come up when you search up a specific BMS board. There are CAD circuit drawings though, however, the only one I found for the 4S BMS is not going to be displayed here, as the creator of the schematic has not responded to me. Here is a close-up of the board we have purchased of the 4S BMS:

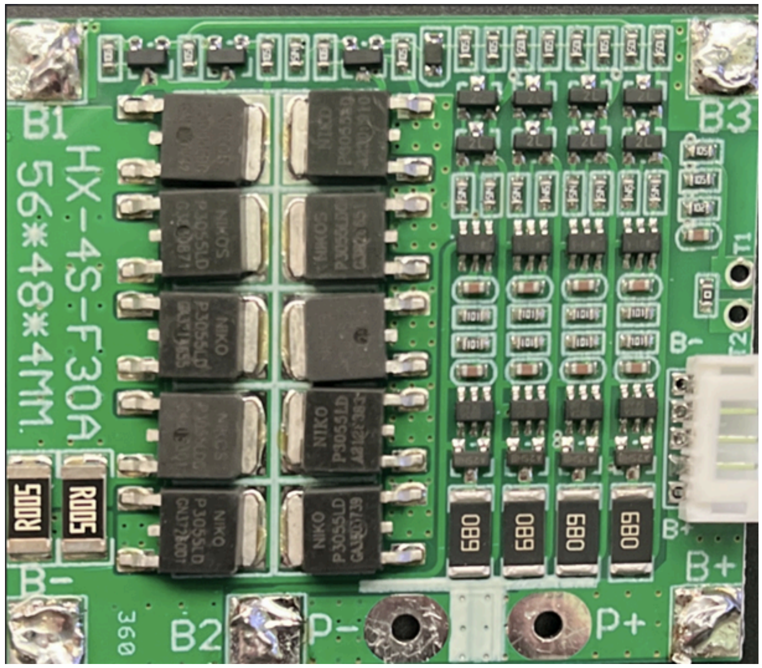


Figure 22: 4S BMS PCB

The important connections of the board is P+ and P- as these are where our output power comes from. These pins are also used to charge the batteries. In order to achieve balance charging to guarantee that the cells do not become more charged (or discharged) than one another is using the balancing leads that connect to “B-, B1,” up to B+.”

6.3 Power Supplies

The power supplies used in this system will be both a custom battery pack and an AC/DC power supply that will be plugged into a wall outlet. The main PCB will be able to decide which power supply to take input from by utilizing the on-board PowerPath controller. Having these two options gives our system more flexibility and even makes it more viable for a user that is constantly moving the system from place to place.

6.3.1 Custom Battery Pack

The battery pack that will be powering the system is 18650 batteries with a nominal voltage of 14.4 volts that has a 6000 mAh capacity. The batteries used are unprotected cells, meaning we must use our own protection methods to ensure they operate as safely as possible. This is achieved by using a 4S2P configuration of batteries, requiring eight cells in total. This configuration means that there will be four sets of batteries, where each set is two batteries in parallel. This is how we quadruple the output of one battery and double the capacity of it, resulting in the nominal 14.4-volt 6000 mAh battery pack. This battery pack was assembled by using 99.6% nickel strips spot welded onto the cells to configure the connections, insulator rings around the positive ends of the cells, Kapton tape around all parts of the battery pack, 18650 shockproof plastic battery holders, is equipped with a battery management system via 16 AWG wire with heat shrink ring terminals and balancing leads for balance charging. It will then sit inside of a fireproof and explosion proof bag specifically tailored for lithium-ion batteries.

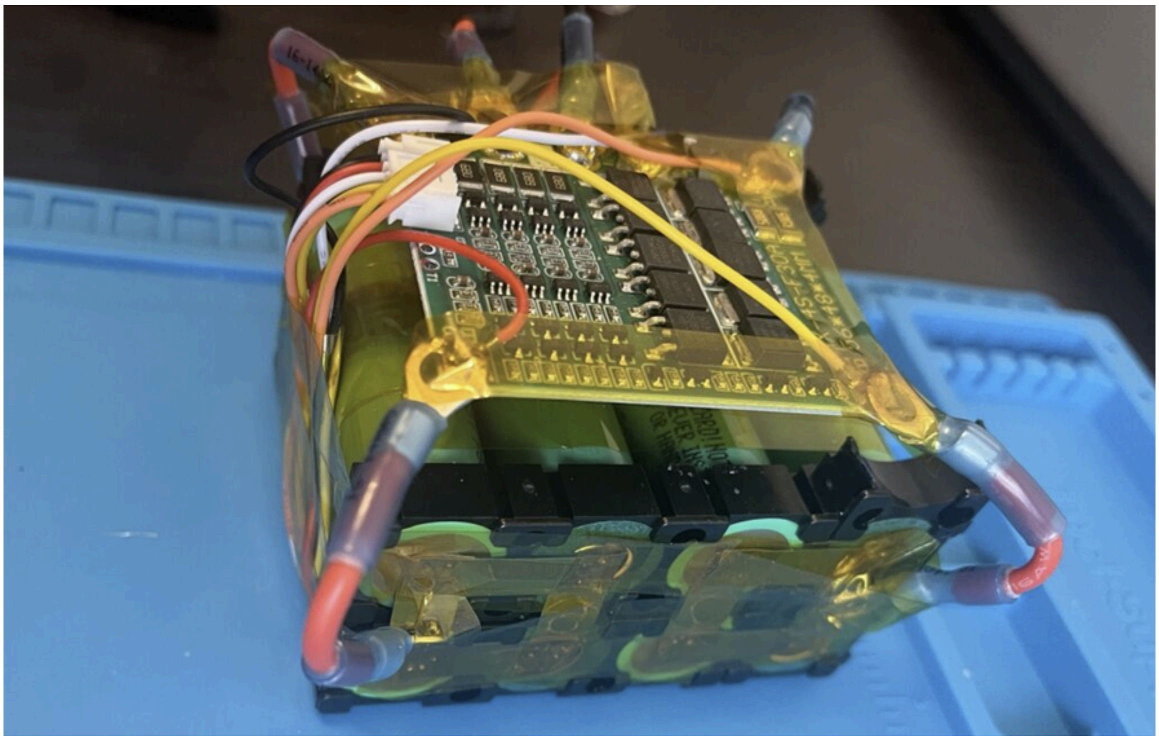


Figure 23: Fully assembled 4S2P Custom Battery Pack

6.3.2 AC/DC Wall Adapter Power Supply

The wall powered connection will be achieved by using an adjustable AC/DC adapter. The reason we want it to be adjustable is because we want to only have it output a voltage that is marginally larger than the maximum voltage our battery pack can produce, which is 16.8 volts. Therefore, we want to adjust our AC/DC power supply to output 17 volts so we can minimize the voltage lost to heat when going through our voltage regulators, specifically the lower voltage ones (5V and 3.3V).

Figure 24: AC/DC Adapter outputting 17 volts

6.4 Printer Configuration

The printer will utilize steel rods that will hold both the paper tray and laser in place, allowing for movement along the rods that will be driven by the motors. The housing itself is still to be determined but will most likely be made of wood or 3D printed parts. The paper tray and laser that will slide across the steel rods will be driven by two stepper motors, one for the y-axis and one for the x-axis. The paper tray will move along the y-axis and the laser will move along the x-axis, resulting in a 2D style printer. The reason we do not need a z-axis is because we are printing a singular dot multiple times. Once we figure out the correct power/PWM settings for the laser to successfully etch a bump into the paper, we will not need the z-axis. The way the motors will be driven is by using timing belts and a pulley connected onto the rotor of the motor.

The reason we are configuring our system to have a separate motor for the paper tray and a motor for the laser is for simplicity. Also, most commercial/consumer 3D printers will also use a separate motor for the bed of the printer while the nozzle moves along the x and the z-axis using other motors. This increases the simplicity of the design as we are not moving our laser in both the “x” and “y” direction.

6.4.1 Laser and Paper Tray Movement

The laser and paper tray will have a mounting device, most likely 3D printed, that connects to the steel rods and allows for a timing belt to be connected. On the flat surface, we will have the paper tray that allows for a piece of paper to be placed onto and one stepper motor will drive the paper tray along the y-axis. Then, we will have the laser mounted onto the steel rods that will be mounted above the paper tray by using poles on each side also being driven by a timing belt. These motors will receive instructions on what to do from the DRV8825 motor controller which receives its signals from the MSP430. The motors will drive timing belts through the use of pulleys to move the mounting devices in correspondence with the signals they receive from the motor controller.

6.5 Main PCB

The main printed circuit board (PCB) was designed to bring all the key hardware components of the Braille etching system together into one organized and functional platform. This includes the MSP430FR6989 microcontroller, two stepper motor drivers (DRV8825), the laser control circuit, user input connections, and power distribution. The goal was to create a board that's not only functional, but easy to assemble, debug, and update during SD2.

We started the schematic design in Autodesk Fusion, organizing each subsystem—such as the microcontroller, motor drivers, power inputs, and outputs—into clean sections. This made it easier to follow signal flow and manage connections during layout. The two DRV8825 drivers were chosen for their ease of use, adjustable current control, and compatibility with the motors we selected. The MSP430 sends STEP and DIR signals to each driver using GPIO pins from Port 2. This allows for organized signal routing and easier programming of motion sequences.

In future versions of the board, we may add features like voltage monitoring, motor current sensors, or SD card storage. The current version of the PCB is fully routed, has passed all design rule and electrical rule checks, and is ready to be manufactured and tested in SD2.

6.5.1 Microcontroller - MSP430FR6989

This schematic shows the MSP430FR6989 microcontroller and its key connections to various subsystems in the Braille etching device. GPIO pins from Port 2 are used to control the stepper motor drivers, with labeled outputs for STEP1, DIR1, STEP2, and DIR2. A separate PWM output pin is used to control the laser diode, allowing precise control over burn duration using software-configured timers. UART TX and RX pins are routed to a USB-to-serial interface for programming and real-time debugging. The SDA and SCL lines are reserved for future I2C communication with optional peripherals such as an LCD display or EEPROM.

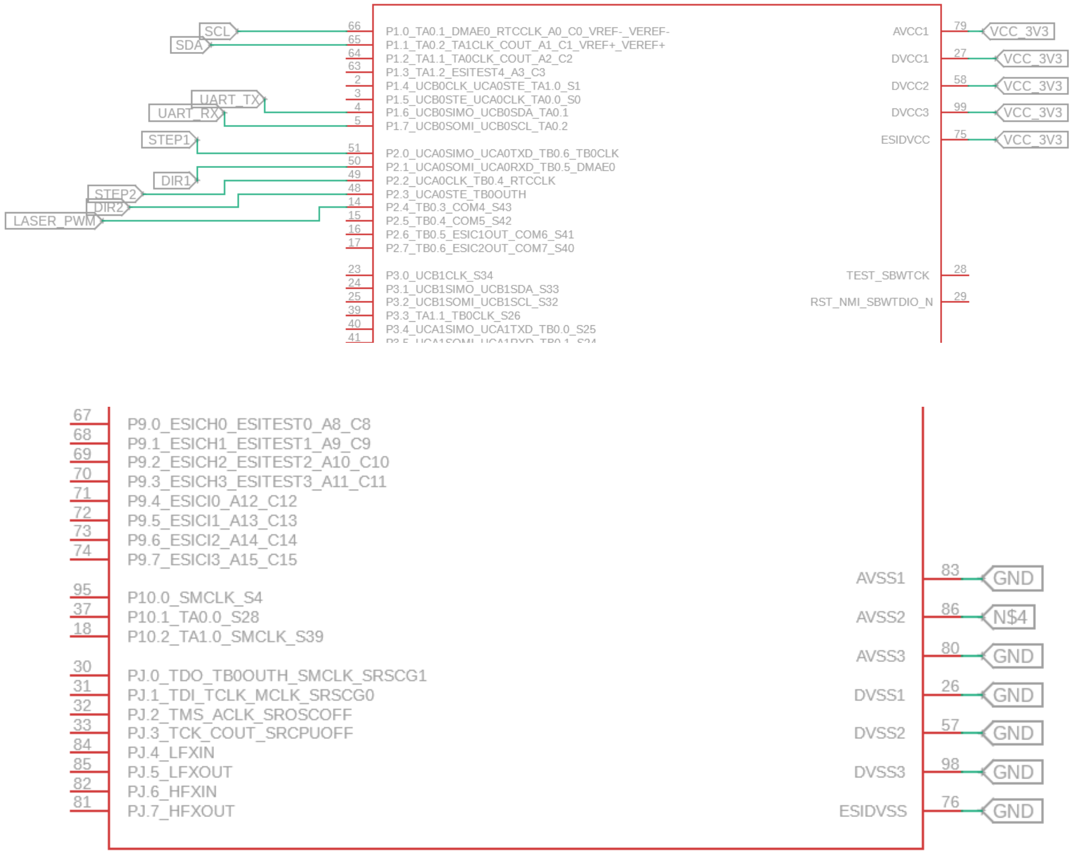


Figure 25: MSP430FR6989 Schematic

Power to the microcontroller is provided through multiple labeled 3.3V inputs, with decoupling capacitors placed near each power pin to stabilize voltage levels and reduce noise. All unused pins are broken out to headers to allow for easy testing or expansion in future revisions. Ground pins are tied to a solid ground plane on the bottom layer of the PCB to minimize noise and ensure consistent return paths. The clean organization of this schematic allows for straightforward routing during PCB layout and ensures that timing-critical signals like the STEP pulses are kept short and isolated from noisy power lines.

This layout supports future software development by reserving key peripherals (I2C, UART, Timer outputs) while focusing on a minimal and stable base system for SD1 testing. The integration of this microcontroller schematic with the rest of the PCB design allows for centralized control of all motion and laser functions in a compact and efficient configuration.

6.5.2 Main Header Connections

This schematic illustrates the key interface headers used to connect the main PCB to external components, including the motors, laser module, MSP430 microcontroller, and Raspberry Pi. Each header is designed to support clean, modular wiring using standardized 1x4 or 1x2 connectors. The MOTOR1 Header and MOTOR2 Header provide separate 12V power and ground lines to each DRV8825 stepper motor driver, which in turn powers the stepper motors. These are supplied from a regulated 12V rail and organized to ensure correct polarity and current delivery.

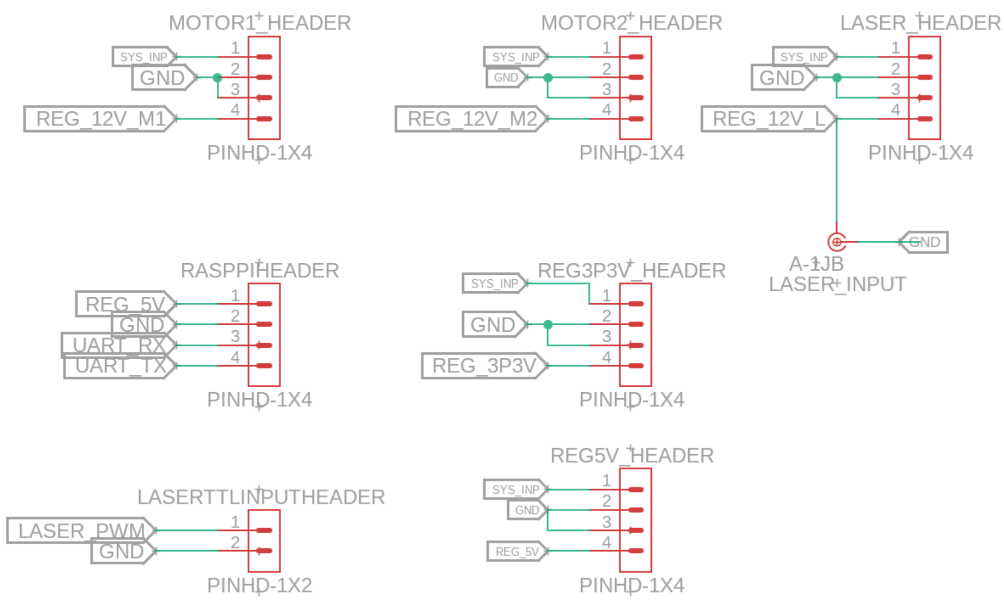


Figure 26: Peripheral and Power Header Schematic

The LASER_INPUT barrel jack delivers power to the laser driver circuit, sourced from the same 12V supply line. The LASERTTLINPUTHEADER receives the PWM signal from the microcontroller, which is used to toggle the laser on and off based on pulse width modulation. This separation of control and power helps isolate digital noise and ensures that signal integrity is maintained.

Two UART communication headers (RASPBPIHEADER and RASPBPIHEADER1) provide connection points for interfacing with a Raspberry Pi via UART TX/RX lines and 5V power. This can be used in SD2 for higher-level input or Braille translation offloading. The REG3P3V_HEADER provides regulated 3.3V power and a ground connection directly to the MSP430FR6989, ensuring a stable supply for logic-level operation.

Overall, this schematic enables modular wiring and easy debugging. Each header is clearly labeled and organized based on voltage level and signal type, which helps avoid wiring mistakes and makes system assembly more efficient. These headers were also placed along the edges of the PCB layout to keep cables tidy and out of the path of moving parts in the mechanical frame.

6.5.3 Undervoltage Cutoff Protection - TPS3808G01

This schematic shows the implementation of an undervoltage lockout (UVLO) and system monitoring circuit using the Texas Instruments TPS3808G01 supervisor IC. The main function of this circuit is to monitor the overall system supply rail and disable power to critical components if the voltage drops below a safe threshold. This protects both the laser driver and the stepper motor controllers from operating in unstable voltage conditions, which could cause erratic behavior or permanent damage.

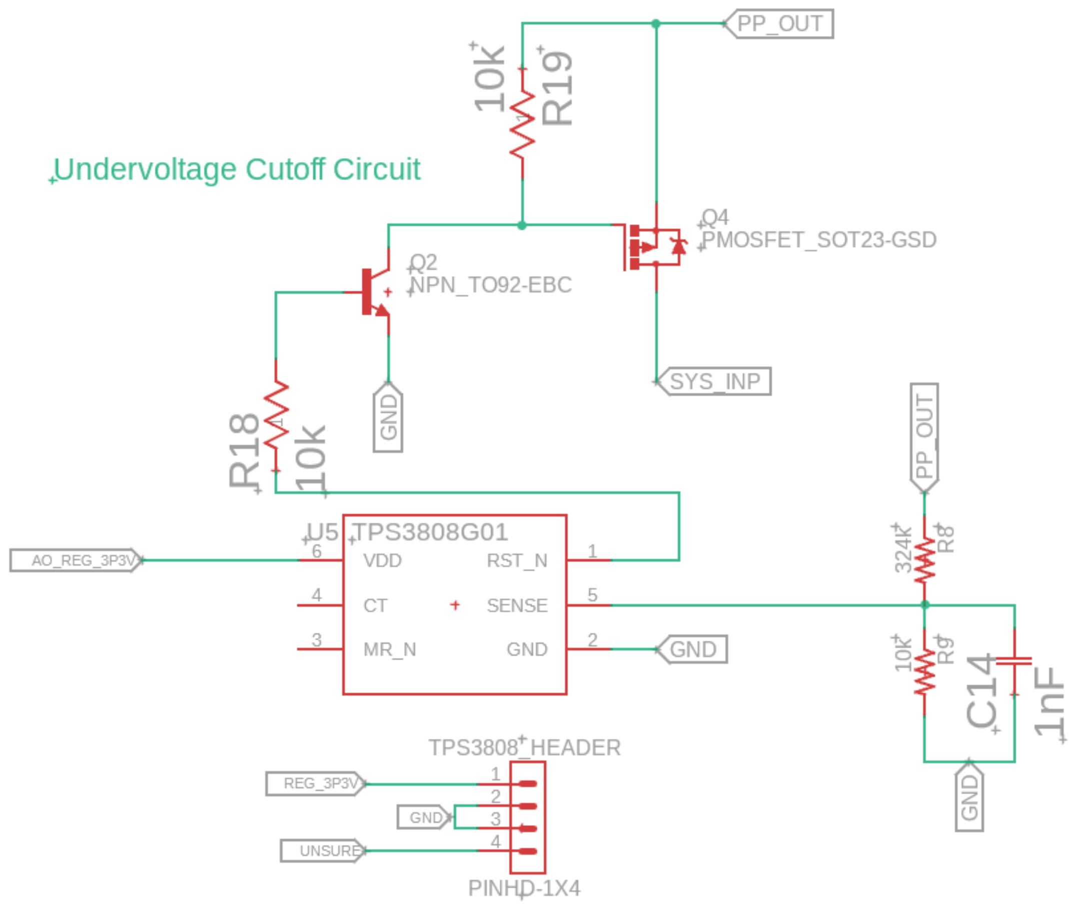


Figure 27: Undervoltage Protection Circuit Using TPS3808

The SENSE pin monitors the voltage level on the SENSE_14V line through a resistor divider composed of a 324kΩ and a 10kΩ resistor. This sets the threshold for when the IC determines the input voltage is too low, in our case, 13.5V. When the voltage falls below the set limit, the TPS3808 pulls the RESET pin low. This RESET is connected to an NPN transistor and then into a P-Channel MOSFET that connects the entire system. When the RESET pin is low, it will turn the P-channel MOSFET off, disabling any current flow to the system. When the RESET pin is high, the P-channel MOSFET will stay on, allowing the system input to power the system. When voltage returns to acceptable levels, the IC releases the reset line after a delay set by the CT capacitor.

The circuit is powered by a regulated 3.3V supply (REG_3P3V) and grounded properly for consistent behavior. The MR_N (manual reset) pin is tied to the supply to disable manual override, although it could be re-routed to a button header in future revisions. A test header (TPS3808*HEADER) is also included for easy monitoring or override during development and debugging.

This undervoltage protection circuit adds an important safety and reliability feature to the overall system, especially considering the power draw of motors and the sensitivity of the laser. It ensures that only when sufficient voltage is present will the system components be enabled, helping to prevent logic faults, brown-out errors, or partial activation.

6.5.4 PowerPath Controller Circuit - LTC4412

This schematic illustrates a power path control circuit built around the LTC4412 ideal diode controller. The purpose of this circuit is to safely manage multiple input power sources—specifically a battery and a wall adapter—and ensure that the system always draws from the preferred power source without conflict or reverse current. The LTC4412 allows seamless switchover between inputs by controlling two external P-channel MOSFETs based on the input voltage conditions.

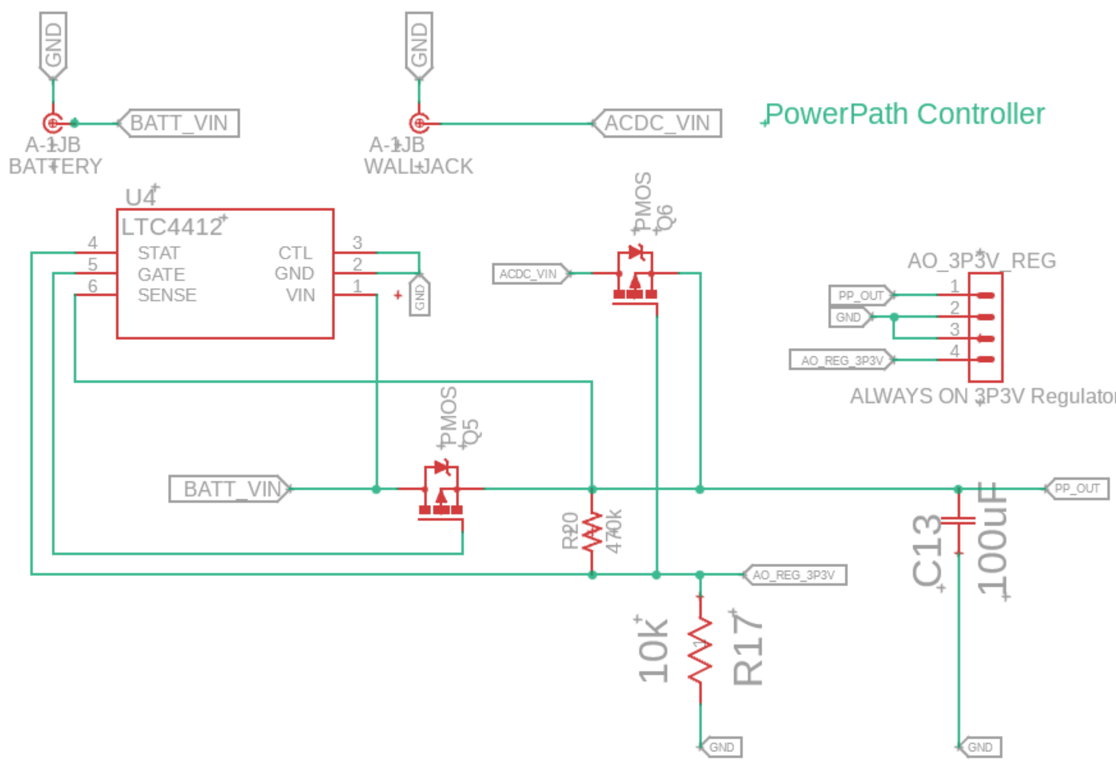


Figure 28: Power Path Controller Circuit Using LTC4412

The VIN lines from the battery and wall jack are fed into the P-Channel MOSFETS. The LTC4412 monitors the system voltage using the SENSE pin and drives the MOSFET gates accordingly. If the wall adapter is present and provides a higher voltage, the gate is pulled low to allow power through. If the wall supply is lost or drops below the battery level, the MOSFET is turned off, and the battery takes over. This ensures the system maintains uninterrupted power and avoids brownout conditions.

The STAT pin controls which MOSFET should be on/off by using a pull-up resistor. A 100nF capacitor on the output line PP_OUT helps stabilize the voltage when switching power supplies.

By using the LTC4412, this circuit eliminates the need for mechanical switching or diode voltage drops, improving both reliability and power efficiency. It is a key component of the system's robust power management strategy, ensuring safe operation regardless of whether the system is plugged in or running on battery.

7 Software Design

7.1 Use Case Diagram

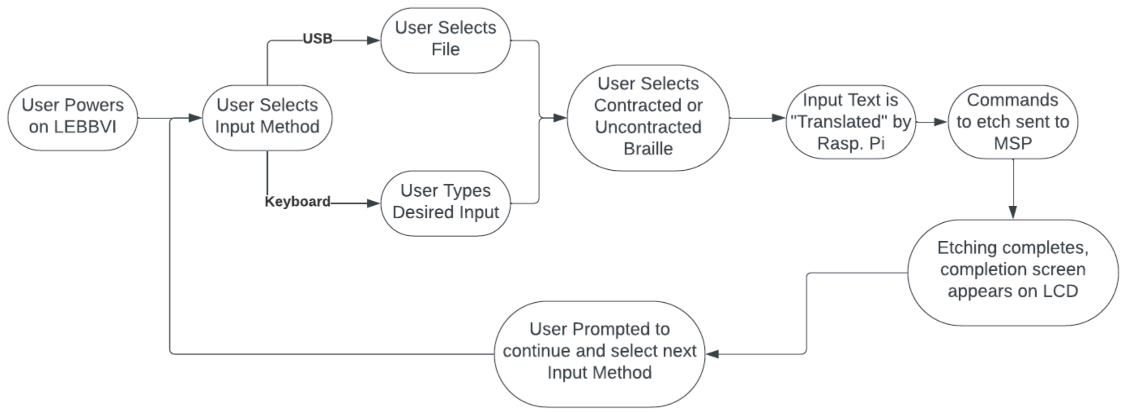


Figure 29: Use Case Diagram

The above use case function, although simplistic, captures the main function and uses of the LEBBVI. The user is able to power on the device with a tactile medium and is then prompted by the device via a LCD screen to select the input method of either a keyboard or MSP. Incorporating the LCD allows for the user to be cognizant of the input method and keep track of progress of the etching. The user is also prompted, after the input is selected and processed, to etch contracted or uncontracted Braille. Having a library saved onboard, the contracted braille can be saved and if there is no 1:1 match the system can opt to use uncontracted in order to avoid errors. For spell checking, python has an onboard and installable spell checker, the autocorrect user inputted words or words on a text file. This is more of an issue for contracted braille as an incorrect word will result in a “missed” translation however this is not a “spell check” machine, the goal is to have a *correct* document uploaded with a safety net for some minor issues. Finally, once the etching is complete, a message prompts the user to continue by restarting the selection loop. Here the user can turn off or continue by selecting another input, whether that be a different text file or a desire to make more copies.

The code for the system diverges when the user selects whether to use a keyboard and USB as well as when the user selects contracted or uncontracted braille. When the user selects to read a USB input, the function must activate to read the USB port and check whether or not it is present. If the user opts for keyboard input, the code checks for a keyboard connection, displays the process is ready to occur, and the user may begin. The paths “converge” as when both inputs are read the user must select the translation method, where uncontracted will access a library of binary assigned to each letter and number in order to correctly print. The 0’s in binary represent a flat spot and 1’s the raised surface. In doing this, there is an easy way to transfer data along to the MSP from the Raspberry Pi via UART. For contracted braille, the code must take the inputs and individually assess if there is a contracted version stored in the library. If there is NO contracted equivalent, the code handles the error by defaulting to uncontracted. This prevents breakdowns mid use. The code connects again when the binary information is sent over UART.

7.2 State Diagram

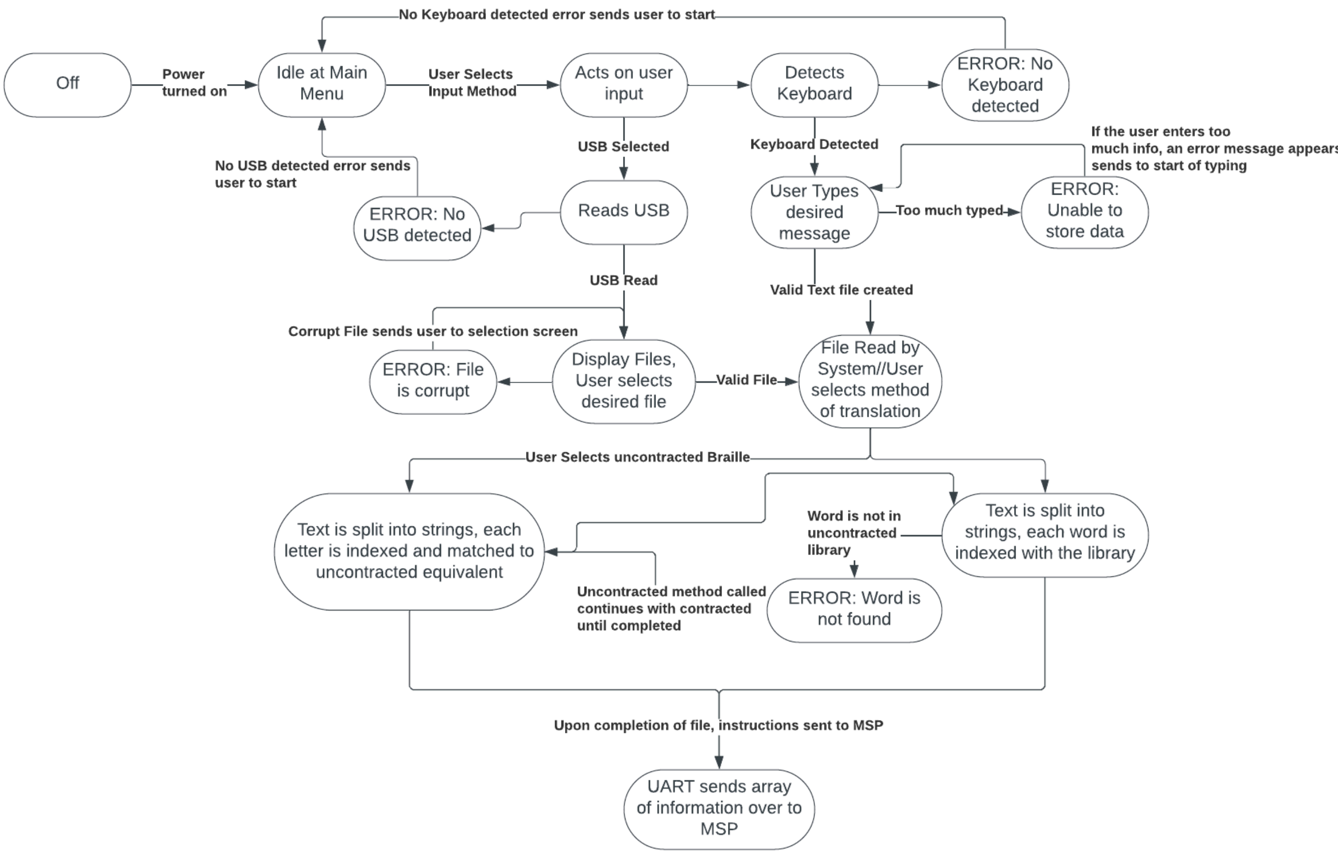


Figure 30: Raspberry Pi State Diagram

The figure above focuses on the case diagram for the Raspberry pi side of the machine. The system is off until a switch allows power to turn the system on. Once on, the LEBBVI is idle at the main menu until the user makes their selection on input method. The system is active until the remainder of the systems use, as the input methods are read and errors handled accordingly. For the USB input, the USB must be detected and then read. If there is an error such as the USB not reading or opening, an error message appears and kicks the user to the main initial menu. The user can attempt again and again. When finally read, the USB's contents can be selected and opened with a similar error handling solution occurring if the file is invalid. Instead of kicking to the main menu, the user is sent back to file selection. A valid file is read by the system and the user is prompted for contracted or uncontracted braille.

With a keyboard, the formula is simple and consistent with the USB. The keyboard is detected and if not present the user is redirected to the main menu with an error message. Upon reading of the keyboard, the user enters the text and selects when complete. Upon completion, if the user entered too much data, as the keyboard portion is meant and developed for smaller texts, an error message appears and the user is sent to the typing screen. The user, when successfully sending a valid message, is prompted with the contracted or uncontracted prompt and the paths converge.

For contracted selection, the files are read line by line and broken up at each word. The individual words are compared against the saved library and if they are not present, an error flag is raised and the function for uncontracted braille is called, translating the word or phrase that way as to avoid a break in the middle of operation. The system continues until completion and sends information to the MSP via UART.

For uncontracted braille, each word is broken up at each letter and each letter is then "translated" using the 1:1 library saved on board. There, theoretically, should be no errors when translating at this step, as each word is broken up. Invalid characters would not have made it passed initial screening but any flag raised can be handled by skipping the invalid character entirely or using the python integrated autocorrect function to salvage any word or phrase. The system, upon completion, sends the information via UART.

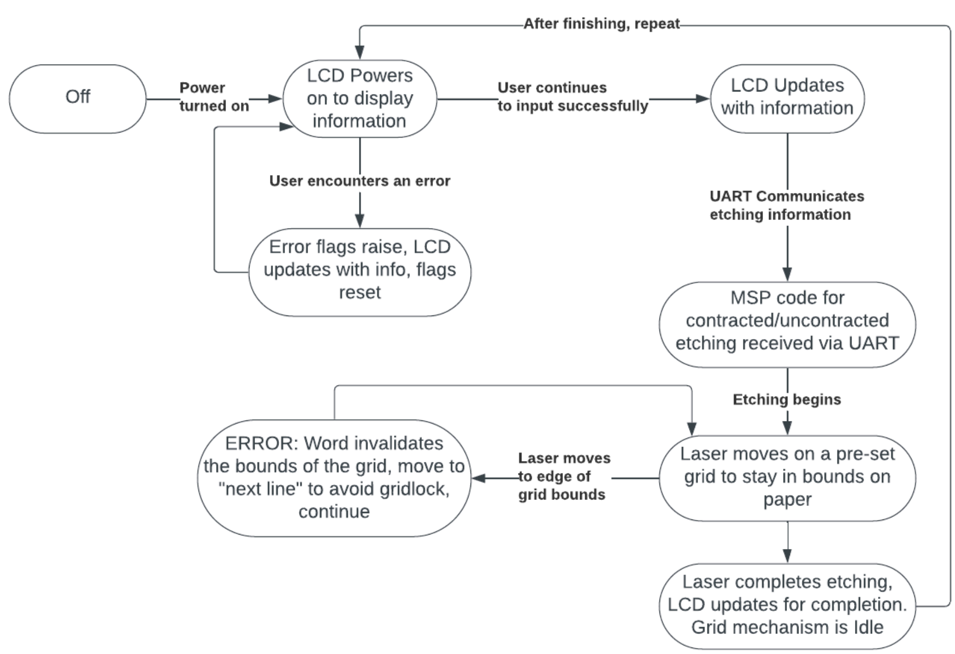


Figure 31: MSP State Diagram

For the diagram above, the MSP typically resides in the active state as it is always in use regardless of the Raspberry Pi input status. Once the device turns on, the MSP is immediately active and not idle as the LCD must display proper start up information and awaits a response from the Raspberry Pi. The MSP processes info and updates with information until error flags raise different display functions that show the user the issue until the user continues.

The MSP commits to another main operative function when the commands to operate the motors are sent. The system uses a grid to keep the motors in line where the MSP can encounter an error of its own. Anecdotally, the laser operates like a 2d grid in code. If a word-dot matrix were to extend out of bounds for this grid, an error flag would raise. To handle this error internally and not cause a critical operation stopping error, the motor will move the word to the start of the next line. This is similar to error handling in typing in a word document, when the word approaches the page margin, the text wraps to the next line. This case is handled internally in our own code, keeping system integrity.

Although primarily always active, the system would be “idle” if the user is not using it. This would appear to be obvious but is an important thing to mention nonetheless.

7.3 Class Diagrams

The class diagrams for the LEBBVI are split into two distinct sections, python and C classes. This distinction increases understandability as the code is operated in two different languages for the different functions of the system.

The class diagram acts as a way to understand the functions each language (and therefore board by extension) undertakes. The Raspberry Pi will mainly handle input loading and translation while the MSP will handle LCD functions and the motor.

7.3.1 Python Classes (Raspberry Pi)

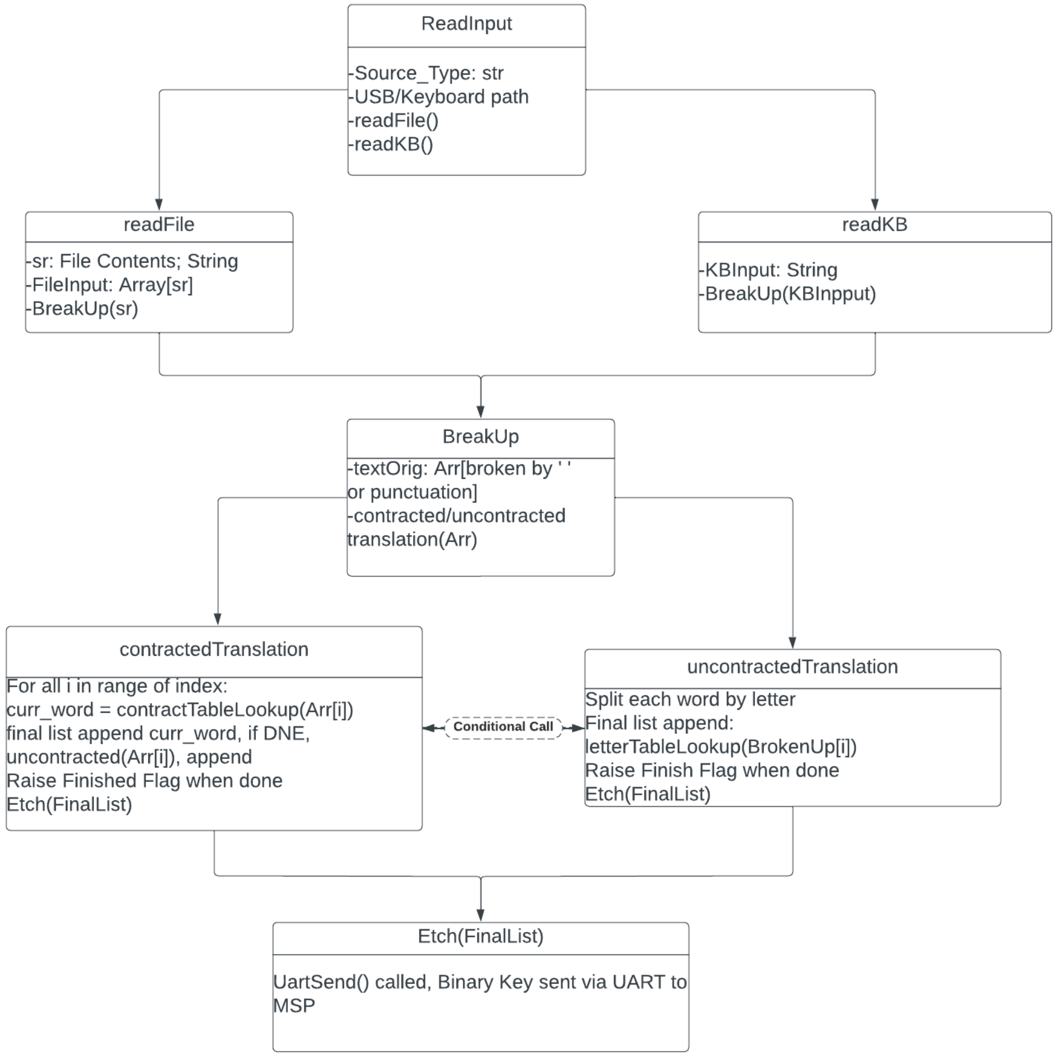


Figure 32: Python Class Diagram

The above python class diagram illustrates the interactions between the classes and function calls in the python side of the system. The initial call is the read input and determines the user using either a keyboard or USB. The functions check and raise any respective, required error flags. The error flags call specific messages from the MSP. The code diverges on whether or not the user is using a keyboard or txt file from a USB. The USB code is taken as a long string, broken apart by spaces or punctuation. Keyboard input is broken up by the same function to streamline the process. Once the inputs have been broken up, the check for contracted/uncontracted occurs.

For uncontracted braille, each element is further broken up letter by letter and the correct binary is sent to a final list via a table lookup function. The text is “translated” letter by letter and is arguably the easiest function to program.

Contracted braille follows a similar method but is sent to case lower and searched through a library of 1:1 translations. If the word is unable to be found, an error handler sends the word to the uncontracted function, which when finished continues through the text. For example, a company name FEDEX, will NOT be in the contracted library, there is no contracted equivalent. The uncontracted('FEDEX') call will splice the word and send individual letters: 'F', 'E', 'D', 'E', 'X', to the final list.

The final lists are sent to the Etching function which requires the activation of the UART_init() code that uses UartSend in order to transmit the data and tag for the MSP to understand how the etcher needs to move. In a long string of binary, each 6 indices will be one "word". In a final array, each index will have a binary string representing the word. The sending of these over UART can signify which "bumps" need to be raised.

7.3.2 C Classes (MSP)

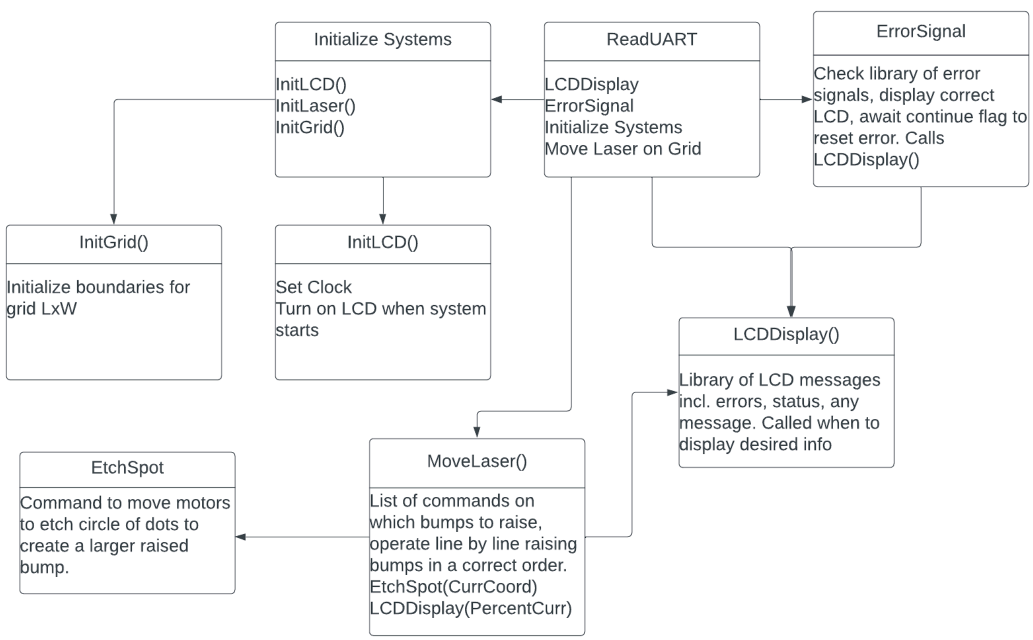


Figure 33: C Class Diagram

The C Class flow follows a similar logic flow as the Raspberry Pi. The MSP reads a message via UART to determine which individual message to appear on the LCD. There are several different error flags required when making the system, the main ones relating to the user are flags for input methods not working or not present. The error flag displays a message for the keyboard or USB not being present, with the USB branch containing an additional message for the file itself not being able to be read. The main error that can come from the keyboard is a flag being raised for the typed text being too long.

When the MSP receives a UART signal for the etching to activate, the code interprets between 0s and 1s to determine where the etcher needs to move on the grid. The grid initializes across the dimensions of the paper with included margins to prevent the laser burning off the page. An error flag is raised when the next word would fall out of bounds and the code internally handles moving the start of the etching to the next line.

To achieve the etching effect, the code to operate the laser includes an initial function that etches several smaller dots in a circle to make a larger etch in order to be felt as a raised bump. This means that, in order to raise bumps on the paper, the C class flow includes the calling of the "raise bump" function at the location on the grid that aligns with each bump.

7.4 User Interface

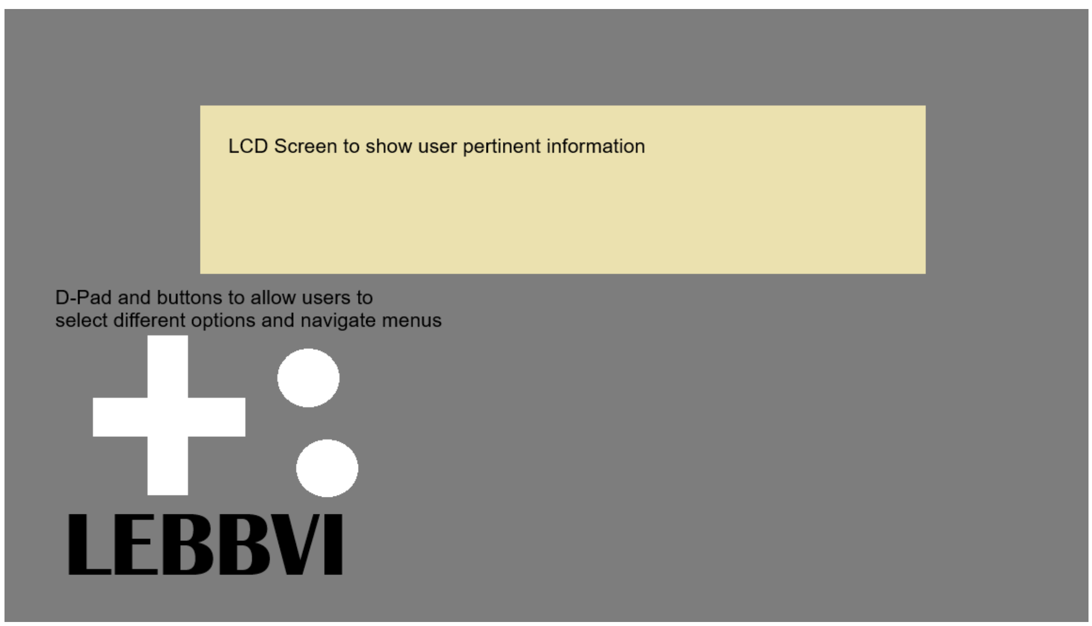


Figure 34: UI example of the LEBBVI

The user will mainly operate using an LCD screen located on the top of the device. Next to the screen will be an input pad with button selections. The LCD screen will display options, error messages, and any other required information. The buttons on the user interface will allow the user to select options to continue. The design is tactile and user friendly, the device can be operated by all individuals including those with visual impairments. The goal of the user interface was to maintain this accessibility while not sacrificing largely on usability. The design is similar to that of a gaming system, the two button system allows for basic advancement and backtracking of menus where the multi-directional pad allows for options and menus to be easily navigated. There is not an app component to the system, the user will only interface with the inputs and device itself.

7.5 Data Transfer

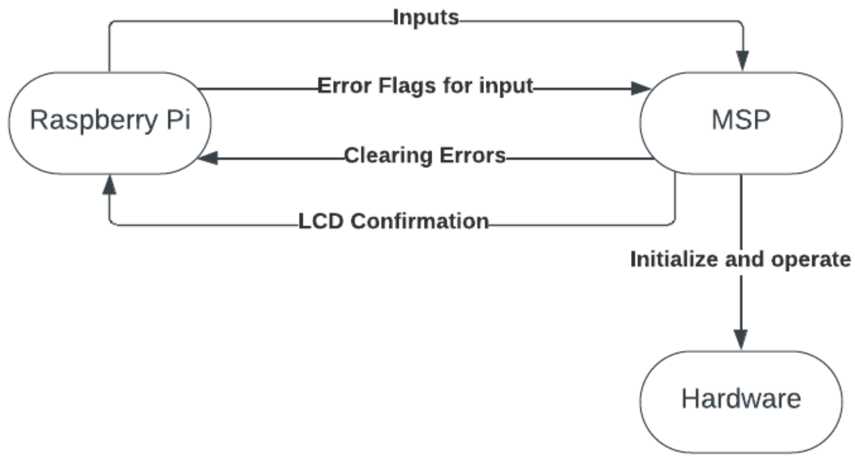


Figure 36: Data flow through system

The transferring of data in the system follows a simple path. Information is requested from the Raspberry Pi and sent to the MSP. Initially, the user is requested what method of input will be used. The information is then taken and the input read from either the USB or keyboard where it is parsed and broken up at each individual word or punctuation. The user is prompted for contracted or uncontracted braille, where this information determines which function to call in order to transfer data. The contracted braille function call splits the strings into words, performs dictionary lookups, and then transmits each contracted word into a new list. This is sent to the MSP over UART. For uncontracted, the words are broken up into each individual letter where the letters are sent over UART to the MSP.

When the MSP receives the data, it is able to perform the correct etching pattern to raise the correct bumps. The MSP displays a “percent completion” that updates as the etching continues to keep the user informed. The etching continues and when finished, sends a message over UART to begin the process again.

In short, inputs are taken from the Raspberry Pi and sent over to the MSP using UART. This also includes error flags and error messages. When the inputs raise errors or the files are unable to be opened, the Raspberry Pi communicates this to the MSP. The MSP controls the motors and LCD functions on the device. The flow of data on the end of the MSP is to receive commands and operate the mechanism controlling the etching hardware. This relationship operates similarly to a conveyer belt. The manager being the Raspberry Pi and the line lead being the MSP. The machine etching is the worker itself, all issues handled by the MSP and certain errors being raised to the Raspberry pi if needed. This is all communicated over UART, using strings and ASCII text read by the MSP to understand which operation is being called.

7.6 Data Structure

The main data structures used in the system are lists, dictionaries, arrays, strings, and structs.

Data Structure	Purpose
Lists	Hold the “translations” of braille for input text
Dictionary	Stores translations for letters and words to do braille conversions
Arrays	Store input data, broken up by word or by letter
Strings	Input text as a whole, LCD messages
Structs	Handle etching mechanics

Table 17: Data structure and respective purpose

The above data table depicts the purpose for each data structure. Inputs are initially taken and compared against dictionaries of stored translations. The broken up words or sentences are placed into arrays sent to the MSP. The LCD uses strings in order to depict messages, error codes, and other pertinent information required for use. The structs allow for control of the motors that allow for the laser to accurately raise correct bumps on the paper. This is all compared against a grid storing the correct paper dimensions, a critical component to functionality.

These data structures allow for the code to operate smoothly while also being readable. There is an emphasis on not attempting to overcomplicate the internal processes in order to easily debug and determine issues within the code itself. Complicating the data systems would make component to component interactions more difficult as well as increase the strain on developing various solutions to the UART receiving different types of information.

7.7 Error Handling Protocols

The goal in programming with respect to error handling was to develop solutions that would not leave the system unable to function or in gridlock. The code’s error catching happens with “try” and “catch” as well as different flags being raised for different errors. Using the flag approach allows for a consistent system across functions that raises the correct error across both the Raspberry Pi and MSP in order to show correct data on the LCD and expect certain user inputs to advance. The main error handling protocols reroute the user to either the start or the previous menu. A common error would be in selecting inputs. If a keyboard/USB is not plugged in or a file/keystroke cannot be read, the error flags raise a message to the LCD and the user acknowledges the error, lowering the flag and pushing the system to the previous menu. If the error occurs inside the code itself, internal flags can raise. One would be an invalid character or a word not in the contracted dictionary. The symbol can be skipped or represented in a way that works, relying on another dictionary for support. As for the second error, the code can call the uncontracted function to translate that specific word, continuing in contracted mode. A hardware error, for example, would be a word pushing the laser off the 2D grid. This error raises a flag that is handled internally but moving the grid down to the start of the next line. If the word were to go off the page, the system will call a special function that alerts the user to change paper and starts in the top right of the grid.

These methods of handling errors are intuitive and rely on internal processing to handle. There are some problems with this, as any reliance on the internal processes can create unforeseen errors, but those can be handled with debugging and rigorous standards testing.

8 System Fabrication and Prototype Construction

8.1 Prototype Board Testing

To test an initial prototype, a MSP and Raspberry Pi have been procured along with the required peripherals. These components can be connected to initially test the programming and various connections. These boards can also be connected to the motors controlling the laser apparatus to test their functions and the laser structure. These boards, although not the final design, provide insight to how the code will work on the finalized PCB. These components are important to initial prototyping to ensure function operation.

For the prototype, we created custom cables that connected to WAGO 221-415 connectors. These cables were created by using 16 AWG and 22 AWG wire and soldering plus shrink wrapping them to create one cable that went from the connector to the regulators. We also used 16 AWG wire to connect the power supplies to the connectors as well. We chose 16 AWG wire as it can handle more than enough current for our prototype and system. We also incorporated a 5A fuse from the battery pack and the AC/DC power supply female barrel jack so we can protect the components down the system in case any component draws too much current, or a component fails.

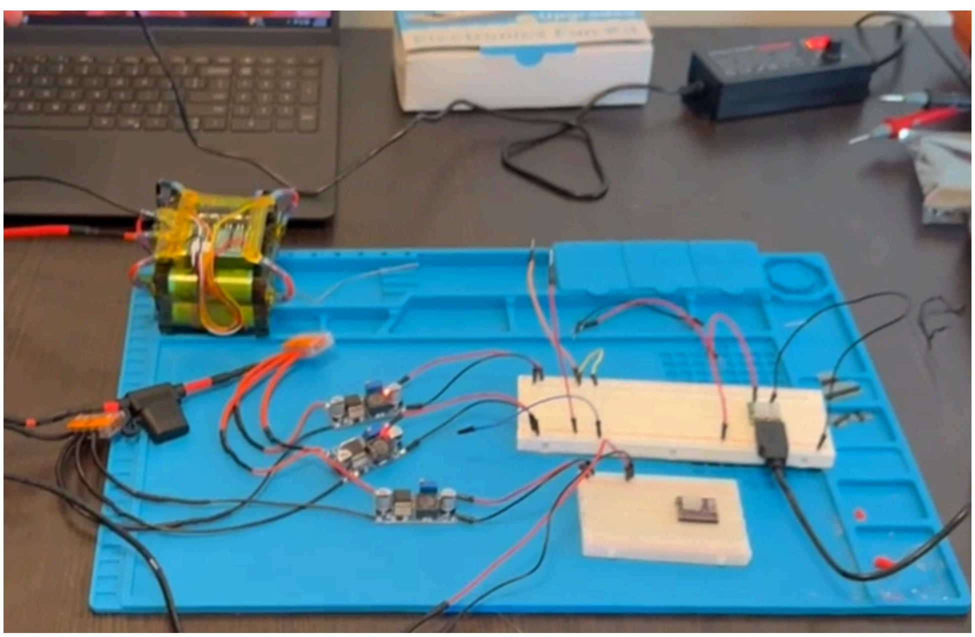


Figure 36: Prototype Demo Station

These connectors then took either the battery pack input voltage or the AC/DC adapter input voltage. This powered the WAGO connector, in which the three regulators were connected to it. These are necessary to power the components we prototyped, which were the MSP430, Raspberry Pi Zero, and the laser. From the regulators, we powered three breadboard rails with regulated voltage at 3.3V, 5V, and 12V. We connected a USB header onto the breadboard that hooked up to the 5V rail to show that it can power both the MSP430 and the Raspberry Pi. We verified that these are powered on by the LEDs and onboard screen of the MSP430 and a laptop connected to the USB header of the Raspberry Pi. Then, we used a custom cable male barrel jack from the 12V rail to power the laser. This was also a success, as the laser powered right on without any issues.

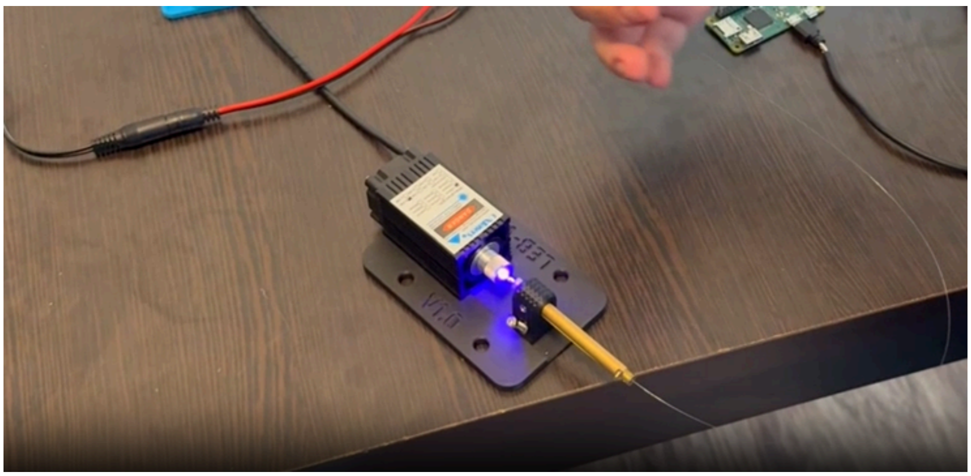


Figure 37: Laser being powered by the 12V regulator by both the battery and AC/DC adapter

Unfortunately, we were unable to test the motor controller and the stepper motor because it would prove to be too complex to manage every piece of the prototype and have everything working congruently. This is why designing custom PCBs tailored to our needs is crucial for a project like this. It heavily simplifies the connections between each component and how they interface with each other.

8.2 PCB Layout

The PCB layout of our system can be found in the *high-level design block diagram* figure. This diagram accurately lays out where each component will sit on the main PCB when the design process fully commences in Senior Design 2, where Dr. Arthur Weeks will go into detail about PCB design.

However, we can go ahead and begin our PCB board layout inside of Autodesk Fusion. The board below shows similarities to the high-level design block diagram, starting with the heart of our board in the center, the MSP430. The other microcontroller, the Raspberry Pi, is sitting below for easy USB peripheral access. On the left side of the board, we have our two barrel jacks where we can connect our two power supplies into. In which they feed into the PowerPath controller and undervoltage cutoff circuit. It also features the motor controllers on the right side of the board with both motor headers. And last but not least, the laser input will be at the top of the board.

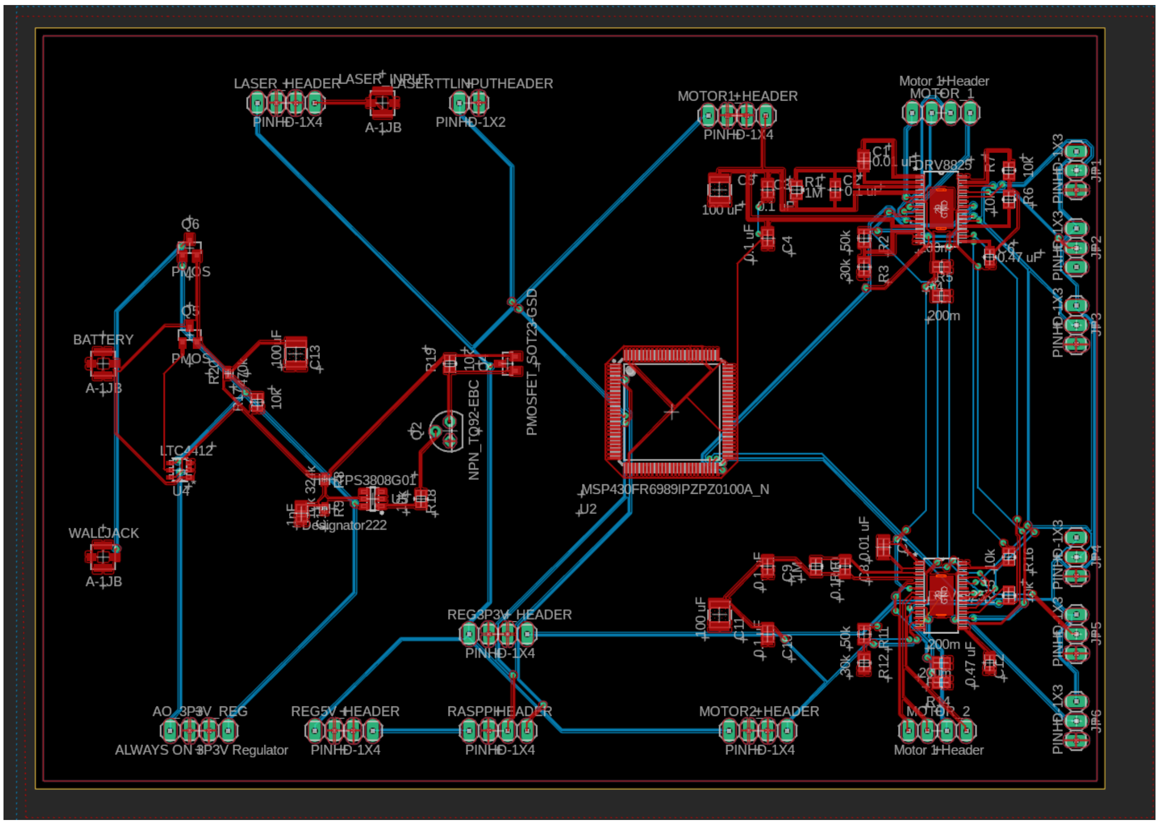


Figure #38: Main PCB Board Layout

During Senior Design 2, we will finalize and do our best to perfect our main PCB, hopefully leaving clean traces across the board and most importantly: have a working board. Now let’s get close up to the main on board circuits starting with one of the DRV8825 motor controllers.

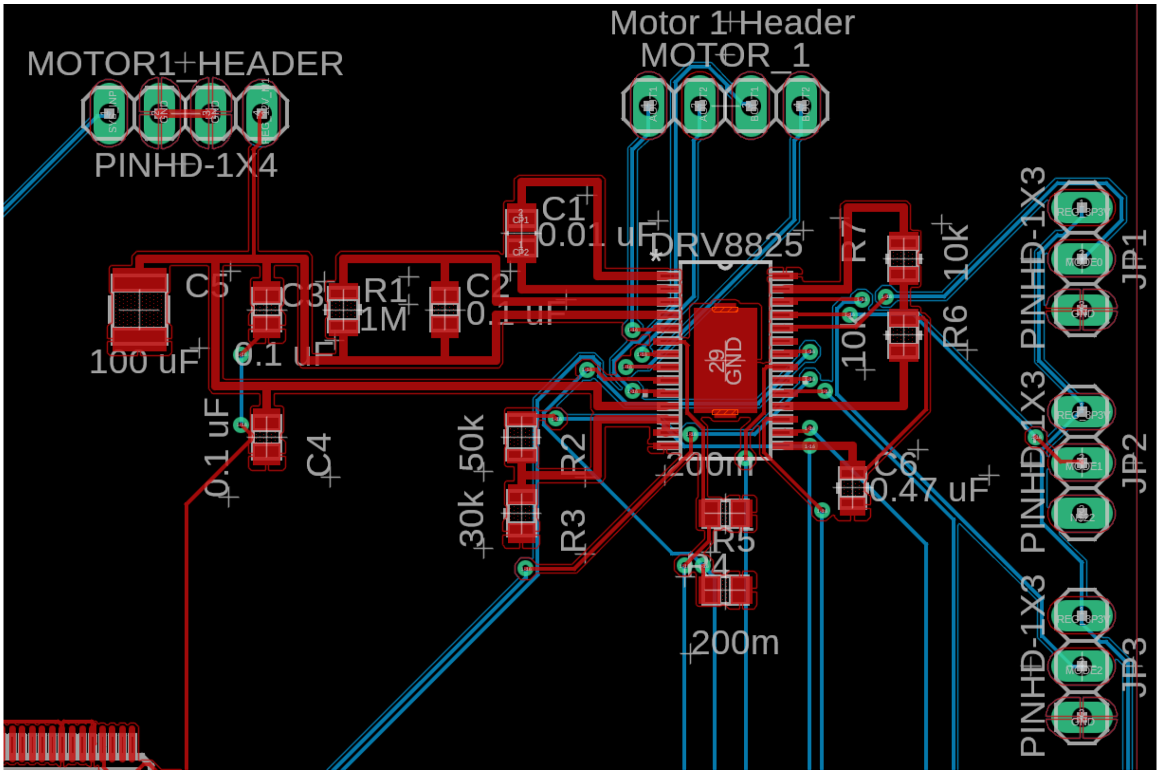


Figure #39: DRV8825 On-board Design

Here we see that the motor controller is being powered by the MOTOR1_HEADER which supplies 12V of regulated input voltage. Then, we have our AOUT1/2 and BOUT1/2 connected to the stepper motor header MOTOR_1. On the right side you will find the microstepping options, Mode 0, Mode 1, and Mode 2. You can select them via a jumper cable that pulls one of the modes high and the rest low. Next we can look at the PowerPath controller that begins the board.

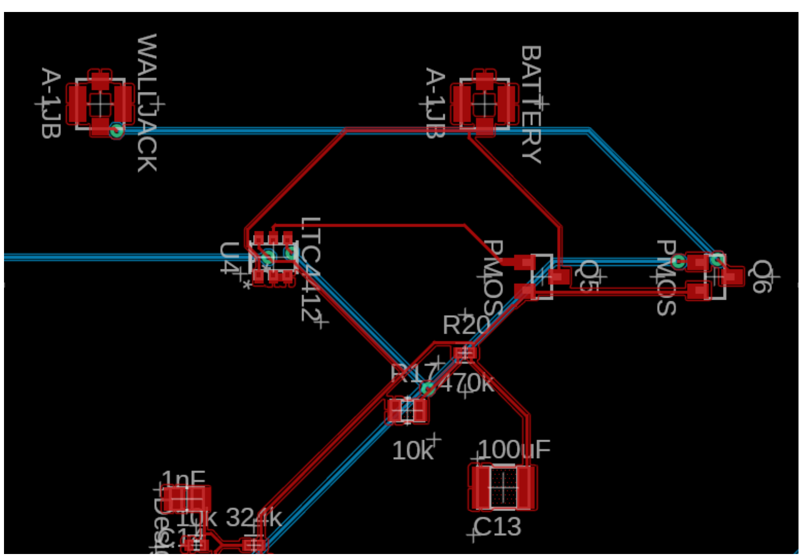


Figure #40: LTC4412 PowerPath Controller Circuit

As we can see, this takes the input of both our battery and AC/DC adapter via barrel jack connectors. I will then choose the highest voltage of the two (which will be the AC/DC adapter 100% of the time when it is plugged in) and supply power to the circuit. But first, it must go through the undervoltage cutoff circuit before supplying power to the main board.

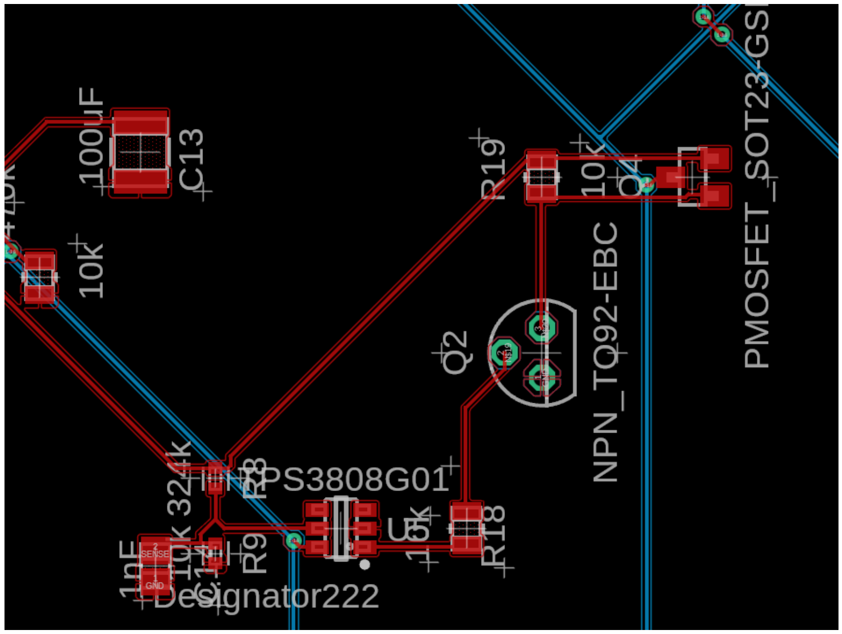


Figure #41: TPS3808G01 Undervoltage Cutoff Circuit

Once the supervisory chip (the TPS3808G01) senses the input voltage falls behind the set threshold voltage of 13.5V, it will turn on the NPN transistor and turn the P-channel MOSFET off by setting the gate voltage equal to that of the source voltage. This will cut off any power to the main circuit, protecting every component down path if the battery were to fall below the 13.5V threshold.

The regulator board has also been designed (the LM2596ADJ regulators), and this board will directly connect to the main PCB via headers and has a relatively simple design. You can also see the 4-pin header on the bottom of the board where we will connect this to the headers on the main PCB.

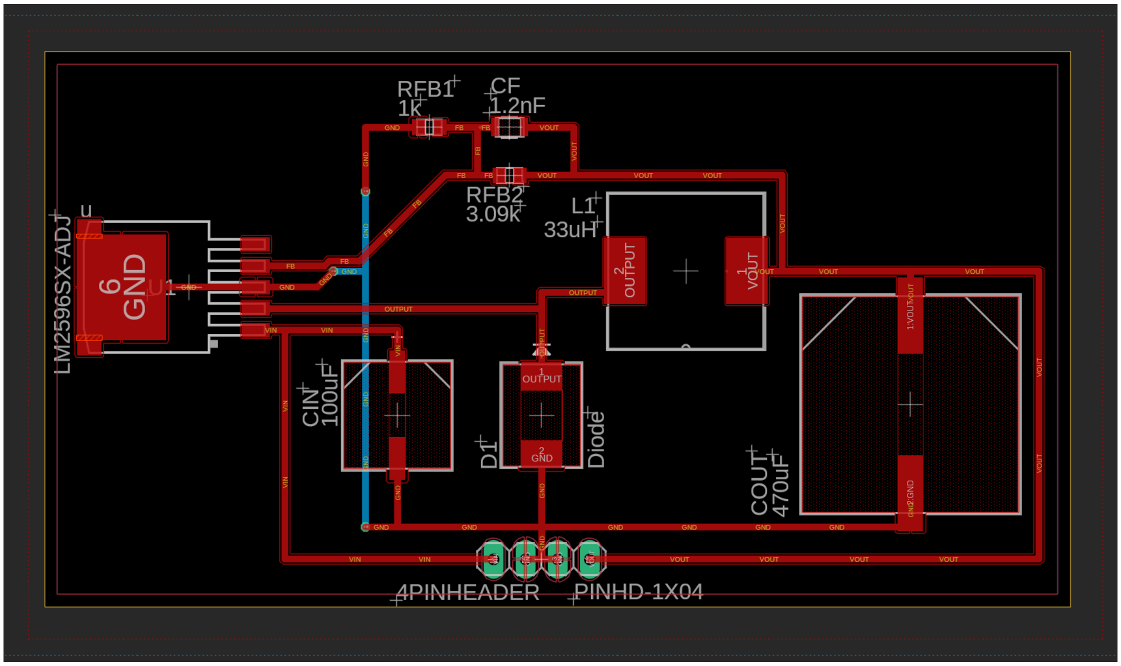


Figure #42: PCB Design of LM2596 Adjustable Regulator

This section will be updated during Senior Design 2 when finalized board designs start rolling in.

9 Testing and Evaluation of the LEBBVI

9.1 Hardware Testing

Hardware testing is a critical component in ensuring the device is functional and presentable. Hardware testing occurs at several different points in fabrication, with some elements being able to be tested at earlier stages. Testing the hardware is broken up into several segments with the laser etching, tactile buttons, and LCD screen needing to be tested.

9.1.1 Etching with the Laser Source

Before any meaningful development of our etching system could begin, the first critical step was to determine whether our laser source was physically capable of achieving ablation. This verification is foundational; without sufficient power density to remove material, the entire concept of laser-based etching would fall apart. These initial tests served as both a proof of concept and a benchmark for the capabilities of the hardware we were working with.

Given the potentially hazardous nature of high-power laser systems, it was imperative that all testing be conducted with strict adherence to safety protocols. We ensured that the laser was only operated in controlled environments and with the proper protective equipment, including laser safety goggles and appropriate beam containment procedures. For our earliest trials, we chose to work outdoors, where ventilation and space could help mitigate risk. This setting also made it easier to control for reflections and allowed for safer beam termination.

The first experiment was simple but revealing: we directed the focused laser beam onto a piece of standard printer paper. Within seconds, we observed the laser beginning to remove material from the surface—clear evidence of successful ablation. This moment was a major milestone, confirming that our laser had enough intensity to perform material processing. It not only validated our hardware selection but also laid the groundwork for the more complex system integration steps that would follow.

This initial success also served as a stark reminder of the laser’s power and the dangers associated with improper handling. The ability to rapidly ablate paper suggested that the beam could easily damage skin or eyes, reinforcing the need for respect and caution throughout the project. Moving forward, we made it a priority to ensure all team members remained vigilant about laser safety procedures during every phase of development. The early testing phase was not only a technical success but also a critical moment for instilling a culture of safety in the project.

9.1.2 Laser-Fiber Coupling

In the early stages of our project, one of the first systems we prioritized was the laser-to-fiber coupling setup. This stage is both foundational and delicate, serving as a critical link between our laser source and the rest of the optical system. Establishing a reliable coupling system early on ensures that the rest of the optical path can be designed and tested with a consistent and stable light source. Because of the high-power nature of our application, achieving maximum coupling efficiency is not just ideal—it's necessary. Any losses in this part of the system would directly limit the performance and reliability of the entire setup.

The physical setup we devised for coupling was intentionally kept simple and robust. Since the coupling interface is static during normal operation, there is no need for dynamic adjustment or regular repositioning. This allowed us to design a permanent mounting system that, once aligned, would remain stable over time without requiring continual recalibration. By minimizing moving parts and potential mechanical drift, we aimed to reduce the maintenance overhead and ensure consistent performance throughout the duration of the course and the system's use.

To realize this design, we used CAD software to model a compact optical rail system that could be mounted directly to the base of the laser module. Conveniently, the laser housing featured three M3 screw holes, which we utilized to secure the rail with a custom-designed bracket. The rail was also designed to include a mount for a standard fiber chuck, positioning it precisely in the beam path. The overall design ensured that the fiber could be held in place with minimal angular or translational drift, which is crucial for stable long-term coupling.

Given the relatively coarse tolerances of the 3D printer available to us, we had to consider how to maintain precision in alignment despite these limitations. To address this, we incorporated heat-set inserts into the printed parts, allowing us to thread in screws with a much higher degree of mechanical stability. These inserts also enabled us to make fine-tune adjustments to the chuck position during alignment, helping us achieve optimal coupling efficiency. Overall, the system represents a careful balance between low-cost fabrication and high-precision performance—an essential theme throughout the rest of the project.

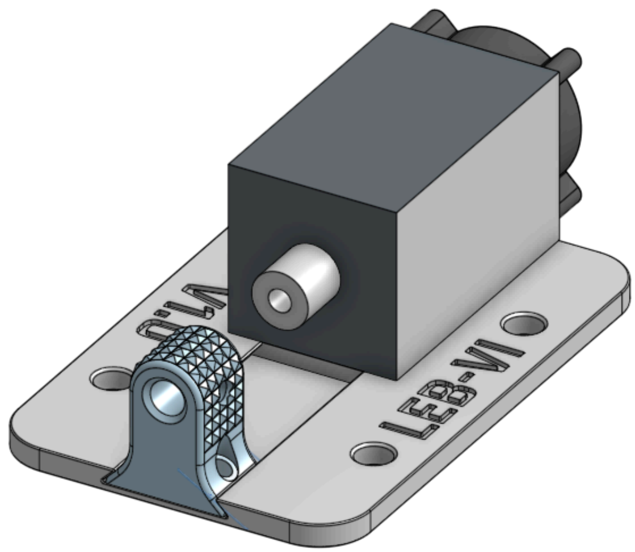


Figure #43: 3D Model of the 3D printed laser-fiber coupling system.

9.1.3 Planned Motion Control Testing

Once the main PCB is assembled and the firmware is deployed to the MSP430FR6989 microcontroller, one of the first critical areas we plan to test is motion control. The goal is to ensure that the MSP430 can successfully generate step and direction signals for the DRV8825 motor drivers, and that these signals result in predictable movement from the stepper motors. Since accurate and consistent movement is essential for positioning the laser across the Braille grid, this will be a key part of our early hardware verification.

To begin testing, we will write a simple firmware routine that toggles the STEP lines on both motor drivers at a fixed frequency using a timer interrupt. This will allow us to confirm that motors respond appropriately to STEP pulses and that the direction (DIR) pin accurately changes the rotation. Initial testing will focus on using full-step mode, with slower speeds to make visual confirmation of motion easier and safer.

After verifying basic movement, we plan to enable different microstepping configurations by adjusting the MS1, MS2, and MS3 pins on the DRV8825. These tests will help determine how the system behaves in quarter-, eighth-, and sixteenth-step modes, and what timer configurations are needed to maintain consistent speed when smaller steps are used. We also plan to observe how changing pulse frequency affects rotation speed and whether the system can maintain smooth operation at higher stepping rates.

All STEP and DIR signals will be monitored using an oscilloscope to ensure timing accuracy and proper waveform shape. Any irregularities in pulse spacing or direction toggling will be used to refine the firmware before full system integration. We also plan to test each axis independently and then together to verify that concurrent motion does not result in timing conflicts or missteps.

This motion testing process will serve as a foundation for future path planning, acceleration control, and coordinated movement in SD2. Ensuring reliable stepper control at this stage reduces the risk of hardware issues during full system testing and gives us confidence in the MSP430's timer performance and signal handling capabilities.

9.2 Software Testing

Software testing for the LEBBVI has occurred and will occur at every step through the process. Software testing is crucial to ensuring the device works properly as improper code can damage the machine or prop up false negative error flags. Having strong code boosts the effectiveness of the system. Operational, high quality code can make the system faster as well, with less bloat the functions can call to one another quicker and the transfer of data can move at a faster pace. All of these contribute to providing a working system to future users.

At the initial stage, software testing takes the form of debugging information and inputs. This includes reading from a predetermined text file and ensuring the library translation operates. This was done pictographically, with "*" representing raised bumps and "-" representing no raised bumps. Using this system, the files were opened, scanned for text, and taken apart letter by letter to "translate" and match the letter with the proper dictionary. The code for uncontracted braille successfully operated in this regard, having lists of binary code to represent where the paper will be raised and where it will not be touched by the laser.

Extrapolating this to contracted braille is not difficult. An uploaded binary library will be stored and accessed by the function, calling on the uncontracted function when no match is found. It is debugged in the same method on the desktop as uncontracted braille for ease.

Using a Raspberry Pi and MSP430 board, files can be sent to each to determine that functions work. Uploaded code to the Raspberry Pi can include error handling messages that can print string statements to the console, allowing for debugging to see what exactly is wrong. To further test the Raspberry Pi board, the board can be “connected” to the console or to itself over UART to ensure the functions are properly sending the correct data packets.

As for the MSP, it can be connected to a desktop and tested in the development environment. This is something all developers in the group are familiar with, especially considering the integration of buttons, LCD displays, and UART communications. The MSP UART can be tested to ensure it is receiving data correctly with functions printing information to the command terminal in order to make sure data is translating effectively.

After debugging on a main computer for both systems has been completed, the code can be uploaded to the respective development boards and peripherals can be attached. The boards can be operated with console commands and can be completely debugged as even the motors can be attached. Confirming operation in this method is smart, concise, and provides a safe way to ensure the code is correct before uploading it to a developed PCB.

9.3 Performance Evaluation

To evaluate the performance of LEBBVI, we will compare its hardware testing to the outlined goals presented at the showcase. The main goal is to primarily ensure the device functions properly as intended. Doing this will ensure that the device at a basic level is functioning as intended, with the ablation occurring and making tactile bumps that can be felt as Braille. The performance of the device will also be judged by the size of the raised bumps, as if the laser works but the paper does not have any raised bumps, the device is faulty.

Another metric of performance is the accuracy of translation. If the code is faulty or if the UART fails to transfer the correct bits over, then the translation will appear on paper but it will not be correct. The initial test for this is in the software phase where debugging occurs and the code can be checked in the terminal for performance. To see if the UART is working, the data sent can be displayed on the LCD for clarity and checking. For the laser etching, the etching needs to be flat and straight, not faltering off the line. There also needs to be a speed element incorporated as the device cannot be too slow or that will make it pointless to use. If LEBBVI fails to meet these criteria or if any of these are inaccurate, the integrity of the device is compromised and it fails the design showcase.

9.4 Optoelectronics feasibility study and testing

In this section, we will discuss and analyze the methods used to test and validate the optical components and techniques implemented in this project. The purpose of this analysis is to demonstrate that, even at these early stages of development, the underlying optical principles are both logically sound and practically achievable. Establishing this foundation is crucial, as it builds confidence in the overall feasibility of the system and informs future design decisions.

To achieve this, we will carry out a series of targeted measurements and evaluations of our optical equipment—such as lenses, laser sources, and fiber alignments. These tests are designed to verify performance metrics including beam quality, alignment accuracy, output power stability, and focal behavior. By quantifying these parameters, we can ensure that our components are functioning as expected and are properly integrated.

This process will not only validate our current setup but also provide us with the baseline data and hands-on experience necessary to confidently design and construct more complex optical subsystems as the project progresses. Accurate early-stage testing helps identify potential issues before they become harder to resolve later in development, ultimately contributing to a more robust and efficient final system.

9.4.1 Characterizing the Laser Source

The first and probably the most important optical element we will be analyzing is the laser source. The laser we are using is an Oxlaser that is stated to operate at 500 mW and 405 nm. But as will all equipment there are discrepancies when it comes to hardware so it is important to validate these values before moving on.

So the first value we want to validate is the output power. To test this I needed to be careful when shining such a high power light into any measuring equipment so I put a neutral density filter in front of the laser source. The optical density of the neutral filter was 2 which means that only 1% of the incident power will transmit. This is helpful because the full power of the beam would definitely cause damage to any electronics it comes in contact with. With the set up aligned and with the proper safety measures set up I turned it on to measure the power. The power measured by the power meter read only 1mW of power. This meant that only 100mW of power was being output by the laser. Now we can assume that less light made it through the filter than was anticipated due to outside factors like reflection off the filter.

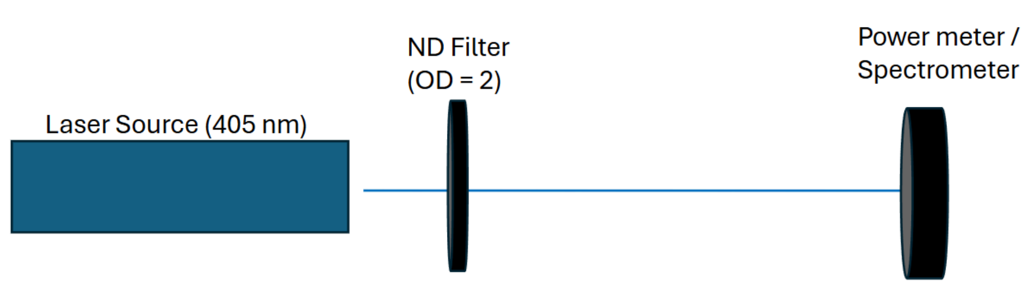


Figure #44: Laser into ND filter into Spectrometer Diagram

Immediately this information is very useful because now we can find the maximum spot size we can have while still causing ablation to occur on the paper. A NASA research article found that paper can ablate at around 6W/cm^2 depending on conditions such as material color, thickness, and environmental conditions. Using the output power of the entire beam we can calculate the intensity by dividing it by the spot area when the laser is most focused. When the laser is focused to the smallest dot size it has a radius of about 1mm. This will give us the maximum intensity we will be able to reach with this laser and will tell us how much wiggle room we have when it comes to spot size.

The calculations are as follows:

$$Intensity = \frac{power}{area}$$

$$Intensity = \frac{100mW}{0.00785cm^2} = 12.74W/cm^2$$

As you can see even with the laser underperforming we still have more than enough intensity to etch into the paper. This is good news because it means we will be able to slightly expand our dot size which will speed up our etching process. Now that we know our upper bound of intensity now let's find our lower bound. Using the information we've acquired we can now find the maximum spot size we can use to etch the paper. By rearranging the equation above we can solve for the spot size that will give us the intensity of exactly 6W/cm^2. With this math we can say the absolute maximum we can make our spot size is a radius of 1.4 mm. We will probably stay at a slightly smaller spot size than this to simply be safely above the ablation threshold. I believe a good happy medium for the intensity will be a 10W/cm^2. Again using the same math we can decide that the best spot size for this system will be around 1.15 mm.

The next part of the laser we need to characterize the beam divergence angle. Or in this case convergence angle. Due to the focusing lens on the laser source the divergence angle can be changed to alter the focal point of the laser. The feature will come in handy when we actually couple the laser source into a fiber.

Lastly, what we want to validate is the operating wavelength of the laser. Using the same setup as before but replacing the power meter with a spectrometer. Then shining the laser light into the spectrometer and using a computer software to graph the spectrum we can analyze and validate the spectrum of the laser. Below is what the spectrum looks like.

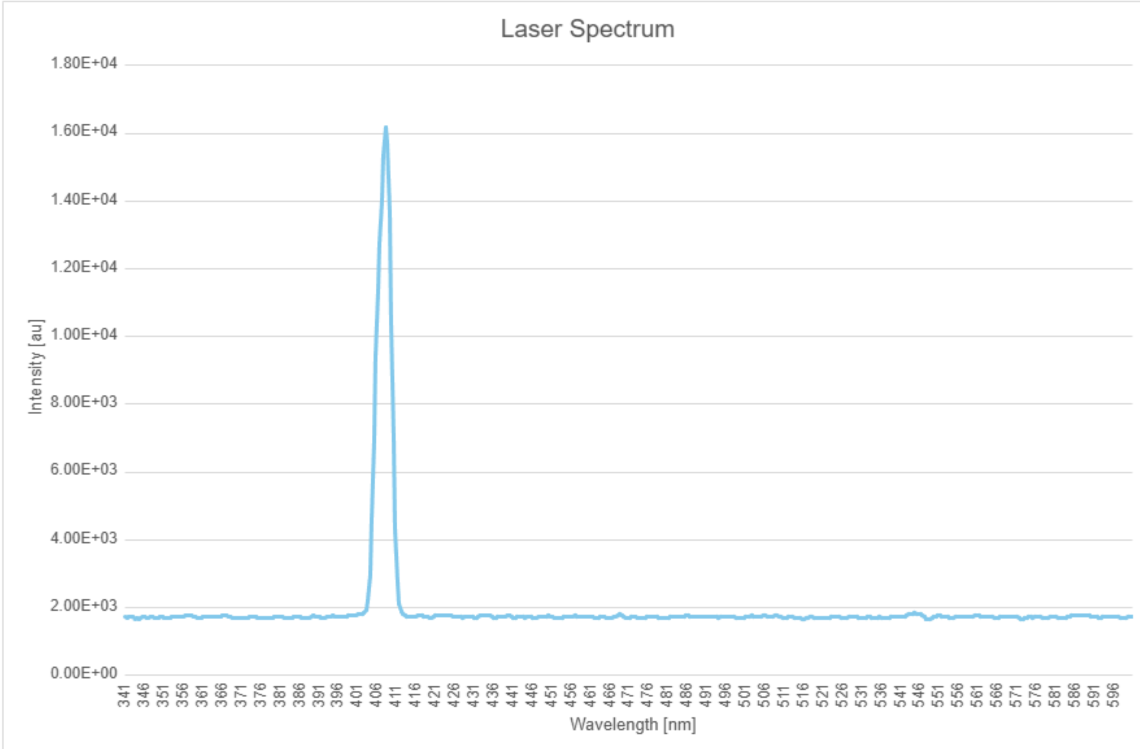


Figure #45: Laser Spectrum of System Laser

This is a graph of the spectrum of the laser source used in this project. It has a peak at 407 nm and a FWHM of 4nm.

This graph offers some very valuable information that could affect the overall optical design of the system. The spec sheet of the laser explicitly states it emits at 405 nm but the peak of the spectrum actually lies at 408 nm. We can also calculate the FWHM of the beam using this information. The peak is actually quite narrow with a FWHM of only 4 nm. Which for the price of the laser is as good as we could ask for.

9.4.2 Using Experimental Data

With this data we now are able to create a concrete design for our optical system. We know our original spot size, and the spot size we want. With this information we can create a beam expander to expand the beam to the maximum size it can be. In this case our initial dot size is roughly 1 mm and our goal will be 1.15 mm in diameter. Luckily the math is simple and we can calculate we need a 1.15x beam expander.

Using the equation $M = \frac{f_2}{f_1}$ we can find the ratio of focal lengths that we should use to have the proper magnification. Of course getting exactly this magnification will be pretty much impossible unless we get custom lenses which are outside of our capital restraints for this project. Through our research we have found that a 45 mm lens in series with a -40 mm lens would be our best option. This ratio of lenses gives us a magnification of 1.125x. This is slightly smaller than what we could theoretically pull off but that ensures we won't have any issues with the ablation process.

To build the actual beam expander the system is quite simple. The light will be coming from the laser source already collimated which means if the laser is aligned properly the first lens which will be the negative lens will diverge the light as if the focal point was in front of the lens. Lens theory also tells us that if light rays originate from the focal point and hit the lens the beams will collimate. This is the basic theory behind the beam expander.

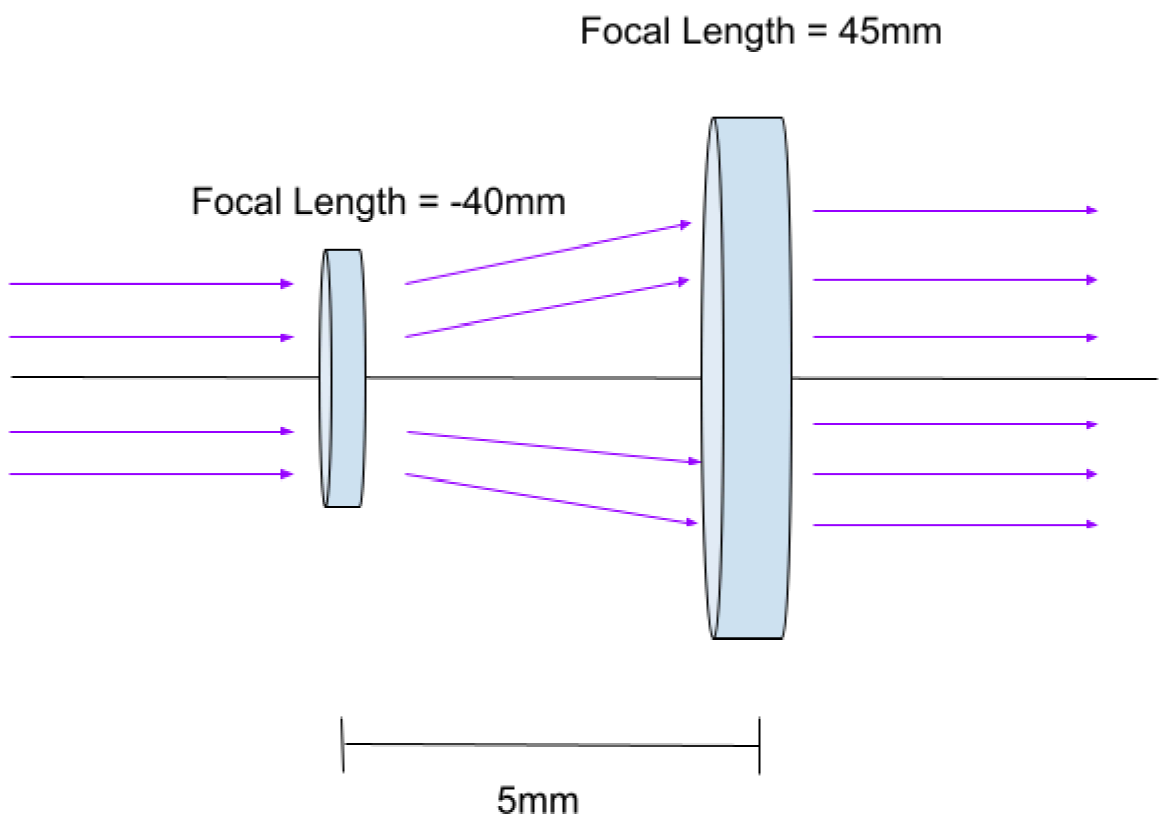


Figure #46: Relative positions and focal lengths of the lenses used in the beam expander.

Based on our calculations and initial experimental measurements, it is now evident that the application of optics in this project is not only technically feasible but also holds meaningful potential to contribute positively to the world. The use of optical systems in this context has proven to be both effective and impactful, reinforcing the value of integrating precision optics into accessible technology solutions.

While the tests conducted so far represent only the early stages of development, they have laid a strong foundation for continued progress. Further testing, refinement, and experimentation will be essential as we work to improve system performance, reliability, and overall product quality. These next steps will help ensure that the final implementation meets both functional and safety standards at the highest level possible.

Although these initial evaluations were relatively simple, the methods we employed to characterize the system components—through measurement, observation, and iterative refinement—will remain central to our approach moving forward. The disciplined process of testing, analyzing results, and applying those findings to improve the system is a core principle that will guide the evolution of the project as it matures from prototype to polished solution.

9.5 Overall Integration

The component integration will require the software and hardware to be tested and completed. The integration begins with the completion of the code on test boards, where the peripherals can be confirmed to work logically as needed. Building the PCB with the correct parts and uploading the code can allow for hardware testing to occur. Once the finalized code is uploaded to the PCB, full testing can be done to integrate the systems. Soldering components, trial running the systems, and tweaking code for day 0 bugs will ensure seamless integration of components.

9.5.1 Laser System Integration

In this project it is important for the laser system to be fully integrated with the electrical systems not just for the sake of the project but also for the safety of the people around. With this in mind we want to make sure that we fully understand how the laser and electronic system can communicate. The laser has a relatively simple electrical design in which it only has three pins: 12V DC, Ground, and PWM. These three pins are all we are going to need to fully control the laser. Since the beam is dangerous to the human eye we want to make sure that the laser is on for as short a time as possible. This minimizes the risk of anyone possibly getting burned or blinded by the laser source. We will mostly be controlling the laser via the PWM pin on the module to both control the ablation process and to control the output power.

9.6 Plan for SD2

The plan for SD2 revolves around integrating the components and code in a way that operates the system to our set specifications. This includes also fabricating a PCB that works with desired peripherals and that has functioning motors. On the software side of the project, the code needs to be finalized and fully tested by the end of quarter 1 SD2. This code will be uploaded to the fabricated PCB board for testing. The main difficulty with software that will be focused on in the break and time in SD2 will be ironing out the software logic behind the motors and rails that operate them. Creating the 2D grid will not be difficult once the motor functions are determined and mastered.

Working together to fabricate a working PCB will take a considerable amount of time. Ensuring the inclusion of proper components and peripherals can make or break the LEBBVI. This step needs to occur early as the likelihood of flaws in the initial PCB design is high. Leaving room for innovation is another key tenant of our work. Continuing to determine which parts will be cost effective solutions to the design at hand while not sacrificing functionality will ensure the fabrication of a working and cost effective solution.

The rails and hardware itself will face evolutions as SD2 goes on as well. The development of the rail and etcher hardware design is currently in prototype phase and will need to be further developed, 3D printed, tested, and finally assembled. This will most likely occur during the early stages of SD2. By the middle of the class, the goal is to have the main body, PCB, and software complete. This will allow for testing of the rail system and completion of the final design.

As Senior Design continues, the document will be updated appropriately. The further development and testing of hardware and software will be updated as well as the fabrication steps. The more concrete information and testing is imperative to include in this document in order to provide a more in depth analysis of the project and its development.

9.6.1 Improvements on the fiber-laser coupling

One of the most effective ways to enhance both the performance and output quality of our laser etching system is by maximizing the coupling efficiency between the laser source and the optical fiber. Coupling efficiency directly influences how much of the laser's power is successfully delivered through the fiber and ultimately to the workpiece. Any power lost during coupling is power that cannot be used for etching, which not only reduces system effectiveness but also adds unnecessary strain on the laser source over time.

In commercial settings, fiber lasers are often used due to their high stability, excellent beam quality, and efficient light delivery. However, these systems are typically expensive and beyond the budget of many small-scale or educational projects. In our case, we’ve taken on the challenge of building a more rudimentary fiber-coupled laser system ourselves. This approach has given us the flexibility to design a system tailored to our specific needs while keeping costs manageable. At the same time, it demands careful attention to alignment, component selection, and precision engineering to ensure optimal performance.

By improving the coupling efficiency of our homemade fiber laser system, we effectively enhance the efficiency of the entire etching setup. Better coupling translates to a higher percentage of the laser's power reaching the fiber output. This in turn provides us with a more intense and usable beam, which can be critical in determining how fast we can etch and how fine our resolution can be. For example, higher power allows for faster scanning speeds without sacrificing depth, or it can be used to achieve finer detail at slower speeds.

Ultimately, investing time into refining our coupling system pays dividends throughout the rest of the project. Whether it's in increasing etching speed, improving detail, or expanding the range of materials we can work with, efficient power delivery sets the stage for high-performance results. As the project continues to evolve, maintaining and optimizing this link between the laser and fiber will remain one of the most important technical challenges and opportunities for improvement.

10 Administrative Content

10.1 Budget

We set aside a budget of $500 in our engineering specifications as this is the estimated average for all Senior Design projects in the past couple of years. This is (hopefully) a good safety net for the items/components we need to purchase to make our project come to life. Some of these items are as listed with their estimated cost:

Item	**Estimated Cost**
Laser	$45.00
Stepper Motor(s)	$30.00
PCBs	$90.00
PSU System	$70.00
PCB Components	$90.00
Total	**$330.00**

Table 18: Estimated Cost

The estimated cost of the power supply unit (PSU) system includes a range of critical components such as the rechargeable batteries, battery management system (BMS), charge controller, and other miscellaneous parts required to assemble a fully functional and reliable power solution. These components collectively form the backbone of the PSU, ensuring safe energy storage, distribution, and regulation. However, it's important to note that this estimate does not currently account for the printed circuit boards (PCBs) associated with the buck and boost converters, as well as voltage regulators, which are essential for adjusting and stabilizing the various output voltages required by our system.

We also anticipate the need to source the PCB components separately. Given current global supply chain conditions, including elevated shipping fees, international handling charges, and potential import tariffs, the actual cost of acquiring these parts may be significantly higher than initially projected. These factors introduce a level of financial uncertainty that we must account for as we move forward with procurement.

To help mitigate some of these costs, we plan to take full advantage of the resources available in the Senior Design lab. Access to shared tools, soldering stations, diagnostic equipment, and even surplus components may reduce the need for external purchases and allow us to perform assembly and testing in-house. This hands-on fabrication approach not only helps minimize expenses but also gives us greater control over the quality and integration of the PSU components.

While our current estimate for parts remains below the $500 budget limit, we recognize that this figure is likely incomplete. It's common in complex engineering projects to overlook smaller, ancillary items that become essential later in the build process. These may include wiring, connectors, mounting hardware, or even consumables such as thermal paste or adhesives. One specific category that may contribute to unexpected costs is the 3D printing material required for custom housings and enclosures. These materials—depending on the design complexity and the quantity required—can add up quickly, especially if multiple prototypes or iterations are needed.

In light of these variables, we are approaching the budgeting process with caution and flexibility. By anticipating potential oversights and making strategic use of university resources, we aim to stay within budget while still achieving a robust and safe PSU design.

10.2 Bill of Materials

The bill of materials consists of every component of our system. The table below details the costs of the prototype, in which some components will be reused for the final design (such as wire, power supply, laser, etc).

Component	Link	Quantity	Price per Item
Samsung 25R 18650 2500mAh 20A Battery	https://www.18650batterystore.com/	8	$2.50
LM2596S Adjustable Buck Converter	https://www.amazon.com/dp/B0CZ78B8W7?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1	3	$1.66
Fermerry 16 AWG Stranded Wire Spool	https://www.amazon.com/dp/B089CPH72F?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1	2	$2.33
4S 30A Li-ion 18650 BMS	https://www.amazon.com/dp/B07TVLKMH6?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1	1	$4.50
USB 2.0 Breakout Board	https://www.amazon.com/dp/B07W7XMV3W?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1	1	$0.70
AIRIC 16-14 AWG Heat Shrink Ring Terminal	https://www.amazon.com/dp/B0DM8BNL6W?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1	~10	$0.09

SHNITPWR 3V ~ 24V 3A 72W Adjustable AC/DC Power Supply	https://www.amazon.com/dp/B08BL4QMGM?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1	1	$17.99
Oxlasers 500mW 405nm UV Laser	https://www.laserse.com/p/oxlasers-500mw-405nm-uv-laser-module-diy-blue-violet-laser-head-for-cnc-engraving-12v-focusable-purple-laser-cut-with-ttl-pwm/	1	$48.00
Raspberry Pi Zero W	https://www.adafruit.com/product/3708	1	$16
MSP-EXP430FR6989 DEV KIT	https://www.amazon.com/dp/B011OM4MHY	1	$45
Total			**$101.73**

Table 19: Bill of Materials of Prototype

10.3 Distribution of Work

Primary	Secondary	Responsibilities
John Childs EE	Raul Perez	PSU, Power regulation, buck/boost layout, Power Distribution
Raul Perez CE	John Childs	PCB, MCU firmware, motion control
Antonio Duford CE	Raul Perez	UI design, comm stack, test automation, braille translator
Vincent Pagliuca PSE	Antonio Duford	Laser optics, safety interlock, ablation tests

Table 20: Distribution of Work

10.4 Milestones

Milestone	**Start**	**Deadline**
Divide and Conquer Formation	5/22/25	5/30/25 NOON
Divide and Conquer Revision	6/1/25	6/6/25 NOON

Midterm Report	6/9/25	7/7/25 NOON
Mini Demo Video	7/3/25	7/23/25 NOON
SD1 Final Report	7/10/25	7/29/25 NOON

Table 21: Milestones

11 Conclusion

The LEBBVI serves an often underserved community. The goal of this device is to fill a void in products designed for individuals with visual impairments, their friends, and their families. The LEBBVI’s ease of use means individuals of all ages can use it for multiple reasons. These can range from individuals learning Braille, translating texts not on audio formats, or quickly translating papers for any miscellaneous goal. The versatility of this device adds to its list of features, as well as its affordability.

Modern Braille printers are several hundred to a few thousand dollars and are not very commercially available. The LEBBVI solves this issue by being affordable and simple to use. The UI of the device is something akin to a video game handheld, usable by individuals with an impairment or younger people looking to learn braille.

The device is built by using a Raspberry Pi to interact and interface with a MSP to perform the operations. The Raspberry Pi, programmed in python, is used to read inputs and perform the proper translation commands to send this data to the MSP. The MSP handles LCD outputs, error flags, and controls low level hardware logic. The laser etching is done using a rail system on a X-Y grid. This is done by coding a 2 dimensional grid, similarly to an array. The MSP handles its own errors internally, preventing the system from breaking itself down. The MSP receives these instructions over UART and works to operate the rails, signaled by binary on where to raise the paper.

The code takes a two language approach as the different devices have different needs. Through research and previous work, both softwares are understood by the team and can easily be integrated in the overall system design. Working to debug this code can ensure seamless integration and is a critical step in completing the LEBBVI. Python is able to handle high level inputs and translation logic, while the MSP is excellent at controlling the hardware peripherals.

The creation of the code is important and when complete can be uploaded to the development boards obtained for debugging. These development boards are used to test the code with practical components that would be on the final design. Fabricating the PCB is done parallel to the completion of the code, when the preliminary PCB prototype is complete it can have the somewhat finalized code uploaded to it for more practical testing. Soldering on needed components and leaving room for improvements is an important part to development.

Most of the above steps will occur in Senior Design 2. The main body of code is being completed as well as PCB fabrication. Making the case, etching hardware, and putting it all together are the final main objectives. SD2 will be used to finalize development and test the main device as needed. The final testing consists of ensuring the device can accurately translate text, do so at an acceptable pace, and do so with an acceptable life span. These goals, outlined in our showcase goals, are important to the device's functionality and are critical to completion.

To complete this work, the group has divided amongst themselves a primary and secondary role for the major tasks. This presents a main system for each person as well as a back up role in case anything requires work or another source of input. The division of labor provides an effective way of achieving laid out milestones that lead to the development of the project. The group consists of 1 Electrical Engineer, 1 photonics engineer, and 2 computer engineers, offering a wealth of knowledge and experience in critical roles of the project. The overlap of knowledge and experience allows for the group to evolve in understanding while also not being "in the dark" towards the hardware and software used.

This project is a challenge aimed at testing and increasing technical knowledge as well as know-how. It also provides an opportunity to create change and develop a piece of technology that can impact lives of those often overlooked. Creating an affordable, easy to use Braille translator using a laser etcher is a grand feat that has the opportunity to increase the quality of life of those with visual impairments. It also offers a chance for people to use it as an academic tool, learning the difference between contracted and uncontracted braille while creating practice sheets or dictionaries of text to learn from. This tool has many uses and limitless impacts.

Appendix A - References

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Appendix B - Lists of Tables and Figures

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