Enhanced Laser Inkless Printer

Group 5 CREOL Authors:

Jack McCain	Electrical Engineering
Miguelangel Otero	Optical/Photonic Science
Sarah Siverio	Computer Engineering

Review Committee:

Dr. Fan Yao	ECE	Research/Lecturer
Dr. Justin Phelps	ECE	Research/Lecturer
Dr. Peter Delfyett	PSE	Research/Lecturer

Advisors:

FNU Sreeram Sundaresh	ECE	Lecturer
Dr. Aravinda Kar	CREOL	Professor

Table of Contents

Chapter 1: Executive Summary

Printers have become an essential piece of technology for home and work related activities. To create an image or include characters on printed paper, ink or toner is utilized. “Refueling” these printers is a common expense for any who use one, but the used cartridges pose great risk to the environment. Despite the damage caused and the perpetual cartridge payments, they remain as the primary means of refueling printers

Products that are able to print without the use of ink exist, but are often limited in application or have tradeoffs that make them less reliable compared to ink printers. The Laser Inkless Printer (LIP) senior design group from Spring and Summer 2021 was able to create a working proof-of concept inkless printer, utilizing a laser to burn into paper and a programmed mechanical gantry system to direct the marking process. Inspired by their work, our group plans to both advance the previous design and test alternatives they were unable to test due to constraints

The previous LIP group used an X and Y axis stepper motor to control the diode’s location as well as a blue laser diode to tightly control how large the characters would be when printed. The previous LIP group also used a bluetooth module to take inputs as well as a master slave model for the microcontroller to control the machine. We plan to adjust the design by testing the applications of a green laser diode as our engraving laser and a laser galvo as our means of adjusting the laser. Both were considered by the previous group, but were forgoed due to financial and time constraints. Their work lays the foundation for our project to move forward with the use of these technologies for a laser inkless printer.

Financial constraints will be the primary hurdle to overcome, as a reliable galvo and laser diode have proven to be high in price. Green lasers are often employed in engraving materials such as wood or plastic, but lack of testing and academic material dissuaded the previous group from this laser’s use. The use of a galvo also requires the development of a correcting lens system to maintain laser integrity as the mirrors adjust to create desired characters. We also chose to forgo a prebuilt mechanical platform like the previous group, as we lacked an additional student to help manage it. This would impact our scanning area to be limited to the width of the final lens, and we would also need to create our own system encasing from scratch.

Mechanical constraints will be another important hurdle to overcome. Power regulation is exceedingly important when working with valuable electronics such as a galvo and diode, so as to not burn out the electronics. Thermal management is also very important, in our testing we saw many areas where components get very hot, hot enough to melt the plastic casings we had them enclosed in.

Powering the motors for the paper feed as well as controlling them is also very important.

Taking on a pre-existing project to build upon it is a fundamental practice done by engineers around the world. Iteration on interaction often leads to a vastly improved design when compared to the original. This project allows our group to test viable alternatives to the design and contribute to the primary mission of the previous group: creating an environmentally friendly alternative to every day printers, devoid of recurring costs.

Chapter 2: Project Description

2.1 Project Background and Motivation

Our senior design project focuses on enhancing the Laser Inkless Printer (LIP), an innovative proof-of-concept device originally developed to eliminate the need for traditional ink and toner cartridges [1]. The prior team's design successfully demonstrated the potential of laser-based printing as a sustainable and cost-effective alternative to conventional printers, addressing the recurring expenses and environmental concerns associated with ink and toner waste. Their prototype demonstrated that a laser can mark paper to create legible text without the use of consumables, thereby opening the door to more eco-friendly and low-maintenance printing solutions. However, their work also revealed critical areas for improvement, particularly in terms of speed, reliability, and system integration, which our team will address to advance the feasibility of this technology further.

One of the most pressing issues identified in the previous design was the slow print speed, which made the device impractical compared to modern printers. Our team is dedicated to tackling this challenge by optimizing both the laser operation and the motion control system to achieve faster throughput while maintaining legibility. Additionally, the earlier project faced power management difficulties that affected stability, as well as challenges with PCB design that necessitated a costly restart late in development. We aim to refine these elements by carefully redesigning the control circuitry, improving thermal regulation, and ensuring efficient integration of all components. Another constraint was affordability, both for the prototype and for eventual consumers, as high costs in parts limited scalability. Our team will focus on cost-conscious component selection and system optimization to strike a balance between performance and accessibility.

By addressing these limitations –speed, power management, affordability, and system reliability – we are motivated to build upon the foundation laid by the previous team and move the LIP concept closer to a practical, consumer-ready device. Our enhancements shall not only improve the overall user experience but also strengthen the environmental and economic benefits of an inkless printer. With each refinement, the project advances the possibility of providing households and businesses with a sustainable, cost-efficient, and low-maintenance alternative to traditional printing.

2.2 Component Sources and Real-World Context

In our updated design, every major component—ranging from the ATSAM3X8EA master microcontroller, ESP32 motor-control and wireless MCU, HC-05 Bluetooth module, and HD44780 LCD, to the stepper motors, laser diode, and driver circuits—was selected through reference to the previous team's documented work and verified against current design requirements. Their report provided the original rationale for each part, including considerations such as cost, availability, and compatibility. In our case, the ESP32 replaces the STM32 series due to its integrated Wi-Fi and Bluetooth Low Energy (BLE) capabilities, strong PWM and timer performance, and FreeRTOS-based architecture, which simplifies multitasking between motion control, laser modulation, and wireless communication.

To place this system in a real-world context, it is worth noting that laser-based printing technologies have long existed in the commercial domain—HP's LaserJet printers remain a benchmark example, utilizing laser scanning and toner rather than ink to achieve durable, high-resolution prints. Although these rely on toner rather than direct laser marking, they highlight the precision, speed, and non-contact advantages of laser imaging. Meanwhile, ZINK (Zero Ink) technology represents a different evolution of inkless printing, using thermally activated color layers within specialized paper, as seen in consumer printers from HP, Polaroid, and Lifeprint. Our project continues this exploration by focusing on direct laser-based paper etching—a true inkless approach that leverages the precision and efficiency of embedded system control.

2.3 Descriptions of Features

The Laser Inkless Printer (LIP) integrates features chosen for performance, safety, and modular scalability. Small motors would be essential to this system, as they would allow for incremental positioning without complex feedback control; ideal for fine-resolution laser scanning. Motor drivers with microstepping support further enhance precision and reduce mechanical vibration. Limit switches are implemented to define homing positions and protect the gantry from physical overtravel.

For laser safety and control, an optically isolated switch (G4 ODC5) ensures complete separation between high-voltage laser circuitry and the low-voltage control logic of the microcontrollers. The power management system, which includes regulated voltage rails, thermal monitoring, and forced-air cooling, ensures reliable laser diode operation and system stability.

At the system level, a distributed microcontroller architecture has been maintained but improved through the integration of the ESP32 as the motor-control and communication unit. The ATSAM3X8EA continues to serve as the master controller coordinating system-level logic and serial communication, while the ESP32 handles motion, BLE communication, and real-time peripheral control. The ATmega328PB remains as a lightweight interface controller managing the LCD and basic I/O. This distributed, modular structure supports parallel processing, reduces latency, and simplifies debugging compared to a single-processor configuration.

The upgraded laser system explores the integration of a galvanometer (galvo) laser setup as an alternative to the previous fixed optical cavity design. Unlike the earlier configuration that relied on mechanical gantry movement for beam positioning, the galvo system employs dual-axis mirrors to rapidly steer the laser beam across the target surface. This approach allows for significantly faster scanning speeds, smoother vector motion, and higher precision in beam placement.

Earlier teams considered green lasers for their superior engraving performance across materials such as wood, metal, and plastic [3], but lacked sufficient data on their performance for direct paper etching. Our project revisits this concept by combining the green laser's optical efficiency with galvo-based beam steering, enabling controlled and repeatable testing of etching resolution, contrast, and material response. The optical subsystem will be modeled and optimized through Zemax simulations to determine the ideal mirror angles, focal lengths, and lens spacing required for beam stability and accuracy. Given the limited availability of plastic lens data, glass lenses with similar specifications will be used during simulation and prototyping to ensure consistent optical performance.

2.4 Functionalities

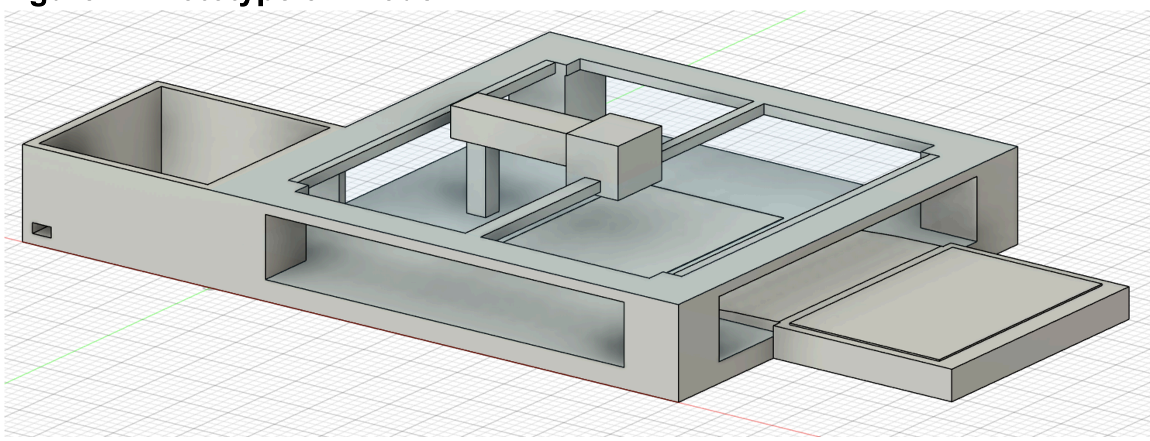
The updated Laser Inkless Printer (LIP) uses a dual-axis galvanometer (galvo) system in place of the previous x–y stepper motor assembly. The galvos steer the 530 nm green laser beam across the paper surface with high speed and precision, eliminating mechanical movement and improving print resolution.

The ESP32 microcontroller, running FreeRTOS, generates synchronized DAC control signals to position the galvo mirrors and modulate the laser in real time. This ensures deterministic operation and smooth, continuous beam motion for accurate image and text rendering.

System safety is managed through an interlock switch, thermal sensors, and optically isolated laser control, preventing operation under unsafe conditions. The integrated Bluetooth interface allows wireless job transfer and status monitoring via LightBurn or a custom host application.

Stable power regulation maintains consistent laser output and galvo responsiveness. Together, these features create a compact, reliable, and efficient platform for high-speed, inkless laser printing.

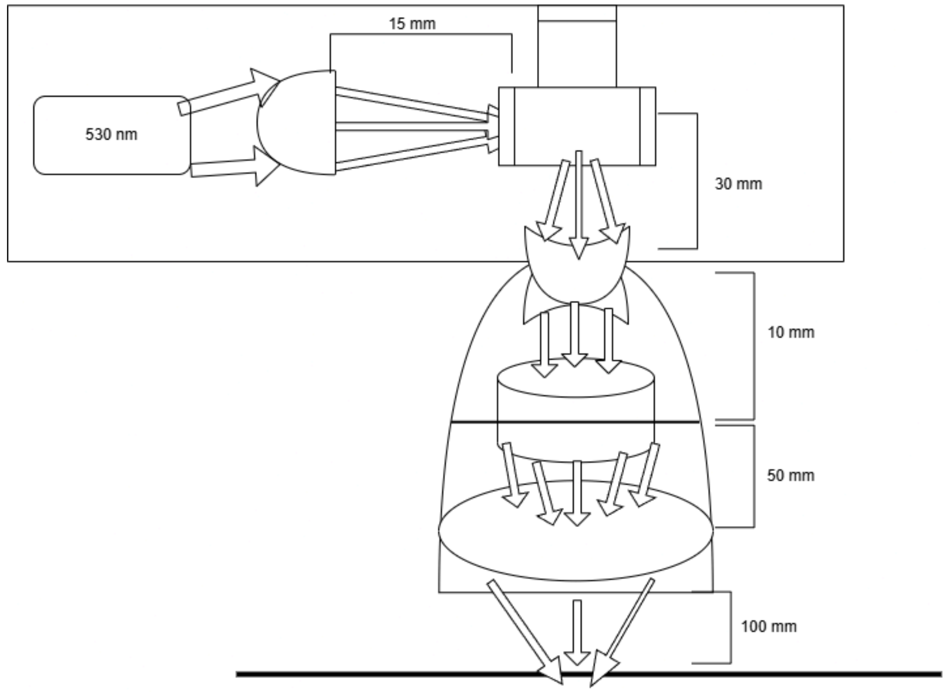
Figure 1: Prototype 3D Model



On the computational side, the master-slave microcontroller arrangement provides efficient task distribution: the ATSAM3X8EA handles high-level coordination and communication, the STM32F303R8 executes precise motor and PWM control, and the ATmega328PB operates the display interface with minimal overhead. This structure ensures smooth parallel operation and reduces system bottlenecks. Collectively, the functionalities achieved allow the LIP to operate as a reliable, efficient, and safe proof-of-concept device that addresses the affordability, speed, and integration challenges of the prior design.

For the optics side, our optical design sketch (Figure 2) is based on part schematics from laser engravers that will be discussed in Chapter 3. The goal of the design is to collimate the laser beam, and, at the focal point, reflect the beam into a lens setup that serves to maintain beam integrity as the mirrors turn to sketch out a desired input.

Figure 2: Optical Design Sketch



2.5 Goals & Objectives

Goals

Basic Goals:

- Develop a compact, enclosed printing system that safely directs a high-power laser onto magenta colored paper without ink or toner.
- Achieve character linewidth of less than 30 microns.
- Ensure user-friendly operation with a basic LCD interface for status updates and control inputs.
- Expand character set support (letters, numbers, symbols) with software-controlled formatting.
- Higher pixel resolution for the numbers, symbols, and characters.

Advanced Goals:

- Optimize scanning speed and synchronization between the laser and stepper motors to improve overall print speed.
- Integrate Bluetooth or USB connectivity for wireless/remote print commands.
- Reduce system footprint by refining PCB design to combine motor drivers, laser driver, and microcontroller on a single board.
- Incorporate safety error detection (e.g., motor stall detection, over-temperature laser shutoff).
- The adjustment for font size (so it can be dynamically changed).

Stretch Goals:

- Implement grayscale or multi-depth engraving capability by modulating laser intensity.
- Enable higher-resolution printing (e.g., >600 dpi equivalent) for more detailed text or graphics.

Objectives

Basic Objectives:

- Implement laser actuation that engraves visible marks on standard office paper without the need for ink or toner, and without causing excessive damage to the paper.
- Implement a multi-lens design to properly focus and correct for beam change. .
- All electronic components (microcontroller, motor drivers, power regulation, and laser circuitry) will be housed in a single compact enclosure with minimal user calibration required.
- Develop and implement basic laser scanning algorithms on the microcontroller to achieve controlled horizontal and vertical movement of the print head across paper.

Advanced Objectives:

- Reduce power consumption by implementing dynamic power scaling for idle subsystems (motors off during laser-only operations, LCD dimming).
- Maintain system power usage under a set threshold (e.g., <25 W during full operation) to ensure compatibility with standard USB or wall adapters.
- Store print logs and diagnostics in non-volatile memory, allowing persistent data across power cycles.
- Ensure communication protocols (SPI, UART, or I^2C) between MCU and peripheral devices remain reliable with checksum or ACK/NACK error-checking.

Stretch Objectives:

- Achieve near real-time performance (<50 ms delay) between job submission and print initiation.
- Investigate machine learning techniques to adaptively optimize print speed and path planning for different document layouts.
- Enable grayscale printing capability through pulse-width modulation (PWM) of the laser to vary burn depth or darkness.

2.6 Required Specifications

Table 1: Component Specifications

Component	Parameter	Specification	Unit
Green Laser Diode	A. Diameter B. Wavelength C. Power D. Threshold Current E. Operating Voltage F. // Divergence G. || Divergence	A. 5.6 B. 530 C. 1650 D. 150 - 500 E. 4.0 - 5.5 F. 0.2 - -0.6 G. -1.0 - 1.0	A. mm B. nm C. mW D. mA E. V F. Degrees G. Degrees
Aspheric Lens	A. Diameter B. Focal length C. AR Coating	A. 5.20 B. 15.29 C. 350 - 700	A. mm B. mm C. AR
Biconcave Lens	A. Diameter B. Focal length C. AR Coating	A. 25.44 B. -100 C. 350 - 700	A. mm B. mm C. nm
Achromatic Doublet Lens	A. Diameter B. Focal Length C. AR Coating	A. 25.44 B. 150 C. 400 - 700	A. mm B. mm C. nm
Positive Meniscus Lens	A. Diameter B. Focal length C. AR Coating	A. 50.8 B. 100 C. 350-700	1. mm 2. mm 3. nm
Paper Delivery Motors	A. Geared DC motor with encoder B. 0.4 N*m torque	Drive paper feed	1
PCB	A. Custom PCB with motor drivers, laser driver, I/O connectors B. ~6" × 8"	System control and integration	1
Onboard computer	A. Rasberry PI B. 1.4 GHz CPU C. Microsd or USB compatibility	Control logic, data handling	1
Power Supply	A. ≤ 15V	Supply power to	1

	Consumption B. Able to use power from outlet, 120V 15 A	system	

Table 2: Engineering Requirements

Engineering Requirements	Requirement Specification	Unit
The system will process inputs from an external source within a specified time frame.	≤ 1	s
The paper will be delivered to the correct location within a specified time.	≤ 10	s
The X and Y axis motors will move the laser to the correct location within a certain margin of error.	≤ 5	mm
The system will maintain safe operating temperature during printing to ensure safety for users.	≤ 150	°F
The system will complete a full-page print within a specified time frame	≤ 120	s
The system will achieve a minimum print resolution to make each letter readable, should exceed that of the previous design.	≥ 30	DPI
The system will produce characters of a linewidth on par with available items on the market.	≤ 20	μm
The system will not exceed a weight that would make it not portable.	≤ 25	lbs
The system will be able to be fixed on a standard desk.	30” x 60”	in

Figure 3: Hardware Diagram

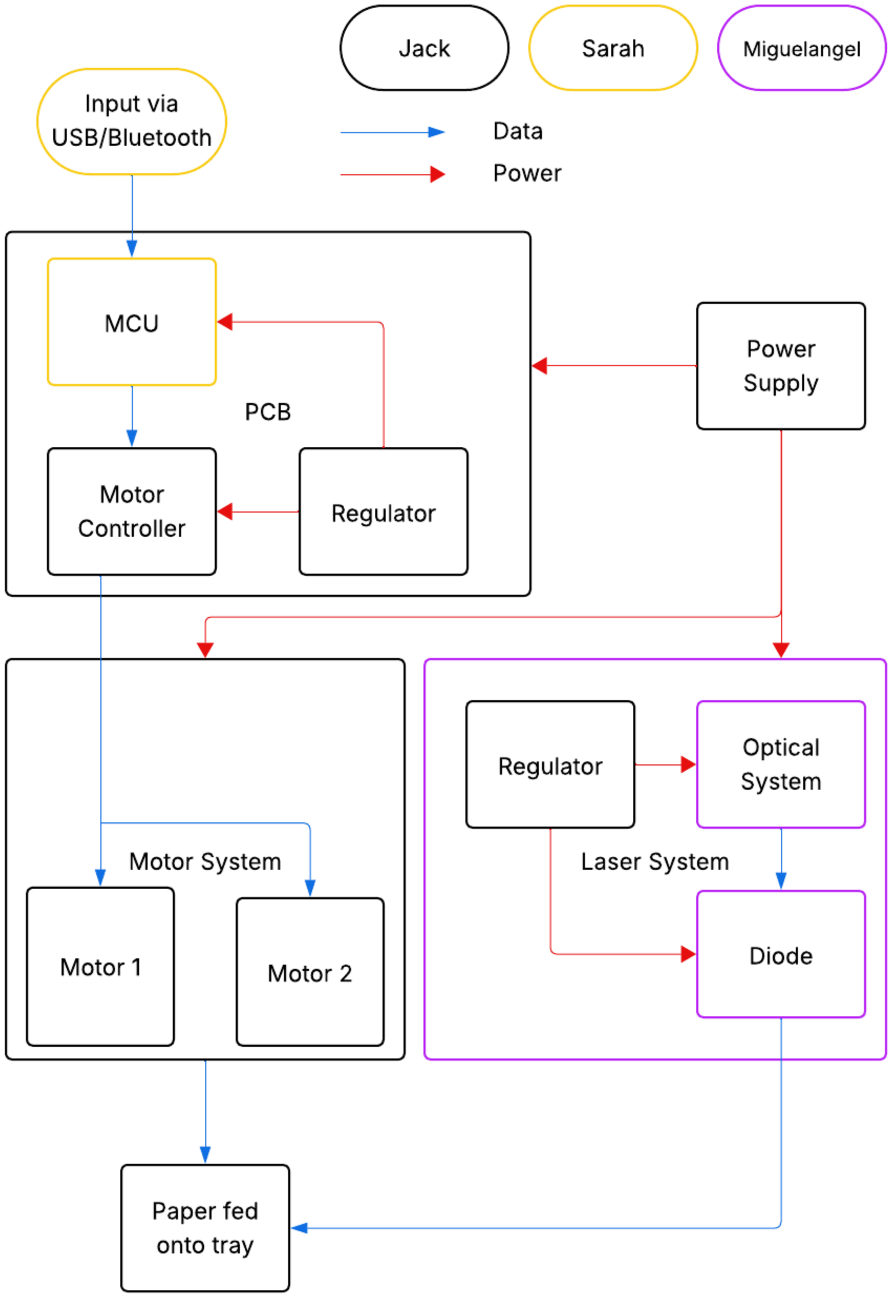
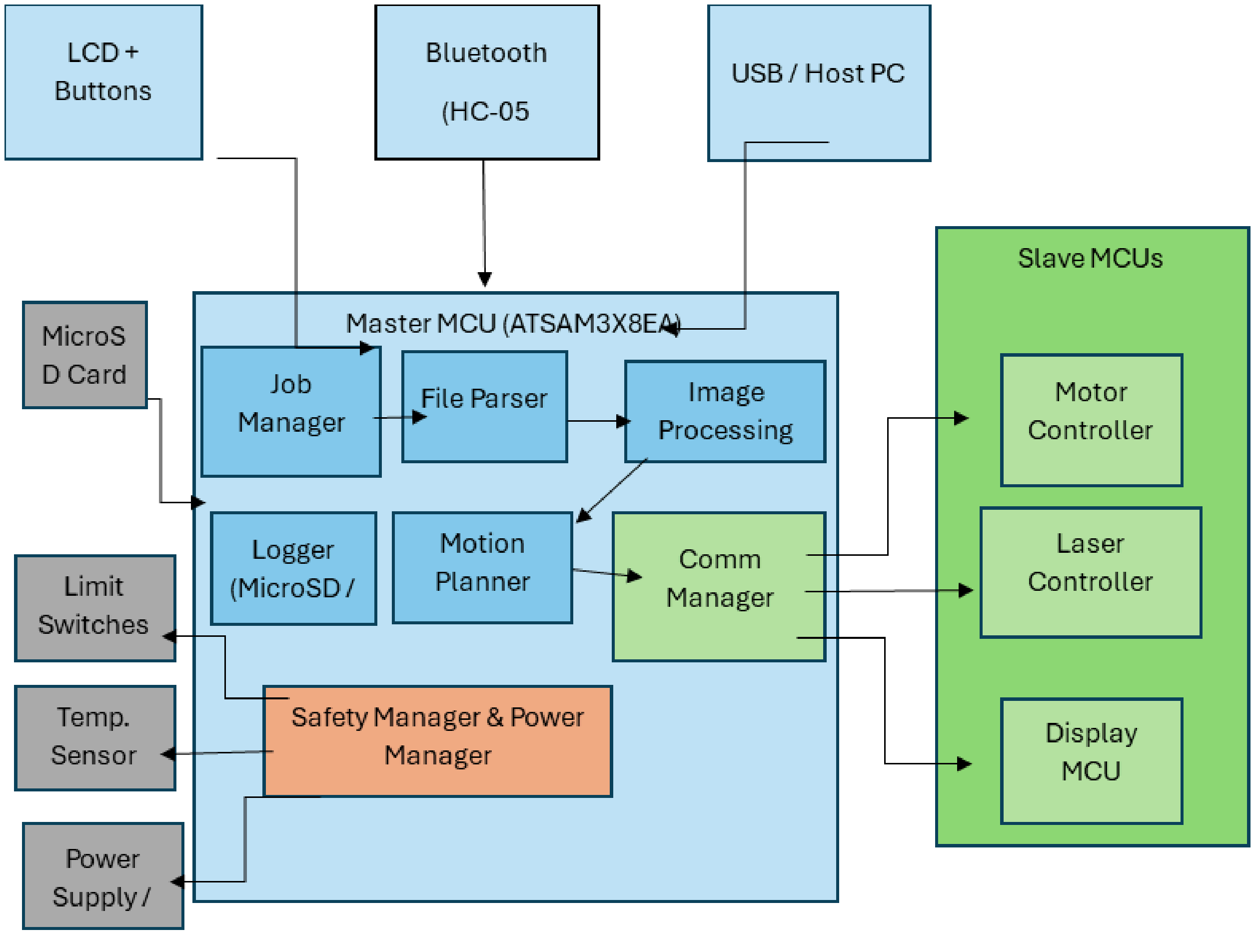


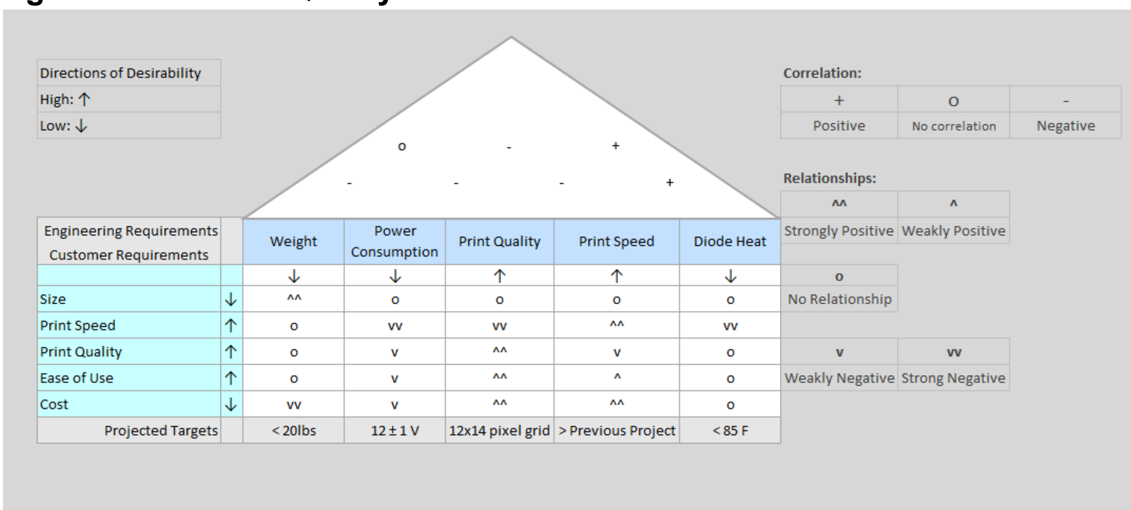
Figure 4: Software Block Diagram



The software block diagram illustrates how the Laser Inkless Printer manages data flow from the user to the hardware subsystems. Input begins through the user interfaces (Bluetooth, LCD, or USB), where print jobs are sent to the Master MCU. Within the Master MCU, the Job Manager and File Parser interpret incoming print data. At the same time, the Image Processing and Motion

Planning modules convert it into rasterized commands for precise laser positioning. The communication Manager then distributes these instructions to dedicated Slave MCUs, which control the stepper motors for X-Y movement, the laser module for marking, and the display for system feedback. Supporting managers, such as those in Safety and Interlocks, Power and Thermal Management, and the Logger, ensures safe operation, proper energy use, and diagnostic tracking. Finally, peripherals like sensors, limit switches, and the power supply provide real-time inputs that feed back into the safety and control loops, ensuring the system remains stable, efficient, and user-friendly.

Figure 5: House of Quality



Chapter 3: Research and Investigation

3.1 Existing products and methods

Incorporating lasers into the design of printing technologies is not an uncommon practice. Understanding how this technology is being developed professionally can provide valuable insight into how we should advance the design of the LIP. In this section, products that use a laser for printing are discussed.

3.1.1 Laser Printers

Rather than using inkjet cartridges to print, laser printers utilize a laser to charge a metal drum within the printer. That negatively charged drum then attracts the positively charged toner (effectively, powdered ink) via static electricity. The toner is rapidly deposited and heated onto the desired print area of the paper to ensure permanent binding [Toner]. Then, the mechanical system within feeds out the freshly printed paper

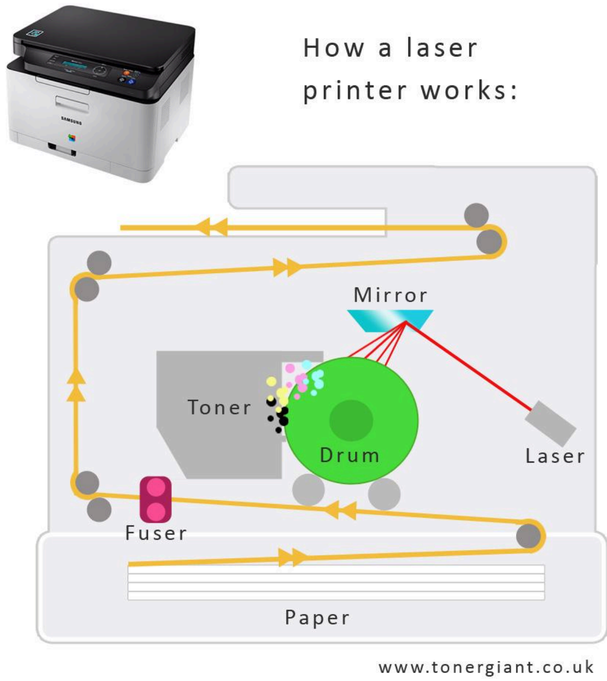


Figure 6: Toner Giant Laser Printer Diagram [54]

While traditional inkjet cartridges are not used, toner still requires cartridges and replacement. Furthermore, even though it is ink-based, it still poses a danger to the environment when cartridges are disposed of.

3.1.2 Engravers

Laser engravers house a laser system within a programmable mobile mount. A set of x-y coordinates is entered, and the engraver then traces the desired image. Another design option involves using laser galvo mirrors. Rather than moving the whole optical system of the laser to form an image, mirrors rapidly steer the laser beam while the rest of the system remains fixed. Both methods result in a concentrated laser beam that heats and vaporizes material to form a pattern.

Figure 7: Laser Engraver without and with a galvo [52, 53]

Engravers are commonly used for working with rigid materials such as wood or plastic. During the previous group's development, they noted available engraver lasers "aren't refined enough to mark paper without burning through it." The size of the engravers was also noted as a downside. Most are large and are incredibly inefficient to move without complete disassembly. Smaller ones are used to create finer designs but are often more expensive than larger ones.

3.1.3 Direct Thermal Printers

Thermal printers use a combination of thermosensitive paper and a laser to print characters without ink. Within the printer, small resistors are electronically controlled to apply heat as the paper rolls out; where heat is applied, the paper darkens and forms an image and/or character. When one receives a receipt after purchase or a package label, a thermal printer is used to print it [50].

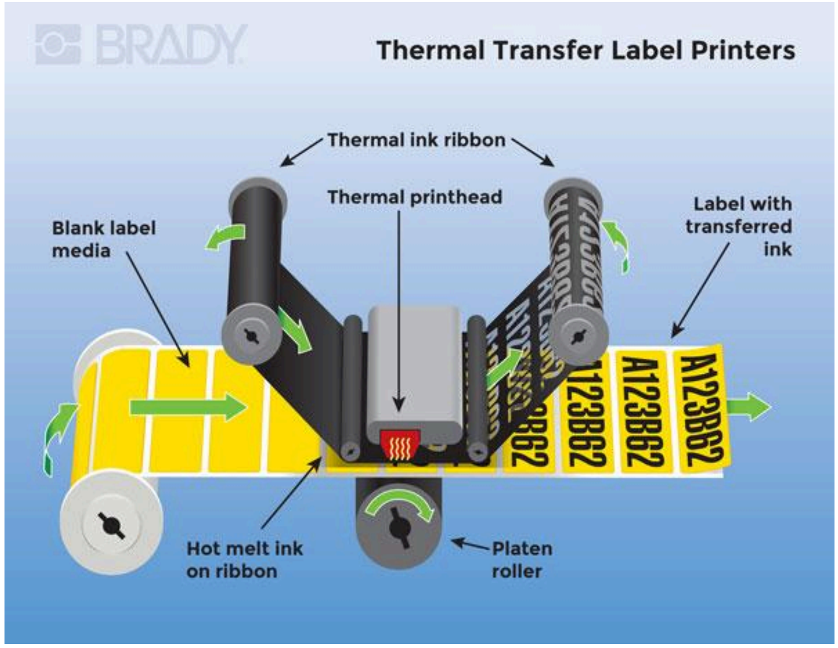


Figure 8: Thermal Printer Internal Mechanism [51]

While an excellent example of laser inkless printing, incorporating this technology into our system would be too arduous. As mentioned, these printers require specialized paper to work properly, which defeats our goal of creating a flexible replacement for traditional printers. Additionally, if overexposed to light over time, the paper would completely darken, ruining any print previously present.

3.2 Market analysis

According to Evolve Recycling, 1.3 billion inkjet cartridges are used annually, but only 30% are being recycled. In the US, 300 million inkjet and 70 million laser cartridges are sold, and over 150 million pounds of these cartridges end up in landfills instead of being recycled. Evolve also notes that, given these cartridges are made of industrial-grade plastics, it can take several hundred years for them to decompose fully.

Today, some companies are working to create an inkless alternative to inkjet printers. While their products do not use inkjet cartridges, they are not at a level to replace traditional printers. [49]

3.2.1 Zink

Zero-Ink (Zink) is an independent company that was formed in 2005 to develop printing technology that doesn't require cartridges. In 2007, their first printer and its associated paper were released to the market. For the printer to function, a specialized, sever-layered paper was designed by the company. Each layer contains billions of dye crystals, as shown in the figure below.

The printing process requires a laser to “activate” each color layer depending on the heat intensity and duration; ie, short pulses of high temperature activate the yellow layer. This process of heating the paper repeats rapidly until an image is formed. While an effective form of inkless printing, the use of specialized paper is beyond our scope for this project. Furthermore, Zink’s printers don’t focus on printing characters; instead, they concentrate on small-scale cameras and have shown no interest in expanding.

3.2.2 xTool

xTtool is a China-based company committed to replacing knives and scissors with their own cutting-edge laser engraving tools and associated software. Since 2021, the company has been designing laser cutters primarily used in at-home small and large craft projects. One of their engravers, specifically the xTool F1 Portable and High Speed Laser Engraver, is a design that inspired our group’s current planned design for the L.I.P. Rather than having an XY axis for the laser to move along, xTool’s engravers utilize laser galvos that rapidly spin together in conjunction with an f-theta focusing lens to engrave the desired image onto the surface. The software of their engravers also allows for seamless image input and adjustment, only requiring a suitably secured surface for the engraver function.

Our group wishes to use laser galvos similarly to advance the design of the L.I.P., but xTools notes a considerable downside to this technology compared to an XY plotter: cost. Purchasing a high-quality f-theta lens and dual laser galvo mirror is considerably expensive, pushing our budget to the limit, assuming no parts require replacement. Additionally, from videos on xTool’s website, it was observed that their software does not operate with text-based inputs; only images. Our group would need to find an alternative software to connect with the laser galvo so our design can function as an appropriate printer.

3.3 Laser Marking System

The following subsections analyze the assembly of the previous group that designed the L.I.P., and will discuss our group’s plan for advancing the design. We also discuss the advantages of laser marking as an alternative to inkjet printers, the marking techniques used in other technologies, and the selection of components, including our laser diode and lens specifications.

3.3.1 Engraver Assembly

The previous group utilized a prebuilt engraver assembly because they lacked a mechanical engineer to construct it. The specific assembly they chose was the OTUR Laser Master 2. For the price of $189 at the time, the engraver was highlighted to include a 32-bit motherboard with a Grbl-based STM32 microcontroller. They were able to utilize the LaserGRBL software to communicate with the system. The engraver also operated at 36 W with a 12V, 3A input, allowing for an engraving speed of up to 3000mm per minute. A considerable advantage of this frame was that the firmware included built-in safety features: it would shut off the laser if the frame was moved and cease laser communication if the laser became too hot [1].

Figure 9: OTUR Laser Master 2

Our group considered an engraver like the OTUR Laser Master 2 for our design, but the inclusion of the laser galvo mirrors changed our plans. A mechanical assembly would be unnecessary for a galvo-based design as the mirrors direct the laser beam without the need for positional change. Implementing this into our design would prove time consuming, especially for our group's electrical engineer. The previous group had a second one to manage the mechanics while the second worked with the PCB Our group considered building a fully 3D-printed assembly, inspired by the products sourced from xTool. It would allow us the most flexibility in implementing our laser galvo design. However, this would take considerable time and resources that we do not have at present.

3.3.2 Laser Marking Methods and Advantages

Laser marking is the process of using a focused laser beam to engrave or etch onto material surfaces. Proper focusing of the laser beam is necessary because marking is possible only at the focal point. The advantages of laser marking are numerous, and various methods depend on the desired mark.

Advantages

The primary advantage of laser marking is its incredible precision. When appropriately focused, a laser marker can create fine and detailed marks or symbols on a surface. Compared to other methods, laser marking is environmentally friendly because it does not produce or use toxic chemicals in its process.

The tools required for laser marking often require little upkeep besides sufficient electrical power. Users do not need to worry about recurring costs like cartridge refueling. Furthermore, the marks of laser markers are incredibly resistant to change. Rather than depositing material like toner on a surface, the laser removes a small layer of present material, embedding the mark into the material itself.

Engraving and Marking Techniques

When designing our version of the L.I.P., our primary objective is to create legible marks without excessively cutting or combusting the paper [Carbonization]. There are a multitude of techniques available in the market for marking materials without completely splitting them. Raster marking, the method performed by the previous group, allows for the creation of characters in the form of a dot matrix. The previous group translated letters into a 4x5 pixel design, and programmed the laser to “draw” the letters by repeatedly opening and closing the laser for each dot that was created. They also included a delay period within the system to detect discontinuous points.

Laser engraving utilizes a highly focused laser beam to remove the surface layer of a material. Common engravers often utilize CO2 or fiber lasers to successfully mark. Factors such as materials used play a great role in how well a laser is able to remove material: there are significant differences between engraving into paper compared to metals. Laser carbonization involves breaking bonds in a material, releasing their carbon to create darker marks. According to FOBA laser, broken plastic bonds create gray to blue-gray and black marks, and light plastic or organic materials, like paper, change the color from light to dark.

3.3.3 Paper Types

The choice of paper is crucial for how well the mark will form on it: one color better absorbs and, theoretically, creates a better mark than others. Per the previous group's paper and discussion with faculty, a yellow-tinged paper worked best and was ultimately used in final testing. With this in mind, we researched what color would best absorb green laser light to ensure a similar visible and small mark, concluding that a magenta-tinted paper would work best. [55]

Our current plan is to test 8.5 x 11, 50lb magenta colored paper from PaperAndEnvelopes. The exact brightness we will need will require further testing. If the previous group's paper is followed, we will need as bright and thick a paper as possible for successful marking.

3.4 Component Selection

The following sections will describe the decision-making process for the items included in the updated optical design of the E.L.I.P., such as the laser galvo and f-theta lens we plan to include, the laser type for engraving, the power supply and laser driver type, and the updated casing design.

3.4.1 Laser Galvo and F-Theta Lens

Per ThorLab's description of their dual-axis scanning galvo systems, the galvo consists of a galvanometer-based scanning motor with an optical mirror mounted on the shaft and a detector that provides positional feedback to the control board. The Proportional Derivative server driver circuit interprets the signals from the optical position detecting system within the motor. Then it produces the drive voltage required to rotate the mirror to the desired position. ThorLabs has always been a reliable source for optics technology and possesses a wide range of Galvanometer systems and related products. Our project intends to utilize a 2D galvo system, requiring X and Y mirrors to function correctly. TL's GVS102 product matches what we would ideally like to use, requiring +/-15V 3A input to power. However, its price of $3,785.20 exceeds the scope of this project. Given that we are not sponsored, we do not plan on using this galvo in prototyping or final production. However, we will consider using the heatsink available for the galvo on TL, as that part is reasonably priced. With further research, we found a galvo system available on Amazon and AliExpress at a much more reasonable $70. Like the TL galvo, it requires a +/- 15 V DC power source, and a peak current of 2A instead of 3A to function. From the provided images, the control board looks similar to TL's boards, so this option will be considered. We would just need to be careful in learning how to communicate with the galvo and exercise reasonable caution with what is likely a more unstable piece of equipment.

The f-theta lens is the most crucial part of any laser galvo system intended for engraving. As a laser beam moves, it often loses peak power when it is not at its focal point: as the angle changes, the focal point shifts, causing power loss. An f-theta lens ensures focus is maintained as the laser rapidly changes due to the mirrors of the galvo system [47]. However, much like TL's laser galvos, a reliable f-theta lens is incredibly high-priced for an unsponsored group like ours. We are still considering whether this implementation will even be possible, considering our circumstances. With some faculty consultation and research, a schematic was developed that theoretically replicates the beam correction capabilities of the f-theta lens. Calculating its transmittance results in some extra power loss compared to using one lens. Exact specifications will be discussed in the Lens-specific section, and the optical design sketch can be seen in Chapter 2.

3.4.2 Laser Diode Comparison

With the previous group's paper in mind, there were three lasers to consider for our updated design: Nd: YAG, a blue laser diode, or a green laser diode. The previous design used a blue diode because of the advantages it had over other options. Nd: YAG, while well researched with notable benefits regarding beam quality and marking speed, had some significant disadvantages that caused the group to decide against this laser. The average power of Nd: YAG lasers was considered too high for use in engraving paper. It also suffered from a large beam waist, beam quality, dimensions, weight, and a much shorter lifetime. Overall, the Nd: YAG laser required too many large and immobile parts to be realistic for its design; thus, our group will not be utilizing this laser.

A UV (or blue) laser diode posed more feasible for the initial design of the L.I.P. The diode, module, coated lenses, driver, heat sink, goggles, and power supply were comparatively cheaper than an Nd: YAG setup. Furthermore, the wavelength of the blue diode allowed for a high-intensity, small-spot-sized beam capable of operating at lower powers without compromising beam integrity. The primary downsides of the blue diode were a slower marking speed and lower resolution due to its low power. Regardless, this diode proved effective for the previous version of the design.

Green was considered as an option due to its history of being utilized for engraving non-paper materials. However, no research was available at the time on the mark depth of green lasers when used for paper, and testing their usefulness required more time and capital. Incorporating a green diode provides an opportunity to test more alternatives to this technology, using their previous work as the foundation. As previously mentioned, they were able to achieve marks on the paper at around 1.6 W. Researching for a green diode at this power proved troublesome, as the highest available single-mode diode at a reasonable price that could be found was a This allows us to begin testing at this range and serves as a reference for future calculations and diode choice.

Table 3: Comparison of Lasers

	Green Laser Diode	Blue Laser Diode	Nd: YAG Laser
Wavelength [nm]	530	445	1064
Average Power [W]	0.6 - 2.75	6 - 8	25
Beam Waist [cm]	0.00483 x 0.00191	0.0219 x 0.0004	0.135 x 0.135
Beam Quality [M^2]	>2	1 - 1.1	1.2 - 1.7
Beam Divergence [mrad]	0.4	0.2	0.34
Lifetime [h]	25,000	30,000	830 (lamp)

3.4.3 Lab Safety Equipment

Operating with a high-power laser requires sufficient safety equipment. Our group plans to purchase appropriate Eagle Pair laser safety goggles that cover the 532 nm wavelength we will be working with. We plan to enclose our system to minimize laser viewing, but a laser shield for added protection will be added regardless. The shield is an acrylic-based material with 6+ optical density (OD6+) at 532 nm. The Laser Standards section of this paper shall cover more information regarding laser safety, standards, and classifications.

3.4.4 Lenses, Encasing, Mirrors

Collimating our laser is necessary because the power loss would be too significant if we shine the laser directly on the mirror. An early consideration was made for the use of plastic lenses, as they are more cost-effective than glass lenses. However, it was noted that plastic typically creates a much larger spot size compared to glass. It would be disadvantageous for our design to utilize a plastic lens, as we require a relatively high focused beam to engrave paper properly.

In our early planning stage, we believed integrating a galvo within the lens design of the previous group would be sufficient, but this was adjusted after realizing the required position of the galvos. Their design had the laser travel directly downward through the collimating and focusing lenses. Compared to xTool's engravers, the galvo must be positioned so that the laser enters one mirror and reflects out the other. The present design involves creating a more L-shaped structure.

Another issue we realized was that a single focusing lens would not be enough to transmit the laser as the galvo mirrors turn. Available engravers incorporate some form of an f-theta lens to create a flat image field, maintaining laser linearity as it engraves the paper: this ensures the laser operates at as much power as possible while engraving. As mentioned before, incorporating an f-theta lens for our project would be incredibly unrealistic with the average price of a single lens. Consulting with faculty and using some artificial intelligence tools led us to a multi-lens design that theoretically replicates the flat field creation effect of an f-theta lens.

Table 4 Lens Specifications

Lens Shape	Aspheric	Biconcave	Achromatic Doublet	Positive Meniscus
Substrate Material	H-LAK54	N-BK7	N-BK7 (S1) SF5 (S2)	N-BK7
Wavelength Range (nm)	350 - 700	350 - 700	400 - 700	350 - 700
Focal Length (mm)	15.29	-100	150	100
Diameter (mm)	5.00	25.4	25.4	50.8

3.4.5 Power Supply

Since we'll be using a laser diode, we'll need a proper power supply to get the most out of it. The previous group's design incorporated their diode into the PCB, supplying 6.4 W to the laser driver to directly drive the diode. This helped resolve the need for multiple outlets for their mechanical setup and the laser. They also utilized an opto-isolator to help manage the voltage of a relatively high-powered laser system. Our current design does not include a mechanical system, so we can either follow the previous PCB integration design or test a wall plug connection.

Currently the galvo that we are using has a power supply that comes with it, so after buying a plug that can split into neutral, ground, and hot and connect them to the locations on the power supply that supply power to it.

We plan to use regulators to keep the electrical system stable so each subsystem receives the voltage it's designed to handle, even when the workload constantly changes. As the printer moves paper, starts or stops stepper motors, fires heating elements, or activates sensors, the electrical demand can swing quickly, and those shifts would create voltage spikes or dips if left unmanaged. The regulator smooths out those fluctuations by holding the output at a steady level, preventing motors from being driven harder than intended, keeping sensors from misreading signals, and stopping unexpected surges from reaching the control board. This stability keeps the internal electronics operating within their safe limits, reduces strain on mechanical components, and helps the printer maintain consistent performance across repeated cycles.

3.4.6 Laser Driver Comparison

The previous group had some issues obtaining their planned laser driver or PCB driver design, so they opted for a triple DC power supply and an opto-isolator instead. This is an option being considered for when we power our diode [1].

3.4.7 Diode Specifications

The specific green diode we decided on has a center wavelength of 530 nm. Its threshold current is 150-500 mA, and it operates at 4-5.5 V. The operating temperature ranges from 0 - 65 ℃. We plan to insert the diode within a heatsink fan to cool it during operation, properly preserving beam integrity. The diode is described as a multimode, so unfortunately, several specifications are expected to be larger than a single-mode diode: beam quality, spot size, and emitter width. To maximize the strength of our diode, we will require a proper focusing aperture with appropriate specifications.

Spot Size

For successful engraving, having a small diffraction-limited spot size is essential. Compared to blue, green has a higher wavelength and heat output. We expect a further decrease in both beam quality and resolution. To calculate, we use the diffraction-limited spot-size formula for a focused beam. It would be essential to have a sufficiently large effective numerical aperture (NA) to achieve a small spot size. To obtain each number, we utilized the diameter and focal length of the positive meniscus lens at the very end of our setup. Chapter 6 will cover specific design calculations.

Resolution, Speed, and Depth

The previous group utilized a CMOS camera to measure the resolution of their L.I.P.'s performance. They achieved a resolution of 20 dpi within 7.5 seconds. Given that our current design will utilize more lenses and mirrors, I expect our resolution to be less than ideal by comparison. With how fast the laser galvos operate, our mark time will have to be increased significantly so it can engrave the paper without needing delay. Our target is to hit over 25 dpi.

3.5 Software Architecture and Platform Selection

With the selection of the Galvo laser, the software design must evolve to meet new demands in precision, control synchronization, and communication efficiency. The previous diode-based laser system required only simple on/off modulation and linear motion control; however, the Galvo system introduces multi-axis feedback, higher motion speeds, and continuous analog signal management. These changes necessitate a robust and deterministic firmware foundation capable of handling concurrent real-time tasks such as beam deflection, laser modulation, and wireless communication. To support these technical requirements, the next stage of our design focuses on the software components – specifically the programming environment and the microcontroller platform. The programming language must enable low-level hardware interaction while maintaining modularity and concurrency through task scheduling. Likewise, the selected microcontroller must provide the computational power, peripheral integration, and real-time responsiveness needed for precise beam steering and Bluetooth data transmission.

The following sections detail our rationale for choosing C/C++ with an RTOS as the core software framework and compare several potential microcontroller candidates to identify the most effective balance between performance, cost, and integration capability for our Galvo-based laser printing system.

3.5.1 Programming Language

For this project, we have selected C/C++ with an RTOS (Real-Time Operating System) as the programming environment for our laser inkless printer system. The decision is grounded in the need for precise and deterministic timing control, which is essential when driving galvanometer mirrors and synchronizing laser modulation.

Benefits of C/C++ with RTOS

Deterministic Scheduling: An RTOS provides predictable, low-jitter task scheduling which ensures that time-critical operations, such as DAC (digital-to-analog) signal output to the galvos, happen at fixed intervals. This level of determinism is critical to maintain accurate beam positioning and print quality. **Concurrency Management:** RTOS enables tasks to run concurrently with assigned priorities. For instance, one thread can handle DAC output while another manages Bluetooth communication, ensuring that communication overhead does not disrupt time-sensitive laser control.

Preemptive Multitasking: With RTOS preemptive scheduling, higher-priority tasks can interrupt lower-priority tasks, which ensures urgent operations are always serviced in time. Preemptive scheduling is particularly important when multiple tasks compete for limited resources. For instance, consider two print jobs in the queue: the first job requires a small amount of paper, while the second requires a much larger quantity. Without preemption, the first job would be executed simply because it arrived first, potentially delaying the second job that could better utilize the available resources. With preemptive scheduling, the system can assign higher priority to the second job, allowing it to run first and complete efficiently within the given constraints, thereby optimizing overall throughput and resource usage.

Built-in Timer and Multithreading Support: C/C++ with RTOS leverages hardware timers to schedule recurring tasks and allows the programmer to logically separate responsibilities. This modularity makes the system more reliable and easier to debug.

Trade-Offs:

System Overhead: The RTOS kernel itself consumes CPU cycles and memory, adding overhead compared to bare-metal C programming. For microcontrollers with limited resources, this can reduce available headroom for application tasks.

Programming Complexity: The introduction of RTOS adds a layer of complexity to the programming model. For team members with strong C experience but less familiarity with C++ or RTOS constructs, the learning curve may be steeper. However, this investment in learning such tools will be very beneficial with concurrency handling and modular task separation.

3.5.2 Development Environments and IDE Comparison

A reliable and efficient development environment is essential for firmware projects that combine RTOS-based concurrency, wireless communication, and hardware-level control. Since the project's programming language will be written in C/C++ using FreeRTOS and targets embedded MCUs such as STM32WB or

ESP32, the chosen Integrated Development Environment (IDE) must provide tight integration with build toolchains, debugging interfaces, and RTOS visualization. Several modern IDEs and tools are available for MCU-based development, each offering distinct advantages depending on workflow requirements and hardware targets.

STM32CubeIDE (STMicroelectronics) is a comprehensive development interface based on Eclipse, fully integrated with the STM32CubeMX configuration tool, code generator, and peripheral libraries. It provides direct support for FreeRTOS configuration through the CubeMX GUI, enabling developers to visualize task structures, assign priorities, and generate the corresponding kernel initialization code automatically [STMicroelectronics, 2024]. The IDE includes RTOS-aware debugging support, register views, and real-time variable inspection through ST-Link and J-Link interfaces, making it highly practical for STM32-based systems that require deterministic control and debugging of concurrent tasks.

ESP-IDF (Espressif IoT Development Framework), the native toolchain for ESP32, provides FreeRTOS integration as its default real-time kernel [Espressif Systems, 32]. ESP-IDF offers a CMake-based build system and supports RTOS task tracing through the “SystemView” and “FreeRTOS Trace” tools. While not as visually integrated as STM32CubeIDE, it is highly optimized for ESP32 hardware and includes drivers, Wi-Fi/BLE stacks, and peripheral APIs. Developers typically use Visual Studio Code (VS Code) with the ESP-IDF extension, combining a lightweight code editor with robust cross-platform build support and integrated serial/flash utilities. This environment is ideal for projects targeting the ESP32, where flexible plugin management and integrated terminal workflows are preferred over large IDE frameworks.

PlatformIO, built as an extension for VS code or standalone, provides a unified environment for developing C/C++ firmware across multiple MCUs (including STM32, ESP32, and RP2040) [PlatformIO Labs, 2024]. It supports FreeRTOS as a portable library, offers automated dependency management, and allows seamless switching between hardware platforms using the same workspace. Its project-level configuration simplifies build environment control for cross-platform embedded systems, making it a practical choice for using either STM32, ESP32, or both.

Visual Studio Code, while powerful for general C/C++ and Windows development, is less suited for direct embedded debugging unless paired with specialized toolchains such as VisualGDB or external extensions. Its advantages lie in structured C++ project management, GitHub Integration, and code refactoring tools, but its overhead and limited native MCU integration make it secondary to STM32CubeIDE or VS Code for FreeRTOS-based embedded firmware.

Finally, GitHub provides cloud-hosted development and version control platforms that integrate seamlessly with all major IDEs. They enable collaborative development, version history tracking, and remote builds in containerized environments [GitHub Docs, 2024]. Codespaces can run preconfigured environments with FreeRTOS toolchains and cross-compilers directly in the browser or via VS Code Remote, which is beneficial for distributed teams working on the same RTOS-based firmware.

In summary, for an ESP32-based development, VS code with ESP-IDF framework or Platform IO remains the most practical and integrated choice, offering robust FreeRTOs configuration, peripheral management, and real-time debugging support. ESP-IDF provides full access to low-level APIs, NimBLE-based Bluetooth stack management, and efficient build integration with CMake and Git. Platform IO further simplifies dependency control and CI/CD integration, making it well suited for scalable embedded development.

3.6 Microcontroller Comparison:

In selecting the microcontroller to run C/C++ with RTOS for the galvo laser system, we evaluated several popular MCUs based on performance, cost, ecosystem support, and suitability for DAC driven galvo control.

Table 5: Microcontroller Comparison

Microcontroller	Advantages	Trade-Offs	Approx. Cost (USD)
STM32F4(e.g., Nucleo-F446RE)	Built-in DACs, strong RTOS support. Supports Ethernet for network integration.	Higher complexity in development compared to Arduino boards.	$14-20
Teensy 4.1	Extremely fast Cortex-M7 core, strong library support, excellent for high frequency control.	No built-in DAC on 4.x series, requires external DAC hardware.	$29-35
Raspberry Pi Pico (RP2040)	Very low cost, strong support, PIO state machines allow precise waveform generation.	No onboard DAC; Ethernet/networkin g requires additional hardware	$4-6

ESP32	Integrated Wi-Fi and Bluetooth, moderate real-time performance, supports FreeRTOS by default.	Limited DAC resolution, high jitter for precision tasks	$5-10
STM32WB / STM32WBA	Dual-core architecture(Cortex-M4 + M0+) with integrated Bluetooth low energy. Built-in DAC for precise galvo control.	Slightly higher development complexity due to dual-core coordination and BLE stack management	$10-$15

The ESP32 provides an excellent balance of connectivity, processing capability, and open-source flexibility for prototyping and production environments. Unlike STM32WB's dual-core separation, the ESP43 utilizes a dual Tensilica LX6/LX7 core architecture where one core can be dedicated to FreeRTOS scheduling and the other to peripheral or communication management. Although its integrated DAC offers moderate precision, this can be compensated with external DAC modules for higher resolution of galvo control. Its built-in Wi-Fi + Bluetooth (Classic + BLE) eliminates the need for separate communication modules and simplifies PCB integration, making it ideal for compact and connected laser control systems [Espressif Systems, 2024].

C/C++ with FreeRTOS remains the foundation of this design, as it provides deterministic scheduling, multitasking capability, and direct hardware control required for synchronized beam steering and real-time feedback. Higher-level languages such as Python or MicroPython cannot ensure the low-latency constraints necessary for galvanometer-based motion control.

3.6.1 Firmware & RTOS Architecture Overview and Rationale

The firmware acts as the core operational layer bridging hardware-level drivers and higher-level control logic. For this project, the firmware runs on an ESP32 microcontroller, selected for its real-time processing capability, integrated wireless connectivity, and native FreeRTOS support [Espressif Systems, 2024].

The ESP32’s dual-core design (one for system tasks and one for application logic) provides deterministic scheduling and timing control critical for precise galvo mirror actuation, while maintaining wireless communication for configuration and monitoring. This “system-on-chip" (SoC) integration minimizes external component count and interconnect latency.

Given the system’s need to handle concurrent real-time operations –such as motion control, print sequencing, and safety monitoring –a real-time operating system was necessary. FreeRTOS was chosen due to its small footprint, predictable kernel behavior and industry –proven performance on MCU-class hardware [FreeRTOS Reference Manual, 2018]. It enables deterministic task execution with fine-grained priority control, ensuring responsiveness even under heavy I/O and communication loads.

3.6.2 FreeRTOS Justification and Task Design

For an embedded laser printing and scanning system that requires real-time synchronization between multiple concurrent processes – including motor control, galvo mirror positioning, data communication and status monitoring –a deterministic scheduling system is essential [TI-RTOS, 2023]. FreeRTOS (Free Real-Time Operating System) provides a lightweight, open-source, and well-tested real-time kernel that has been widely adopted across microcontroller-based applications. It is designed to meet the strict timing, resource, and modularity requirements of embedded systems while maintaining portability and scalability across hardware platforms such as the ESP32, MSP430, and ARM Cortex-M families [ESP32 Technical Reference Manual, 2023; FreeRTOS, 2018]. In this design, FreeRTOS serves as the central scheduling and synchronization layer that allows multiple software tasks to be executed independently while maintaining strict control over execution timing. Compared to traditional superloop architectures that sequentially poll each subsystem, FreeRTOS enables concurrency and responsiveness –critical for systems that must drive multiple hardware peripherals in real-time.

3.6.3 Suitability and Proven reliability for Microcontrollers

FreeRTOS has become one of the most widely used embedded operating systems in both academic and industrial contexts due to its deterministic kernel behavior and portability. Its kernel size can be as small as a few kilobytes, making it practical for microcontrollers with limited Flash and SRAM resources. Furthermore, FreeRTOS has been validated through extensive field use in safety-critical applications such as industrial automation and automotive systems [FreeRTOS, 2018; TI-RTOS, 2023]. The portability and deterministic performance have been validated across thousands of MCU designs in industrial, medical, and aerospace systems, making it an ideal choice for this project's safety-critical, precision-oriented design goals.

Key reasons FreeRTOS is particularly suited for MCU-based systems include:

Deterministic Scheduling: Implements a preemptive, priority-based scheduler to guarantee time-critical responsiveness [ESP32 Technical Reference Manual].

Minimal Overhead: Provides fast, context switch, making it suitable for low-resource MCUs like the ESP32 and RP2040[ESP32 Technical Reference Manual] [TI-RTOS: Real-Time Operating System].

Modular Architecture and Portability: Kernel components (tasks, queues, semaphores, etc.) can be included or excluded as needed to reduce resource usage [FreeRTOS Reference Manual].

Safety Certification: Variants such as SafeRTOS are certified under IEC 61508 and ISO 26262, evidencing the system's reliability.

FreeRTOS is a preemptive, priority-based kernel designed for embedded systems and microcontrollers with limited resources. The ESP32's native FreeRTOS integration through ESP-IDF enables efficient peripheral management –especially for timers, SPI, UART, and PWM modules –which are critical for synchronized galvo operation and laser timing [Espressif Systems, 2024]. Real-time execution ensures that high-priority control loops always meet their deadlines, while background processes such as data logging or BLE communication are handled in lower priority threads.

3.6.4 Task-Based Architecture

The system firmware, illustrated in Table 6, will be partitioned into multiple FreeRTOS tasks, each handling a distinct subsystem:

Table 6

Task Name	Function	Priority

Print Control Task	Interprets raster/vector print commands and manages laser firing synchronization.	High
Galvo Control Task	Communicates with the galvo driver via DAC outputs, performing coordinate updates and feedback monitoring.	Real-Time
Status Reporting Task	Handles UART/Bluetooth telemetry, including temperature, alignment, and operational status updates	Medium
System Supervision Task	Monitors inter-task health, manages safety interlocks, and handles error states	Low

Each task runs independently but communicates through FreeRTOS queues and semaphores to ensure synchronized operation [FreeRTOS, 2018]. For example, the Print Control Task dispatches coordinate data to the Galvo Task through a queue, while a binary semaphore ensures that the laser only activates once the galvos reach the correct position.

3.6.5 Integration with LightBurn and Controller Compatibility

The firmware is designed to ensure compatibility with LightBurn, a PC-based laser control platform supporting both GCode and Galvo modes. Since this system uses a galvo scan head (e.g., ThorLabs LSK-GG) with a custom controller, the firmware adopts a protocol structure similar to EZCAD2 or other DSP-based galvo systems [Thorlabs LSK-GG Datasheet, 2018]. LightBurn interprets job files and transmits corresponding motion and laser modulation commands, which the ESP32 firmware processes and executes through FreeRTOS-managed control tasks.

Wireless communication through Bluetooth not only enhances system portability but also enables safe operation by allowing the host PC to remain physically separated from the laser environment. Combined with FreeRTOS's deterministic scheduling, the result is a responsive, reliable, and secure wireless laser marking platform [Espressif Systems, 2024; LightBurn Documentation, 2024].

3.6.6 Software Peripherals

The ESP32 microcontroller in this Galvo laser system interfaces with a range of hardware peripherals, each managed through FreeRTOS tasks and deterministic scheduling. The following peripherals are essential for system functionality, safety, and real-time performance:

1. Digital-to-Analog Converters (DACs)
    - Purpose: Generate precise analog voltage signals to drive galvo mirrors for beam positioning
    - Usage: Controlled by the Galvo Control Task under FreeRTOS. Analog outputs are filtered via RC circuits to reduce jitter.
    - Constraints: Output range limited to Thorlabs specifications. Avoid toggling DAC in ISRs to prevent timing errors.
2. Analog-to-Digital Converters (ADCs)
    - Purpose: Monitor sensor feedback including galvo positions, temperature sensors, and voltage/current fault indicators
    - Usage: ADC reads are queued to supervisory tasks for safety checks and logging
    - Constraints: ADC channels are shielded and averaged in software to mitigate interference from DAC or BLE activity,
3. Pulse Width Modulation (PWM)
    - Purpose: Alternative or supplemental analog control for laser modulation and galvo actuation if high-resolution DAC is unavailable
    - Usage: PWM channels filtered via low-pass RC circuits to produce stable analog control voltages
    - Constraints: Use DMA to reduce CPU load and maintain real-time timing.
4. General Purpose Input/Output (GPIO)
    - Purpose: Monitor hardware safety interlocks, emergency stop switches, and control laser enable signals.
    - Usage: Safety Supervisor Task continuously reads GPIOs to ensure operational constraints before activating laser output.
    - Constraints: Must trigger immediate fail-safe hardware responses when out-of-range or interlock conditions are detected
5. Timers
    - Purpose: Provide deterministic scheduling for control loops, ISR timing, and periodic FreeRTOS tasks.
    - Usage: Timers drive high-frequency DAC updates for galvo positioning and trigger ADC sampling routines
    - Constraints: High-priority control loops require microsecond-level precision with minimal jitter
6. Direct Memory Access (DMA)

- Purpose: Transfer DAC and ADC data without CPU intervention to ensure precise real-time control.
- Usage: Galvo control loops and analog sampling leverage DMA to offload repetitive data movement
- Constraints: Configured to prevent resource conflicts with FreeRTOS tasks and minimize latency.

7. UART / Serial Interface
    - Purpose: Debugging, telemetry, and optional wired communication with host PC or LightBurn
    - Usage: Status Reporting Task sends system metrics and logs through non-blocking queues to UART.
    - Constraints: Communication must not interfere with timing-sensitive galvo control loops.
8. Bluetooth (Classic + BLE)
    - Purpose: Wireless configuration, job transmission, status reporting and OTA firmware updates.
    - Usage: Managed on a dedicated ESP32 core using NimBLE host stack under FreeRTOS. Status messages and commands are exchanged asynchronously.
9. Flash / Non-Volatile Memory
    - Purpose: Store configuration parameters, calibration data, and audit logs of safety events.
    - Usage: Accessed through controlled tasks to prevent blocking time-critical loops.
    - Constraints: Use checksums and factory reset mechanism to recover from corruption or failed updates.
10. Watchdog Timer
    - Purpose: Ensure system safety by detecting software stalls or critical task failures.
    - Usage: Refreshed only after all safety and control checks pass
    - Constraints: Must preemptively shut down the laser if safety or timing violations are detected.

The software peripherals of the ESP32 are fully leveraged under a FreeRTOS-based firmware architecture to achieve deterministic galvo control, laser modulation, and wireless communication. By isolating critical real-time tasks from asynchronous communication and logging, the system ensures safe, reliable, and precise laser operation while maintaining compatibility with LightBurn and OTA firmware updates.

3.6.7 Synchronization and Safety Considerations

FreeRTOS's synchronization primitives –semaphores, mutexes, and event groups –enable safe and deterministic coordination between concurrent subsystems. For instance, when the Galvo Task is moving to a new coordinate, the Print Task must wait for confirmation before activating the laser. A counting semaphore ensures this sequence is strictly enforced. This synchronization ensures safe, real-time coordination between beam positioning and laser output –critical to both engraving precision and operator safety. In addition, FreeRTOS timers and interrupt service routines (ISRs) will manage hardware–triggered events such as limit switches, interlocks, or emergency stop conditions [FreeRTOS, 2018; TI-RTOS, 2023].

By leveraging FreeRTOS on the ESP32 MCU, the firmware achieves deterministic task scheduling, modular scalability, and safe concurrency management. Each subsystem –printing, galvo control, and communication is implemented as a task with precise timing and isolation. The LightBurn –compatible control layer ensures seamless user integration while maintaining hardware –level precision through DAC –driven galvo positioning. Together, these architectural choices provide a robust foundation for a professional –grade laser marking system that is both scalable and industry–compatible.

3.7 Bluetooth Wireless Communication

The ESP32 was selected for this project due to its dual-core architecture, combining a high-performance Tensilica Xtensa LX6 processor for application-level control and a dedicated wireless subsystem for managing both Bluetooth Low Energy (BLE) and Wi-Fi communication [ESP32 Technical Reference Manual, 2025]. This design allows concurrent execution of real-time tasks without interrupting wireless throughput. The integrated radio operates under the Espressif Bluetooth controller, which runs alongside FreeRTOS without requiring a secondary coprocessor, simplifying both timing coordination and firmware development.

FreeRTOS tasks execute critical real-time operations such as galvo position updates, pulse modulation, and interlock management, while the wireless stack maintains a consistent Bluetooth connection for telemetry and configuration. This separation of timing-sensitive control from asynchronous communication ensures deterministic performance, even during high-frequency scanning or user command bursts.

Bluetooth Role and Application Integration

Within the system, Bluetooth communication serves several key roles:

1. **Remote Control and Configuration**

Users can wirelessly interface with the laser printer via a PC or mobile device using LightBurn or a custom-built companion app. Through Bluetooth Serial (SPP) or BLE GATT profiles, users may send motion commands, adjust engraving parameters, and modify scan profiles without requiring a direct USB or UART connection [Bluetooth SIG, 2024][Bluetooth Serial Integration, 2023].

2. **Status Monitoring and Diagnostics**

The ESP32 periodically transmits operational metrics –such as temperature, system task health, and galvo position feedback –to a paired host device for real-time diagnostics. This communication is handled through non-blocking FreeRTOS queues, allowing background telemetry to occur without disturbing motion timing.

3. **Firmware Updates Over-the-Air (FOTA):**

Using the ESP-IDF OTA API, firmware can be securely updated wirelessly via Bluetooth or Wi-Fi, improving maintainability and minimizing physical service requirements. OTA support also facilitates iterative firmware testing and future software expansion [ESP-IDF Programming Guide, 2025] [PlatformIO: Open-Source Ecosystem for IoT Development, 2024].

3.7.1 BLE Stack and Firmware Layering

Espressif's ESP-IDF framework provides a fully integrated Bluetooth 5.4-compliant stack, implemented through the NimBLE host and BT Controller components. The Bluetooth controller operates in coordination with the FreeRTOS kernel, while the NimBLE host runs as an independent task that handles GATT operations, connection events, and data exchanges asynchronously.

This layered architecture enables clean isolation between real-time motion control and communication routines. Inter-task communication follows a queue and semaphore model, ensuring thread-safe event handling across system boundaries. For instance, a dedicated "Status Task" can post diagnostic messages to a shared queue that the "Bluetooth Task" retrieves and transmits to the host device at periodic intervals, maintaining precise timing across all system layers.

The result is a highly modular and deterministic firmware structure that balances real-time control accuracy with low-latency wireless responsiveness, fully aligning with the needs of an industrial-grade galvo laser printing system.

3.7.2 LightBurn and Bluetooth Compatibility

Although LightBurn typically communicates via USB or serial interfaces, the ESP32's Bluetooth capability allows emulation of a virtual COM port via SPP (Serial Port Profile) or a custom GATT-based protocol for wireless command and data exchange [LightBurn Documentation, 2024; Bluetooth SIG, 2023]. This enables LightBurn or equivalent host software to interact with the controller without physical tethering, improving safety and usability in confined or enclosed steps.

Using NimBLE (ESP-IDF) for BLE communication provides secure pairing, low-latency transmission, and efficient packet handling, ensuring stable communication even while FreeRTOS handles real-time control tasks.

3.7.3 Bluetooth and Wireless Communication Risks

Interference and Range Limitations: BLE operates in the 2.4 GHz ISM band, which is prone to interference between Wi-Fi routers and other Bluetooth devices. This can result in dropped packets or lag in command transmission from Lightburn [Bluetooth SIG v5.4; TI BLE Interference Whitepaper].

Data Throughput Constraints: BLE 5.4 offers limited bandwidth compared to wired UART or USB connections. Large raster image data or vector job streams may need to be buffered or compressed before transmission, potentially increasing latency [STM32 BLE Throughput Note; Nordic BLE Data Rate Analysis].

Connection Dropouts: Loss of BLE connection during active laser operation could cause incomplete print cycles or unexpected halts. Implementing a timeout-based safe shutdown or “pause state” is critical to prevent hardware damage or unsafe conditions [ST BLE Stack Manual, 2023].

3.7.4 LightBurn Integration and Software Compatibility

Protocol Mismatch: LightBurn primarily supports standardized controller protocols (e.g., EZCAD). If custom firmware deviates from expected G-code or Galvo command structures, the connection may fail or produce inaccurate motion [LightBurn Docs, 2024].

Unsupported Wireless Configurations: LightBurn is optimized for serial (USB/UART) communication. BLE-to-serial emulation layers may introduce additional latency or incompatibility if not implemented with flow control and error correction [LightBurn Community Forum, 2023].

Calibration Inconsistencies: Incorrect mapping between LightBurn's coordinate system and galvo mirror angles can lead to distorted prints. A calibration routine must be implemented to align physical and logical coordinates [LightBurn Calibration Guide, 2024].

3.7.5 General Safety Considerations

Laser Activation Timing Errors: A synchronization fault could cause the laser to fire while galvos are stationary or moving to the next coordinate, resulting in burns or unintended markings. Hardware-level safety interlocks and beam-enabled gating are required [OSHA Laser Safety, 2023].

Emergency Stop Responsiveness: In a real-time system, interrupt latency must be low enough to guarantee that the laser shuts off immediately when an emergency stop or fault signal is triggered [ST Interrupt Handling Note, 2023].

Overheating or Overcurrent Conditions: Prolonged high-power laser operation without adequate cooling or current limiting can lead to component degradation. Firmware should include temperature monitoring and automatic power throttling [Coherent Thermal Management, 2022].

3.8 Mechanical Subsystems

The mechanical part of the project includes the paper feed, motion stages, and frame. Since our design relies on very small, repeatable movements, we compared multiple types of motors to see which could deliver good precision without adding unnecessary complexity or cost.

Table 7: Motor Technology Comparison

Motor Type	Principle	Pros	Cons	Suitability for LIP

Stepper Motor	Moves in fixed steps	Precise position control, high torque at low speed, simple open-loop, affordable	Can lose steps, vibration at some speeds, limited high-speed torque	Best choice for precise X–Y laser motion
DC Motor (Brushed)	Speed proportional to applied voltage	Simple, low cost, widely available	Wears over time, poor precision, needs encoder for feedback	Good for paper feed or non-critical motion
Servo Motor	Closed-loop with encoder feedback	High torque, precise control, smooth motion	Expensive, complex driver setup	Suitable for high-speed or industrial LIP versions
BLDC Motor	Electronic commutation replaces brushes	Efficient, quiet, long life, high torque-to-weight	Needs controller, higher cost, limited incremental precision	Good for continuous feed or scanning tasks
Linear Actuator	Converts electrical input to direct linear motion	Accurate, compact, no belts/gears	Costly for long travel, less durable for repeated motion	Optional for vertical feed or fine Z-axis control

Stepper motors move in precise, fixed steps, giving them excellent position control and strong torque at low speeds while staying affordable and easy to drive in open-loop setups. Their downsides are potential missed steps, some vibration, and weaker high-speed torque, but they remain the best fit for precise X–Y motion in laser positioning systems.

DC brushed motors offer simple operation with speed proportional to voltage, making them cheap and widely available for general motion. However, they wear over time, lack precision, and require encoders for accurate control, so they’re mainly suited for non-critical tasks like paper feeding or basic transport mechanisms.

Servo motors use closed-loop feedback to provide high torque, smooth rotation, and very accurate position control, making them ideal for demanding or high-speed applications. They are more expensive and require more complex drivers, but they're a strong choice for advanced or industrial versions of motion systems.

BLDC motors use electronic commutation instead of brushes, resulting in high efficiency, quiet operation, long lifespan, and excellent torque-to-weight ratio. They still need a dedicated controller and don't offer the fine incremental positioning of a stepper, but they work well for continuous-motion tasks like scanning or feeding.

Linear actuators directly convert electrical input into linear motion, offering compact, accurate travel without belts or gears. They tend to be costly for long-distance movement and can wear under frequent cycling, so they're best used for optional vertical feed mechanisms or fine Z-axis adjustments.

After comparing the options, we chose bipolar stepper motors for the paper feed, the NEMA 11 geared stepper is used to handle the paper feed since it doesn't need much torque or speed.

Table 8: Frame Material

Material	Properties	Pros	Cons	Suitability for LIP Frame
Aluminum (6061 / 5052)	Light, strong, corrosion-resistant	Rigid, easy to machine, good heat control	Costly, carries vibration	Works best for our frame setup
Acrylic (PMMA)	Clear plastic	Light, easy to laser cut, cheap	Brittle, weak under heat	Okay for covers, not for frame
Steel (Mild / Stainless)	Heavy, very strong	Very rigid, stable	Heavy, harder to cut	Only needed for large builds

Polycarbonate (PC)	Tough plastic	Strong, flexible, durable	Scratches easy, pricier	Good for mounts or shields
Wood (Plywood / MDF)	Low-cost composite	Cheap, easy to work with	Warps, burns, weak	Fine for test builds only

Aluminum (6061/5052) is a lightweight, strong, and corrosion-resistant material that machines very well and provides excellent rigidity and heat control. Its main drawbacks are cost and its tendency to carry vibration, but overall it's one of the best choices for a structural frame, especially in systems that need precision and durability.

Acrylic (PMMA) is a clear, lightweight plastic that is very easy to laser-cut and inexpensive, making it great for cosmetic covers or panels. However, it is brittle and performs poorly under heat or mechanical stress, so it isn't suitable for load-bearing frame components.

Steel, whether mild or stainless, offers extremely high strength and stiffness, making it ideal for large, heavy, or high-stability builds. The trade-off is that it is heavy, more difficult to machine, and often overkill for small systems, so it's typically only used when maximum rigidity is required.

Polycarbonate (PC) is a tough, flexible, and impact-resistant plastic that is more durable than acrylic and works well for protective mounts or shields. Its downsides are that it scratches easily and tends to be more expensive, but its mechanical resilience makes it valuable for safety-critical or high-impact parts.

Wood materials like plywood or MDF are very low-cost and easy to work with, making them convenient for quick prototypes or test fixtures. They warp, burn, and lack mechanical strength, so they're generally unsuitable for long-term or precision builds, but they're perfectly adequate for early concept testing.

From our frame material comparisons, aluminum turned out to be the best overall choice. It's rigid, lightweight, and relatively easy to machine, which helps with maintaining alignment for the optical system. Even though it costs more than acrylic or wood, it gives the stability we need for accurate motion during printing.

3.8.1 Cooling system comparison

Table 9: Cooling System Comparison

Cooling Option	Complexity / Cost	Reliability	Pros	Cons	Suitability for LIP
Passive Heatsink	Low	Very high	Silent and cheap with no moving parts	Limited cooling and depends on airflow	Works fine for low power lasers or test setups.
Heatsink + Fan	Low to Moderate	Good	Good cooling and easy to mount	Fan noise and dust buildup	Used in our build to help keep temps stable.

A passive heatsink is the simplest and most reliable cooling option since it has no moving parts and costs very little. It operates silently and works well when heat loads are low, but its performance depends heavily on ambient airflow, so it can struggle with higher-power components. This makes it suitable for low-power lasers or controlled test setups where temperatures don’t rise quickly.

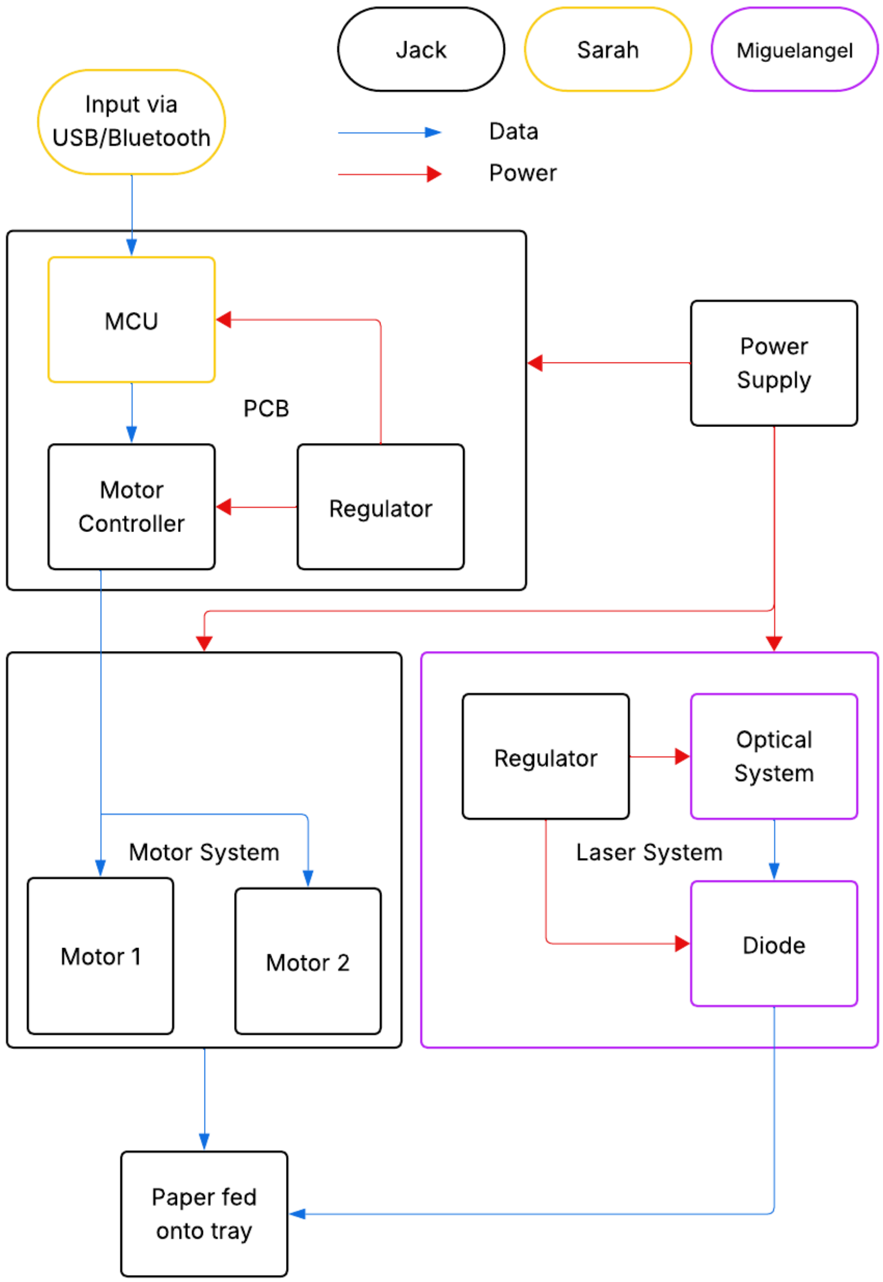
A heatsink paired with a fan provides much better cooling performance and is still relatively easy to mount, making it a practical choice for keeping temperatures stable during operation. While it introduces fan noise and potential dust buildup over time, the added airflow significantly improves heat dissipation. This approach is ideal for builds that need active cooling to maintain consistent thermal performance.

Based on the cooling comparison, we went with a heatsink and fan setup. It’s simple, compact, and offers plenty of cooling for our laser and drivers without adding extra maintenance or cost.

3.8.2 Electrical Subsystem

The electrical system provides regulated power for the microcontrollers, motors, and the laser. Each stepper motor and the laser diode need separate current regulation to work properly. We use a 12 V DC supply as the main input, and onboard regulators step it down to 5 V and 3.3 V for control logic and sensors.

Figure 10: Power Distribution and Requirements



Our design needs stable DC voltage to run the logic, motors, and optics safely. We reviewed multiple options including wall adapters, chassis-mounted supplies, and battery packs.

After comparing them, we picked a regulated 12 V, 5 A adapter since it provides enough power for all subsystems, includes built-in protection, and keeps the system simple to assemble and maintain.

Table 10: Power Supply Options

Power Source	Voltage / Current	Portability	Efficiency	Cost	Notes
Wall Adapter (120V→12V DC)	12 V @ 2 A	Stationary	85–90%	$10	Used in LIP system
Rechargeable Li-ion Pack	11.1 V @ 2 A	Portable	80%	$25	Future portability option
Bench Power Supply	Variable	Stationary	95%	$100+	For lab testing only

A standard 12 V wall adapter is the most practical choice for a stationary prototype because it provides a stable, regulated output with good efficiency and very low cost. It removes the need for charging circuitry and keeps testing consistent, which makes it ideal for early development or permanent installations.

A rechargeable 11.1 V Li-ion pack offers the advantage of portability, making it suitable for future versions of the system that need to operate away from an outlet. Although it's slightly less efficient and more expensive than a wall adapter, its ability to power the device on the go makes it valuable for mobile or field-use scenarios.

A bench power supply provides adjustable voltage, high accuracy, and excellent efficiency, making it the best option for lab testing, debugging, and characterization. However, its high cost and stationary nature limit it to development environments rather than practical deployment.

3.8.3 Energy Source Selection

While battery packs could allow portability later, the fixed adapter is safer and easier to manage for our current prototype. It also keeps testing consistent and avoids charging issues.

Table 11: Regulator Options

Regulator Type	Example IC	Efficiency	Output Ripple	Cost	Notes

Linear (L7805)	L7805CV	60–70%	Very Low	$0.50	Simple and low noise but inefficient at high loads
Buck Converter	LM2596S	85–90%	Moderate	$1.50	High efficiency and ideal for main 12V to 5V/3.3V rail
Synchronous Buck	MP2307	92%+	Moderate	$2.00	Compact and efficient with a lower heat output
SEPIC / Boost	LM2577	80–85%	Moderate	$3.00	Useful for mixed-voltage or battery systems

Linear regulators like the L7805 are straightforward to use and provide extremely low output ripple, making them great for sensitive analog or low-noise digital circuits. However, with only 60–70% efficiency, they waste a lot of power as heat at higher loads, so they're mainly suitable for low-current sections where simplicity and clean output matter more than efficiency.

Buck converters such as the LM2596 step down voltage much more efficiently, typically around 85–90%, which keeps heat generation low and makes them ideal for converting something like 12 V down to 5 V or 3.3 V for the main digital rails. Their moderate output ripple is usually acceptable in most embedded systems, and their cost efficiency makes them a strong default choice.

Synchronous buck converters like the MP2307 improve on traditional buck designs by using MOSFETs instead of diodes, boosting efficiency above 92%. This makes them excellent for compact designs where thermal constraints are tight. They deliver solid performance with moderate ripple and reduced heat output, making them well-suited for power-dense embedded boards.

SEPIC and boost converters such as the LM2577 are useful when the input voltage can swing above or below the target output, like in battery-powered systems. Their 80–85% efficiency is lower than a buck converter, but the versatility of maintaining a stable output under varying conditions makes them ideal for mixed-voltage or regulated battery applications.

To create our 5 V and 3.3 V rails, we will use a buck converter (LM2596) for the main step-down from 12 V and LDO regulators for low-noise circuits. This combination keeps efficiency high while limiting electrical noise that could affect the control system.

Table 12: Power Requirements Table

Component	Supply Voltage	Estimated Current	Notes
Raspberry Pi 4 Controller	5 V DC	2.5 A	Main control and communication hub
Stepper Motors (X, Y, Feed)	12 V DC	1.2 A each	Driven by A4988 drivers with independent channels
Laser Diode (405 nm)	5 V regulated	1.5 A peak	Constant-current driver with PWM modulation
Cooling Fan	12 V DC	0.2 A	Provides airflow for laser and drivers
Display / User Interface	5 V DC	0.1 A	Touchscreen or OLED status display
Sensors / Limit Switches	3.3 V DC	0.05 A	Input protection and filtering included

The Raspberry Pi 4 controller requires a stable 5 V rail at roughly 2.5 A and serves as the primary processing unit for motion control, communication, and system coordination. Its role as the central hub means its power rail must remain isolated from motor noise, and the note indicates its function as the main control interface, reinforcing the need for a clean and reliable supply.

The stepper motors operate from a 12 V source and draw about 1.2 A each under load. Their consumption is determined by the A4988 drivers, which independently regulate current per motor. The note clarifies that each axis receives its own driver channel, which affects how power is distributed and ensures that load variations on one axis do not interfere with others.

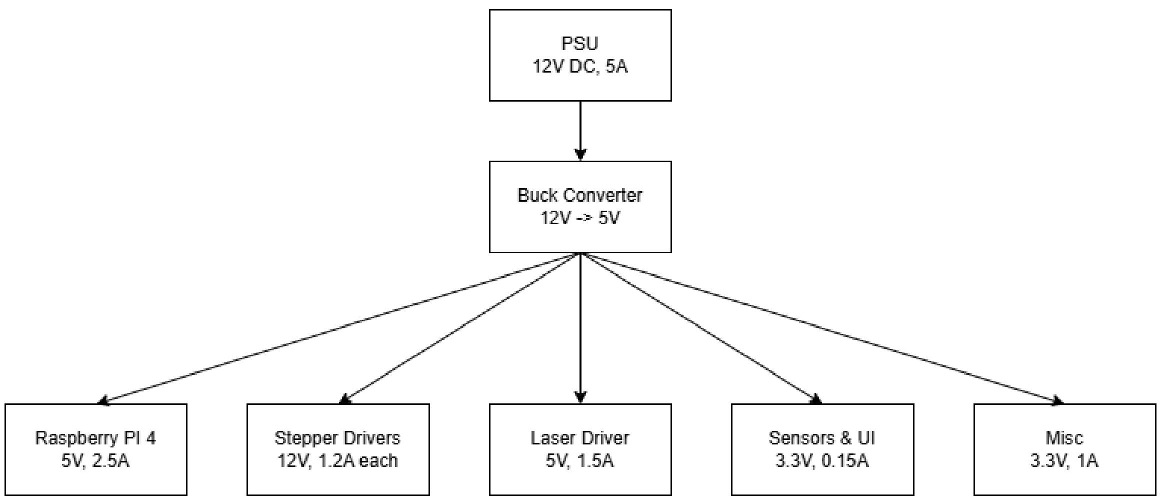
The 405 nm laser diode runs from a regulated 5 V supply and draws up to 1.5 A during peak emission. Its constant-current driver with PWM modulation controls optical output while preventing overcurrent damage. The note emphasizes this driver arrangement, which dictates that the diode’s current spikes must be accounted for in the 5 V power budget.

The cooling fan is powered by 12 V and consumes approximately 0.2 A, providing airflow across the laser and driver electronics. The stated function in the note confirms that active cooling is a thermal management requirement, meaning its supply must remain continuous whenever the system is active.

The display or user interface draws 0.1 A from the 5 V rail and provides operational feedback through either a touchscreen or an OLED module. The note clarifies the display type, which affects both current draw and electromagnetic noise considerations for routing and regulation of the 5 V supply.

The sensors and limit switches run on 3.3 V at about 0.05 A and are used for positional referencing and motion safety. The note highlights that input protection and filtering are included, indicating that the 3.3 V rail must remain clean and that these components require stable logic-level power for consistent triggering.

Figure 11: Power Distribution Diagram



This prototype diagram serves as a clear map for structuring the power distribution, showing how a 12 V supply feeds each subsystem through the buck converter and direct 12 V lines. By laying out the current requirements for the Raspberry Pi, stepper drivers, laser module, sensors, and miscellaneous 3.3 V components, it helps verify that the PSU can handle the combined load and that each device receives the correct voltage. It also provides a straightforward reference when wiring the system.

Table 13: Summary of Selected Technologies

Category	Component	Specification	Notes
Main Controller	Raspberry Pi 4 Model B	Quad-core @ 1.5 GHz, 4 GB RAM	Main system controller; easy to code and connect.
Motor Controller	Arduino Mega 2560	8-bit MCU @ 16 MHz	Handles real-time motor control; simple and reliable.
Laser Module	405 nm Laser Diode	~1.5 A peak, focusable lens	Good engraving contrast and low cost.
Laser Driver	Constant-Current PWM Driver	5 V in, 1.5 A out	Keeps laser power stable with PWM control.
Motion System	NEMA 17 (X/Y) + NEMA 11 (Feed)	1.8°/step, A4988 drivers	Accurate motion; smaller feed motor saves space.
Frame Structure	Aluminum 6061	Lightweight, rigid, machinable	Strong and easy to cut in the lab.
Cooling System	Heatsink + 12 V Fan	40×40 mm aluminum block	Simple cooling setup that worked well.
Power Supply	12 V DC Adapter (5 A)	Regulated with protection	Enough current for all parts; safe and simple.
Voltage Regulation	LM2596 + L7805 LDO	12 V → 5 V → 3.3 V	Efficient step-down with low noise.
Software Platform	Python + Arduino IDE	Control scripts and firmware	Python for coordination, Arduino for motion.

Power Budget	~50 W (12 V×4.2 A)	—	Includes all subsystems with 25% margin.

After comparing several technologies and testing smaller subsystems, we selected components that offered the best mix of performance, safety, and affordability. The final setup includes a 405 nm laser diode, NEMA 17 stepper motors, a Raspberry Pi 4 for coordination, and an aluminum frame for rigidity.

This combination gives us accurate motion control and enough computing power to expand later on, such as adding multiple lasers or automated calibration. Our modular 12 V DC power system and cooling setup also make the prototype easier to maintain and safer to operate during extended use.

Chapter 4: Standards and Design Constraints

For any senior design project, constraints should be considered, as time will be limited with no opportunity for delay. They create limitations on the scope of our project when everything is considered. Time, cost, and safety affected the choice of material and overall design schematic for this project.

4.1 Cost Constraints

The cost of components played a large part in the components utilized in this project. We were not sponsored, so all materials were paid for out of pocket by each group member. The scope of our design was most limited, as a larger budget would have enabled us to use higher-quality materials to improve the overall design. Our galvo engraver design, in tandem with the previous mechanical setup, could create a viable printer if capital were not a significant constraint.

4.1.1 Optics Cost Constraints

The cost of optical components significantly influenced our component selection. We wished to test the effects of a green diode for this project, as a blue diode had been proven to work in the previous project. However, finding a single-mode high-powered green laser diode proved most troublesome, as several high-quality ones were priced beyond this project’s scope. We found a reasonably priced multi-mode diode, but even this component was expensive on its own, and the cost of replacement would be significant.

A reliable laser galvo setup also proved expensive. ThorLabs laser galvos and f-theta lenses exceeded our budget by multiple magnitudes. The galvo we found on Amazon and the multi-lens setup are cost-effective and fit the budget we set for ourselves. However, how they'll perform is questionable at present. As we further test, we expect some parts to break or require replacement, so further cost increases are to be expected.

4.1.2 Social, Environmental, and Ethical Constraints

Social and political constraints shape designs by favoring a group or a way of thinking over others. This design doesn't favor a political or social group over another, and no prior knowledge is required to use the LIP system.

Ethically, we understand this can lead to replacing printer ink cartridges, thus displacing the jobs of those who design the printers currently available. This product, were it to become mainstream, would encourage the replacement of this printer type as companies migrate to creating their own designs as a standard.

Considerations must be made if a product produces harmful chemicals or could harm living creatures if they come into contact with it. UCF's EHS provides several rules that explicitly encourage avoiding products that target living creatures directly without proper safeguards. With too high a power, our laser can potentially cause the paper to combust, so integrating some form of temperature detection in the design is crucial. The most dangerous part of our design is the Class 4 laser; direct exposure can cause significant damage to the naked eye. Eye-wear is planned for use during construction. To address user safety, an appropriate viewing window will be installed to protect others from possible reflections from the laser. Furthermore, we plan to fully encase our laser, except for a small output beam used for engraving.

Regarding environmental impact, the E.L.I.P. is intended to provide an ink-free alternative to paper printing. The use of a laser prevents the production of harmful chemicals during operation and eliminates the need for chemically hazardous cartridges to reload the printer.

4.1.3 Economic and Time Constraints

Laser engravers and the parts to design them are incredibly expensive. As mentioned before, reliable galvos and f-theta lenses are priced between $1,500 and $ 5,000. Given our budget, we had to make careful choices about our components. Compared to the previous design, we're not planning to use a mechanical system because we lack an additional EE to integrate it into our PCB setup. This allows room in the budget for other parts of our design, such as 3D-printing our laser encasing, or incorporating a laser galvo.

Should our design move to market, it would compete with traditional printers and engravers. We do not have the flexibility of a mobile gantry in our design, but using a galvo would drastically improve speed compared to the previous design. With enough power, the laser may be able to engrave non-paper material, but this is not our ultimate goal. While a class 4 laser, the E.L.I.P.’s planned laser diode won’t have enough power to mark metal, wood, or plastic.

Time served as a significant constraint for our design. We had the Fall 2025 and Spring 2026 semesters to write, design, prototype, and eventually create a working prototype of our project. Furthermore, each member in this group either worked and/or took other classes in addition to Senior Design. We have the fortune of building on the previous group’s work as a foundation, but incorporating the new aspects discussed in this paper will take up most of the group's time. The skills we have developed at the University of Central Florida will be put to the test. Planning time to work on the project and maintaining a schedule will be essential for success on our final demo day.

4.1.4 Design Constraints

The following subsections discuss constraints relating to several aspects of our project design. We cover general design, PCB design, temperature, power supply, and size constraints that affected our project.

4.1.5 General Design Constraints

Our goal is to take the Laser Inkless Printer and build on the previous work by introducing technologies they considered but could not afford to test due to cost or time constraints. Though we have their work as a solid foundation, there are still some constraints for our design that affect our project. One of the largest constraints was the cost of a reliable laser galvo and f-theta lens. We planned to reduce the budget for the previous design, but the price of either of the new technologies would exceed our budget by several orders of magnitude. We found some alternatives, but their quality will require further testing and, most likely, replacement.

Our lens design also proved a significant constraint. Laser engravers that use a galvo often require an f-theta lens to maintain the laser’s focus and provide a flat image field during engraving. Our lens design’s purpose is to simulate that effect, but whether it will work remains to be tested. Faculty have mentioned that the design can work with, but the theory requires testing.

In our group, we decided against using a mechanical gantry to avoid overloading our members. So, we'll be creating a 3D-printed casing for all of our electrical and optical components. This will require proper knowledge in 3D printing to ensure our design is sound and won't fall apart during operation on the final demo day.

Maintaining a balance of speed and resolution will be crucial for our updated design. We want the E.L.I.P. to act like a laser pen, drawing the input text as if a person were writing. We won't be able to traverse the entire page, but the speed would increase drastically with the galvo.

4.1.6 Software Development Constraints for Galvo Laser Control High-Level Goals (must-haves):

The software for galvo laser control must adhere to strict safety, timing, and modularity standards. The system must never allow the laser to operate without a verified safety interlock and a functioning watchdog, in accordance with OSHA laser safety guidance. Control loops driving the galvos must be deterministic and meet real-time deadlines derived from the galvo bandwidth specifications (Thorlabs scan-head datasheet). Additionally, software must be modular, testable, and traceable, including unit tests and integration tests, to ensure maintainability and reliability.

4.1.7 Real-Time Control and Timing Constraints

Control Loop Frequency: The control update frequency is determined from the galvo specifications. Standard practices dictate that the control loop frequency should be at least ten times the closed-loop bandwidth of the galvos. This ensures stable digital control and minimizes phase lag.

Hard Real-Time Loop Constraints: Worse-case loop execution time (WCET) must be measured, and latency must remain below the loop period. Jitter should be minimized, ideally below 100 microseconds for kHz-range loops. Hardware timers and DMA should be used for analog output and ADC sampling whenever possible to reduce CPU load.

Watchdog and ISR Design: A hardware watchdog must only be refreshed after all safety checks pass. Interrupt Service Routines (ISRs) must be kept short, capturing timestamps, setting flags, and writing to lock-free buffers, while heavy processing is deferred to RTOS tasks. DMA and timer triggers should be employed for ADC and DAC to maintain precise timing [Thorlabs].

4.1.8 Microcontroller-Level Constraints

Processing Bottlenecks: Although the ESP32 series features dual-core architecture, intensive DAC operations, Bluetooth communication, and multitasking under FreeRTOS can still lead to CPU contention during high-frequency galvo control. This contention may introduce timing jitter in time-critical loops if FreeRTOS task priorities and core pinning are not carefully managed [Espressif Documentation, 2025; FreeRTOS Docs]. The control loop should be explicitly assigned to a dedicated core using task affinity to prevent interference from non-real-time tasks such as communication or logging.

Memory and Peripheral limitations: The ESP32 shares Flash and SRAM resources across the FreeRTOS kernel, Bluetooth stack, and control application. Excessive stack allocation or dynamic memory use can lead to heap fragmentation and watchdog resets. Using static allocation and pre-sized buffers in conjunction with “heap_caps_malloc()” for DRAM/IRAM separation ensures stability during long print cycles [ESP-IDF API Reference, 2025]. Peripheral access (DAC, ADC, SPI) should be coordinated through DMA channels to reduce CPU load and maintain precise analog timing for galvo signals.

Thermal and Electrical Noise: High-frequency DAC output and wireless transmissions on the ESP32’s 2.4 GHz radio can introduce electromagnetic interference if analog routing and ground planes are not properly isolated. Analog outputs to the galvo driver should use low-impedance paths and hardware filtering, while sensitive ADC inputs should be physically shielded or averaged in software to mitigate RF coupling [Analog Devices Layout Guide, 2023; Espressif Hardware Design Guidelines, 2025].

Firmware Update Failures (FOTA): During Over-the-Air (OTA) updates via Bluetooth or Wi-Fi, power loss or disconnection may corrupt flash memory. To avoid bricking the MCU, ESP-IDF's dual-partition OTA scheme should be used, with rollback protection and integrity checks via SHA256 validation [ESP-IDF OTA API, 2025]. This mechanism ensures a safe fallback image is always available.

4.1.9 RTOS and Software Environment Constraints

Task Starvation and Priority Inversion: Improper task prioritization or lack of mutex handling can lead to low–priority tasks blocking high–priority control loops. Implementing priority inheritance mechanisms and watchdog monitoring is critical for maintaining real-time guarantees [FreeRTOS Priority Inheritance, 2023; DigiKey TechForum].

Timing Drift and Jitter: Even with deterministic scheduling, timing drift can accumulate if the system clock is not synchronized or if tasks block longer than expected. Regular calibration and use of hardware timers are required to maintain consistent beam motion [STM32 Reference Manual, 2023].

Concurrency Errors: Shared resource conflicts (e.g., SPI bus, DAC interface) may occur if semaphore or mutex protection is misused. Such synchronization bugs can lead to erratic laser pulses or incomplete print jobs [FreeRTOS Mutex Docs].

Debugging Complexity: Multithreaded systems are inherently difficult to debug due to non-deterministic execution. Race conditions or riming anomalies might not appear consistently, requiring advanced debugging tools such as STM32CubeMonitor [ST Debug Tools Guide, 2023].

4.1.10 RTOS Concurrency, Scheduling and Synchronization Constraints

Scheduler and Task Design: A preemptive scheduler is used for control tasks, pinning critical loops to the highest real-time priority. Long blocking calls are avoided in high-priority tasks; ISRs capture data and defer processing via queues to lower-priority tasks. Shared resources are protected with mutexes only when necessary; queue or message passing is preferred for exchanging sensor and command data [FreeRTOS].

Priority Inheritance and Monitoring: Priority inheritance is enabled to prevent priority inversion. Task priorities and CPU utilization are documented to ensure safety diagnostics, interrupts and timing constraints are met.

Synchronization Between Subsystems: Synchronization is enforced between laser activation, galvo positioning, and motion acknowledgement using FreeRTOS primitives, including semaphores, mutexes, and events. For example, the Print task waits for a semaphore from the Galvo Task to confirm mirrors are in position before enabling the laser. This prevents laser pulses during transitional motion, protecting hardware and operators.

Safety Supervisory Task: A Safety Supervisory Task continuously monitors watchdog status, temperature thresholds, and BLE connectivity. Any safety violation immediately triggers a laser disable interrupt, resets the safety relay, and logs the event to nonvolatile memory.

4.1.11 Software architecture & design constraints

Layered Architecture: By this we want our layers to be something like, hardware abstraction layer (HAL), driver layer (DAC/ADC/PWM/GPIO/comm), control algorithms, application UI, and safety supervisor. This would be in sequential order from left-to-right for the developing done on the software side. We will also need to ensure that the PCB design will also incorporate some of these software constraints into the design. Control algorithms must be time deterministic, use fixed-values or documented floating-point values (for specific precision), and saturation handling for the galvo laser control. Configuration parameters must be stored in nonvolatile memory and have checksum as well as a “factory reset” just in case anything fails and causes catastrophic failure onto our system.

4.1.12 Hardware interface & electrical constraints

For the galvo scan-head specification is referenced in the guide for the electrical limits regarding max input voltage, input impedance, recommended analog ranges. The software DAC output range to the safe range mentioned in the Thorlabs specification. We also must use dedicated DAC or high-resolution PWM and filter analog command outputs for galvo drivers; avoid toggling DAC settings in the ISR that can potentially cause jitter. While protecting inputs/outputs sanity checks (e.g., clamp values, detect out of range ADC readings) and fail safe on fault.

4.1.13 Safety, laser interlocks & operational constraints

Laser only enabled when hardware interlock is closed, safety key present (if essential), temperature within limits, and software watchdog OK. Failure occurs then immediate laser disable and document/log. We then will continuously monitor interlock pins, key switches, temperature sensors, and current/voltage fault indicators. When any value is out of the specified range or the interlock opens, immediately trigger a fail-safe and disable laser drive. Then we will continue to keep track of the motors/power converters electrically isolated from sensitive ADC or DAC circuits. Use digital filtering and sanity checks in software to detect bad samples or bad values (for PCB design).

4.1.14 Communications, protocols & operations

As mentioned above, in chapter 3 we will be using a BLE (Bluetooth device) to send print jobs to the system. In order to accomplish good communication tactics, we ensure communications stack (BLE/USB/UART) is nonblocking with bounded buffers. Communications must not be able to directly assert laser enable without supervisor and authentication. For host integration, Lightburn is a viable option for integrating with LightBurn. We follow the supported device/protocol guidance and preferred transport (Network or Bluetooth serial gateways). Then we will authenticate/control access to laser-enabled commands. Log all enable and disable events and the issuing source (LightBurn Document). We will also provide timestamped logs for faults, safety events, interlock changes, and actual galvo positions (position feedback). We will save the audit log of critical safety events for later experimentation and logging.

4.1.15 Synchronization and Safety Considerations

By leveraging the ESP32’s dual-core architecture, real-time control and wireless communication remain isolated. One core (typically APP_CPU) executes deterministic control and safety logic under FreeRTOS, while the second core (PRO_CPU) handles the Bluetooth stack and network transactions. This division prevents timing jitter in safety –critical galvo control tasks, even during wireless data transfer or logging operations [Espressif, 2025; Bluetooth SIG v5.4].

FreeRTOS synchronization primitives –including queues, semaphores, and task notifications –ensure deterministic coordination between subsystems such as the Galvo Task, Print Task, Bluetooth Task, and Safety Supervisor. For example, before enabling the laser output, the Print Task receives a semaphore from the Galvo Task confirming both mirrors have reached their commanded coordinates. This prevents unsafe laser activation during motion. The ESP-IDF timer and event loop libraries further provide low-latency callbacks for safety-critical interrupts (e.g., interlock faults, watchdog resets, or overtemperature events), maintaining system integrity under real-time constraints.

4.1.16 PCB and Embedded Hardware Interface Considerations

Software timing and safety constraints directly affect/influence the PCB layout and component selection. According to Analog Devices *'Mixed-Signal PCB Layout Guidelines' (2023)'*, analog galvo command signals (DAC outputs) must be isolated from high-frequency digital traces and BLE lines to prevent coupling noise and drift. The PCB should maintain separate analog and digital ground planes with a point of connection near the power entry. To minimize DAC switching noise and timing skew: The MCU's DAC peripheral should drive differential, low-impedance signal paths with RC filtering at the output stage. Analog traces must be protected and routed to the galvo driver for inputs as specified in the ThorLabs datasheet. The PCB design must also include watchdog-controlled power gating for the laser enable. In the event of a thermal fault or watchdog timeout, the hardware circuit must automatically drop the laser enable signal-independent MCU firmware complying with the OSHA Class 4 laser safety results.

4.1.17 PCB Design Constraints

According to the guideline given for this project, the PCB must include at least one MCU, an integrated power supply network, and all required peripheral interfaces. Solderless or multiple development boards are NOT allowed in final design. For power regulation, we need to provide regulated 3.3V and 5V outputs for MCU, sensors, and actuators. Regulators must be positioned to minimize switching noise near sensitive analog circuits. Include visual status indicators for undervoltage or overvoltage detection. As well, analog and digital domains must be physically separated with dedicated ground planes. DAC and ADC traces must be routed away from high-speed digital signals and filtered to reduce the noise. For the component placement, we need analog components close to signal paths; high-current and switching components must be thermally isolated. Using layer stacking and minimizing loop areas to reduce noise.

All PCB revisions should be documented with schematics, BOMs, and layout notes. Changes such as trace width adjustments, component placement shifts, or inclusion of jumpers need to be annotated. Design files must be version-controlled and archived to enable reproducibility and future modifications.

4.1.18 System Testing and Validation Constraints

Comprehensive testing and validation are essential to ensure the ESP32-based laser control system meets safety, precision, and timing requirements. Hardware-in-the-loop (HIL) testing should verify FreeRTOS task synchronization, Bluetooth connectivity stability, and DAC timing accuracy under operational load. Signal integrity tests must confirm that analog outputs remain linear and noise-isolated from digital domains. Wireless testing should evaluate both Bluetooth and Wi-Fi performance for latency, range, and coexistence resilience. Firmware validation includes endurance testing under heavy multitasking conditions and watchdog-trigger recovery. Together, these validation steps confirm deterministic performance and compliance with real-time safety constraints.

4.2 Standards

This segment of Chapter 4 will discuss the design standards considered when creating the E.L.I.P. Topics covered will include laser safety, PCB design, software, and copyright.

4.2.1 Laser Safety, Standards, and Classifications

Laser safety standards primarily come from the American National Standards Institute's (ANSI) Z136.1-2022 document, available on their website [57, 58]. This most recent documentation provides crucial laser safety information for programs ranging from medical, military, industrial, or educational. Per ANSI's documentation, each type of laser is classified based on its potential for biological harm from Class 1 - 4, with 1 not requiring any form of protective measure [56].

The classes of lasers themselves aren't tied to a specific wavelength, but rather by how much power they emit. The higher the power, the higher the class, with Class 4 covering all power values greater than or equal to 500 mW. Class 3B and 4 lasers require, by law, appropriate eye protection when operating. The United States Occupational Safety and Health Administration relies on ANSI's work to serve as the national standard.

4.2.2 Copyright

Standards for copyright are essential to ensure proper credit is awarded to researchers and contributors to a given field. Copyrighted material is protected by law from being reproduced and taken credit for by another individual or researcher. Correctly referencing and proving a given piece of material is allowed. The Copyright Act of 1976 in the United States prevents the use of copyrighted work.

4.2.3 Compliance and Software Quality Standards

The firmware and hardware design adhere to relevant safety and quality standards to ensure professional-grade reliability. Development follows principles for functional safety, emphasizing fault tolerance, redundancy, and safe shutdown mechanisms. Software implementation needs to align with guidelines for portability, maintainability, and robust coding practices under FreeRTOS. Static analysis and continuous integration testing are used to maintain code integrity throughout development. Electromagnetic compatibility (EMC) and electrical safety testing ensure compliance with mixed-signal and wireless systems. Collectively, these standards establish a structured, traceable framework for producing safe, reliable, and certifiable embedded control firmware.

4.2.4 PCB Electrical Standards

Our PCB design follows IPC-2221B, which defines layout and safety guidelines for general printed circuit boards. This standard ensures that our board can safely handle the expected voltage and current while keeping heat and noise under control.

We designed the motor driver traces to handle up to 2 A per channel, based on IPC guidelines. Spacing between power and logic traces was kept within clearance limits to prevent arcing or electrical noise. Heat-producing parts like regulators and drivers have thermal vias and copper pours to spread heat and reduce hotspots.

Large components such as connectors and power jacks were positioned at the board edges to reduce stress on the solder joints and to make wiring cleaner.

Overall, following IPC-2221B helped us create a board layout that is reliable, easier to manufacture, and safe under load.

4.2.5 Power Supply Standards

The power system was designed using principles from IEC 62368-1, which focuses on equipment safety by identifying possible hazards and applying appropriate protections instead of just following rigid rules.

Since our system operates at 12 V DC, it falls under the SELV (Safety Extra-Low Voltage) range, meaning shock hazards are minimal. The laser, motor drivers, and regulators are mounted in an aluminum housing that acts as both a physical barrier and a grounding path.

Fuses, reverse-polarity protection, and short-circuit safeguards were added to protect the user and the electronics.

Thermal limits were also considered — heat sinks and small fans keep hot components within safe temperatures. Surfaces accessible to users stay well below the 70 °C limit recommended in the standard.

By applying IEC 62368-1's safety approach, we ensured the design can operate safely without exposing users to electrical or thermal risks.

4.2.6 Motor Standards

The stepper motors used in our design follow both NEMA MG 1 and IEC 60034 standards. These standards define motor dimensions, insulation, and performance requirements, ensuring that our motors are both safe and easy to replace if needed.

Our NEMA 17 and NEMA 11 motors match the mounting-hole and shaft dimensions set by the standard, which keeps them compatible with standard frames and couplers. The motors also meet thermal class B limits, which means their windings can handle up to 130 °C — well above what they'll reach in normal operation.

Following these standards gives us predictable performance and avoids issues with motor overheating or vibration during printing.

Table 14: Motor Design Constraints

The motors needed enough torque to move the laser head smoothly without skipping steps. We estimated about 0.5 N·m per axis and chose NEMA 17 steppers that could handle roughly twice that.

The motors we will be using will not require that much torque which means cheaper options such as the NEMA 11 stepper motor can handle what we will be using them for.

Constraint	Specification / Limit	Rationale	Design Solution / Mitigation
Maximum Continuous Torque	≥ 0.5 N·m per axis	Ensure stable paper feed and consistent motion	Selected NEMA 17 motors with 2× torque margin
Positional Accuracy	≤ 0.1 mm per step	Maintain print alignment and resolution	Implemented microstepping with tuned step rate
Maximum Step Rate	≥ 3000 mm/min travel speed	Achieve target print throughput	Set motion profile and acceleration in firmware
Thermal Rise	ΔT ≤ 40 °C above ambient	Prevent coil overheating and loss of torque	Limited current per phase and added airflow
Vibration / Resonance	No structural resonance in 0–500 Hz range	Reduce motion noise and print distortion	Adjusted acceleration curve and frame damping
Connector Durability	≥ 5000 mating cycles	Ensure reliability under repeated service	Used locking JST connectors and strain relief

Table 15: Power Supply Design Constraints

Our system pulls around 4 A at 12 V, so we picked a 5 A adapter to have some safety margin. The aluminum housing also helps keep the supply cool and safe to handle.

Constraint	Specification / Limit	Rationale	Design Solution / Mitigation
Output Voltage Regulation	12 V ±5% under load	Maintain stable motor and laser operation	Selected regulated DC adapter with local buck converter
Output Current Capacity	Continuous ≥ 5 A, Peak ≥ 6 A	Prevent brownout during laser firing or motor surge	Added bulk capacitors and current margin in PSU
Efficiency / Heat Dissipation	≥ 80% efficiency, <25 W heat loss	Maintain thermal stability of enclosure	Used synchronous buck converters and passive cooling
Fault Protection	Overcurrent, overvoltage, and reverse-polarity protection	Prevent component damage and safety hazards	Integrated fuse, TVS diode, and MOSFET protection
Safety Isolation	SELV classification (<60 VDC)	Prevent user electric shock	Utilized certified wall adapter with double insulation

Output voltage regulation defines how tightly the supply maintains its nominal 12 V level under load. Keeping the voltage within ±5% prevents unstable behavior in motors and laser circuits that depend on a consistent operating point. Using a regulated DC adapter with an additional local buck converter ensures the output remains within the required tolerance even when load conditions vary.

Output current capacity sets the minimum continuous and peak current the supply must deliver without entering a brownout condition. Motors and laser drivers produce transient surges, so meeting a 5 A continuous and 6 A peak requirement prevents voltage collapse during these events. Adding bulk capacitors and selecting a supply with current margin stabilizes the output during rapid load changes.

Efficiency and heat dissipation constraints limit how much power the supply can waste as heat. Operating at ≥80% efficiency and keeping heat loss below 25 W maintains manageable internal temperatures and prevents thermal stress on the enclosure. Using synchronous buck converters and passive cooling improves conversion efficiency and reduces the thermal load.

Fault protection ensures the supply can tolerate abnormal events such as overcurrent, overvoltage, or reverse-polarity connection without damaging downstream electronics. Integrating a fuse, TVS diode, and MOSFET-based protection gives defined shutdown or clamping behavior during faults, preventing component failure and reducing safety risks.

Safety isolation establishes that the supply must operate below 60 VDC and comply with SELV requirements to minimize risk of electric shock. A certified wall adapter with double insulation ensures the user is physically isolated from hazardous mains voltages, satisfying regulatory limits and providing verifiable electrical safety.

Table 16: PCB Design Constraints

The PCB was designed to handle the current from the motors without overheating or noise issues.

Constraint	Specification / Limit	Rationale	Design Solution / Mitigation
Trace Current Capacity	≥ 2 A per motor channel	Prevent trace overheating and voltage drop	Sized external layer traces per IPC-2221B tables

Creepage and Clearance	≥ 1.0 mm (12 V circuits)	Prevent arcing between power and logic traces	Maintained isolation spacing and routed high-current paths separately
Thermal Dissipation	Component junction ≤ 125 °C	Improve reliability of laser driver and regulators	Added copper pours and thermal vias under high-power ICs
Grounding and Noise Control	Isolated power and logic grounds	Reduce noise coupling into microcontroller	Used star ground layout and ferrite isolation

Trace current capacity defines the maximum continuous current a PCB trace can carry without exceeding its thermal limits. Exceeding this limit increases resistive heating and raises the risk of trace damage or voltage drop. Sizing the traces according to IPC-2221B provides dimensioning rules based on copper thickness and allowable temperature rise, ensuring the traces can conduct the required current safely.

Creepage and clearance specify minimum distances between conductive features to prevent unintended arcing or surface tracking, especially in circuits operating at elevated voltages such as 12 V systems. Maintaining ≥1.0 mm separation reduces the probability of breakdown across the board surface or through air. Routing power and logic paths separately and preserving this spacing reduces coupling and lowers the chance of electrical failure.

Thermal dissipation limits define the allowable junction temperature of components to maintain reliability and prevent thermal runaway. Keeping junctions at or below 125 °C is a verifiable standard for many power devices. Adding copper pours and thermal vias increases effective heat-spreading area and provides conduction paths to cooler board regions, reducing steady-state device temperatures.

Grounding and noise control address interference created by high-current motor paths that can couple into sensitive logic circuits. Isolating power and logic grounds reduces shared impedance and prevents noise from propagating into microcontroller reference levels. Implementing star grounding and ferrite isolation further restricts high-frequency noise paths, stabilizing signal integrity.

4.2.7 Cost Constraints

Cost constraints play a significant role in selecting the power supply because the system must stay within budget while still meeting electrical performance requirements. Higher-rated supplies often rise sharply in cost as current capacity increases, so the design must balance headroom with affordability. Protection features such as overvoltage and short-circuit safeguards need to be included, but only within the price range that aligns with the overall system budget. This creates a limit on selecting industrial or specialized supplies that offer more capability than the prototype requires.

PCB cost constraints are driven by fabrication parameters such as board size, layer count, and material choice. Increasing the number of layers or specifying premium finishes can raise manufacturing cost. To keep expenses controlled, the design often requires staying within a defined board area and using standard FR-4 substrates. Component density also influences cost because tightly packed layouts may force the board to use multiple layers. These constraints guide decisions such as trace routing, component placement, and the selection of parts that do not require costly assembly steps.

Motor cost constraints influence both the type of motor and any additional features included. Motors with integrated encoders or high-precision gearing can exceed the allowable cost, so selections must align with the mechanical performance required without introducing unnecessary expense. Choosing a motor also affects driver cost, since some high-end motors require equally expensive control electronics. Keeping these factors within the mechanical subsystem budget ensures the design remains financially feasible while still meeting torque, accuracy, and reliability requirements.

It is important to keep these constraints in mind because we are on a very tight budget considering the entirety of the funding for this project is from out of our pockets. When keeping this in mind there may be differences in what is optimal and what is practical to use in a project of this scale, so we have to make sure we are keeping this in mind to ensure that every component choice remains financially realistic, aligns with the core functional requirements of the system, and allows the project to be completed without sacrificing critical performance or exceeding the limited resources we have available.

4.2.8 Hardware Safety Constraints

Safety constraints play a major role in the selection and operation of power supplies because these components directly handle the system’s electrical input. The supply must stay within safe voltage limits and include protections such as overcurrent, overvoltage, and short-circuit shutdown to prevent damage to downstream electronics. Proper insulation, grounding, and thermally stable operation are also essential to avoid exposed conductors, reverse-polarity faults, or overheating during extended use. These constraints ensure that the power subsystem operates reliably without introducing electrical hazards.

On the PCB side, safety is tied to both electrical and thermal behavior. Trace widths must be sized to carry expected currents without overheating, and creepage and clearance spacing must meet minimum thresholds to prevent arcing between power and logic paths. High-current or switching components require effective heat dissipation so that regulators and drivers stay within their rated junction temperatures. Clean solder joints and proper component placement also reduce the risk of shorts, open circuits, or mechanical failure during handling and testing. These design requirements help keep the board electrically stable and prevent unintentional faults during operation.

Motor safety constraints involve both electrical loading and mechanical stability. Motors must operate within their rated current to avoid overheating the windings or drivers, and the applied torque must not exceed the mechanical limits of the shaft or couplers. Secure mounting is critical to prevent vibration or movement that could damage the frame or misalign the motion system. Proper wiring and strain relief prevent conductor fatigue, and maintaining safe motor temperatures preserves insulation integrity over time. These constraints ensure consistent motion while minimizing the chance of mechanical or electrical failure.

It is important to keep these constraints in mind while working on this project because we want to ensure that the team can build a system that is reliable, safe to operate, and resistant to common failure modes despite limited experience and a limited budget. Applying them not only protects the group from electrical or mechanical hazards but also demonstrates sound engineering judgment and ensures that the final prototype functions consistently throughout testing and evaluation.

Chapter 5: Application of ChatGPT and Other Similar Platforms

The development and popularization of artificial intelligence over the past decade have been nothing short of extraordinary. AI has been beneficial in the academic sphere, trivializing what were once complicated assignments that could take hours to complete into tasks that can be completed in a few moments. To deny its use in this project would be disingenuous, as the convenience is undoubtedly helpful for the two-semester duration of senior design.

AI tools are interesting when it comes to how it can benefit or harm our learning in Senior Design. The premise of this course is to pair 3 - 5 students if differing engineering backgrounds to create a prototype solution to some problem, or advance the design of a previous group's project. We each bring our own unique skills and understanding of our specialties together to create a working prototype so we can graduate. Some groups are fortunate to have multiple engineers, who can relay ideas to one another, helping integrate their respective designs. However, in our case, there are just some concepts each of us is not familiar with, e.g., optics calculations or PCB integration. AI tools like ChatGPT create a peer we could potentially relay information to and receive feedback on a convenient basis.

There are multiple limitations to ChatGPT. For instance, it might not provide completely reliable or verifiable answers if it is not given specific constraints or detailed input. We'll start by discussing the advantages of ChatGPT. One benefit is its ability to suggest alternative phrasing or reword statements, which can be especially useful in professional or everyday communication.

For example, if I need to write an email to a colleague or professor but am unsure of the wording, ChatGPT can provide guidance. By providing the relevant details, the platform can generate a professional draft (see Appendix 1a). This allows users to quickly receive a polished email template that they can send after reviewing and making minor adjustments if needed. This demonstrates how ChatGPT can simplify communication and assist users who may face language barriers or uncertainty in phrasing.

In more technical applications, ChatGPT can also be used to support research and assist with component selection. In this project, my team and I are building a laser (inkless) printer and implementing a galvo laser system. For example, when inquiring about microcontrollers compatible with galvo laser control, ChatGPT initially provided a detailed technical response, followed by a shorter, concise summary (see Appendix 2b). These suggestions included considerations for performance, analog precision, and real-time control –critical factors when selecting MCUs for precise laser applications.

For this project, the ESP32 microcontroller was ultimately selected, as outlined in Chapter 3. This decision was guided by factors such as its dual-core Xtensa architecture, integrated Bluetooth and Wi-Fi connectivity, high-speed DAC/ADC support, and native FreeRTOS integration. ChatGPT's recommendations aligned closely with this selection, as it identified the ESP32 family among other real-time capable MCUs suitable for mixed-signal control and wireless applications (Appendix 2b). This provided additional validation for the chosen platform and information detailing the specifications of each.

However, a key limitation of AI-generated guidance is the lack of specificity in the initial inquiry. Parameters such as cost, environmental conditions, firmware toolchain compatibility, and exact input/output requirements were not always considered, which are essential for optimizing MCU selection in embedded design. While ChatGPT provides valuable support and can reduce research time, it should be regarded as an assistive tool rather than a definitive decision-maker, particularly for complex technical projects that require hands-on testing, datasheet verification, and safety compliance analysis.

During our research, the utilization of ChatGPT was heavily encouraged by our professors, due to its development as a useful tool that will probably not be going away any time soon. I had very low experience with using AI for research at this point but luckily it was pretty straightforward. Doing research with the assistance of ChatGPT has the ability to greatly increase the efficiency of our research. During my research on types of motors that we could use, ChatGPT was very helpful in summarizing the different advantages and disadvantages that come along with the different types of motors. When trying to come up with ideas for things we need to research, ChatGPT is very helpful to use to quickly come up with a large list of things that we need to do.

As previously discussed in this paper, incorporating an f-theta lens into our design is complicated by its extremely high price. F-theta lenses were created to simplify what a multi-lens system could do, but how exactly that lens system looked before was difficult to ascertain. ChatGPT was consulted to develop a simulated f-theta lens-like system that, in theory, replicates the flat image field produced by an actual f-theta lens. However, some lens specifications were questionable and not available on the market. Consulting with faculty proved surprising, as the design was found to be feasible with proper considerations of the lens specifications. At present, we have not yet designed the pseudo-f-theta lens, but parts are being considered for the design and casing. Responses from the tool should always be confirmed through independent research or expert consultation. However, the insight provided by ChatGPT was quite valuable and could greatly benefit our project.

ChatGPT was also useful in speeding up the creation of tables used to compare different types of components we would be using in the project. When creating the summary of selected technologies that we would be using, ChatGPT was helpful in combining the many things we had selected into one set of data that I could use to quickly make the table. When writing a large amount on a particular subject that you have researched a draft is very useful to have, and ChatGPT is very useful in its ability to quickly create a good draft that can be used to assist in writing.

The largest limitation in the utilization of ChatGPT for research is its reliability, which comes into question many times while using it due to its lack of citing and inability to find specific values such as ones that come from datasheets. When using ChatGPT for writing it will occasionally give very general information that does not tell the full story of how a component works, and it is relatively difficult to parse when that happens and when a component is just basic in its usage. "Hallucination" is a common phenomenon in some responses, completely making up information when it can't discern a proper course of action or calculation. OpenAI acknowledges this, emphasizing the importance of guessing rather than failing to provide an accurate response. Failure in analytical calculations when working with electrical components can, in the worst case, prove dangerous for us as aspiring engineers. Fact-checking is crucial for safe and proper use of AI tools, as sources can often be of dubious quality. An article from over 20 years ago may require further analysis before utilizing it as a source for our work.

Another limitation of ChatGPT use for research is that there may be safety concerns mentioned in the datasheets or papers that ChatGPT fails to report when returning information that it had gathered, which means that we still have to carefully research every part to ensure that we are staying safe while designing and building the LIP.

A potential harm that AI poses to us is the slow decay of soft skills that make one valuable as a potential hire. If AI can do all the research or work for itself, what purpose would it serve at a company? Another harm AI can pose is diminishing students' incentive to dedicate time to academics. In other words, it encourages procrastination. If the AI can solve all the homework questions due next week, why bother starting now? AI can make things easier for a student in the moment, as life events or balancing classes can be difficult, but there will be consequences if habits built in the present carry on to the future.

Chapter 6: Hardware Design

6.1 Optical Hardware Design Calculations

The goal of our project is to provide an environmentally friendly and fast alternative to traditional printers. We plan to use a laser galvo for positional control of our laser and a lens system to replicate the corrections and focusing required to maintain beam integrity during printing. For a diagram of our setup, observe Chapter 2's Figure [5].

As mentioned in chapter 5, the core of our f-theta lens design was developed through the use of ChatGPT. The core of the design was deemed feasible when consulting with faculty, but lens choice required some adjustment. The design includes a biconcave and an achromatic doublet lens to maintain the laser's focus, and a positive meniscus lens to provide a flat image plane for the laser. The tools also offered a list of focal lengths to work with, but we will instead choose available lenses on the market. The rationale for each focal length was to ensure a small distance between lens components, similar to the interior layout of a proper f/theta lens. All planned lenses are AR-coated, implying a <0.5% loss of laser power, and the galvo mirrors are assumed to have a reflectance of 0.98. The website for this part did not provide data regarding this on the mirrors. Replacing said mirrors or finding an alternative product is something we are considering if testing yields poor results. We are currently discussing with ScannerMax representatives regarding the use of one of their galvos.

For our pseudo-F-theta lens, we will utilize the effective focal length equation to obtain an estimate focal length of our combined lens system. For the distances between the lenses, we tested 10 - 100 mm combinations in the formulas below for our dAB and dBC that would allow for a small output spot size. We conclude that dAB = 10 mm and dBC = 50 mm would be a good balance of effective focal length and small output spot size for our focused laser beam. After solving with the focal lengths from Table 4, we obtain an effective focal length of 115.4 mm.

- $f_{AB} = (1/fbiconcave + 1/fachromatic - dAB/(fbiconcave * fachromatic))^{-1}$
- $f_{eff} = (1/fAB + 1/fmeniscus - dBC/(fAB * fmeniscus))^{-1}$

Using the 1.65 W laser diode, we estimate a 0.11 W loss using the following formulas, resulting in 1.54 W of output power.

- Pt = Pin*(1 - T)^n
    - Pt is our transmitted power
    - T is our transmission coefficient from the AR coating (0.5% → 0.005)
    - n is the number of transmission surfaces for the lens
        - Each lens has two surfaces
- Pr = Pin*R
    - R is our reflectance of the mirrors

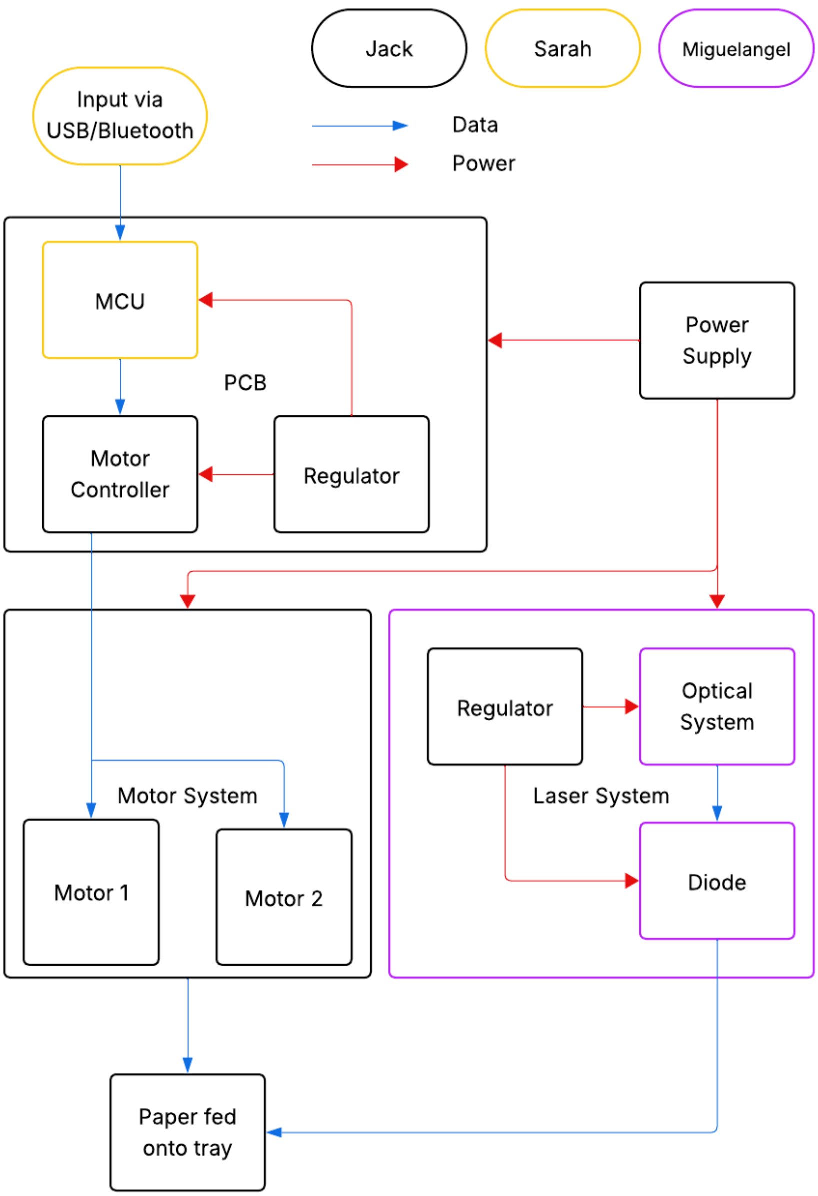
To calculate our diffraction limited and focused spot size, we will use the diameter of our positive meniscus lens, as it is the final lens in the system, and the effective focal length of our combined lenses. (D = 50.8 mm, f = 115 mm). Our input spotsize was determined by consulting the datasheet of our aspheric lens (w_{in} = 5.72 mm), and our M factor was estimated to be 4, as our diode is multimode.

- $w_o = M^2 * \lambda * f_{eff}/(\pi * w_{in})$
- Dfs = 4/π * λ/NA
    - NA = D/f_{eff}
- Intensity = P/A

Our resulting calculation returns a numerical aperture of 0.44 and a diffraction-limited spot size of 1.53 μm. Our focused beam spot size w_o was determined to be 13.61 μm. Using half of w_o we obtain a radius of 6.805 μm.

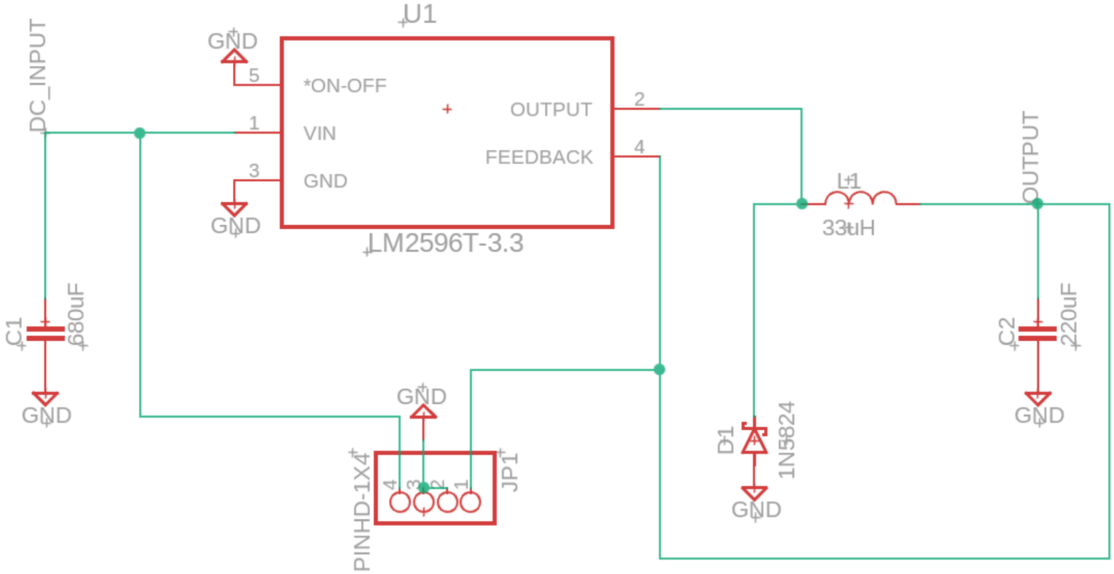
Solving for intensity with the power we obtained earlier in this section and the area formula $4\pi r^2$, we get an Intensity of 0.003 W/μm^2.

Figure 12: Subsystem Block Diagram



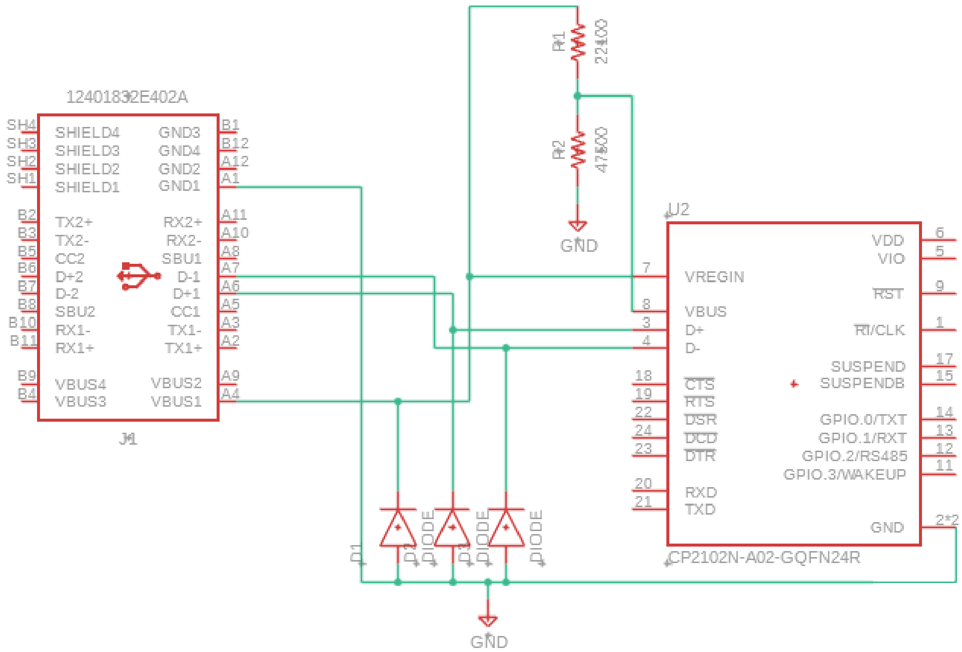
This diagram overviews how the basic structure of the LIP will be divided among the three of us.

Figure 13: 3.3V Regulator



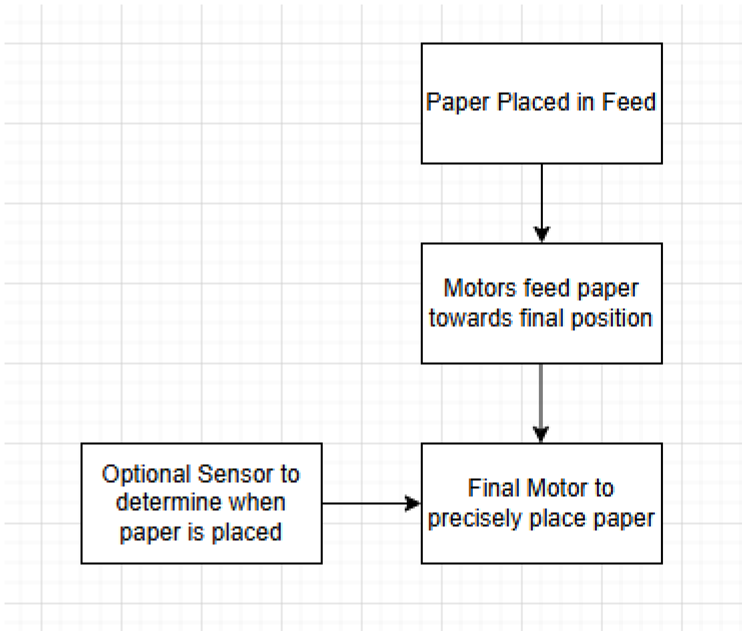
This circuit uses an LM2596T-3.3 voltage regulator to convert a 15 volt DC input, down to a stable 3.3 volts DC output. The input capacitor smooths out any voltage ripple before it enters the regulator. Inside the LM2596, the voltage is switched on and off rapidly to control the current through the inductor, which reduces the voltage efficiently without wasting much power as heat. The Schottky diode provides a path for current when the internal switch is off, helping to maintain continuous current flow. The output capacitor then filters the voltage to ensure a clean and steady 3.3-volt output. The feedback pin monitors this output to keep it regulated, while the on/off pin can be used to enable or disable the regulator. This circuit provides a reliable and efficient 3.3-volt power source for our microcontroller. This will ensure that our microcontroller can be run at the correct voltage.

Figure 14: USB Bridge



The CP2102N is a USB-to-UART bridge, and the components around it, including the ESD diode array, exist to protect and support its USB interface. In this diagram, the CP2102N's USB pins (VBUS, D+, D–, and ground) connect directly to the outside world through the USB connector, which makes them vulnerable to electrostatic discharge. The SP0503 diode network sits between those lines and ground so that any sudden voltage spike from someone plugging in a cable or touching the connector is safely diverted before it reaches the CP2102N. This ensures that the chip's internal USB transceiver can reliably detect VBUS, handle differential data on D+/D–, and maintain signal integrity without being damaged by fast, high-energy ESD events.

Figure 15: Paper Feed



This diagram outlines a straightforward paper-handling system where the system starts with a sheet being loaded into the feed mechanism, then uses a primary set of drive motors to move the paper toward the working area. An inline sensor can detect the sheet's arrival and confirm that the feed stage completed correctly, which helps the controller transition to the final positioning step. A dedicated motor then performs the precise placement needed for alignment, making the overall sequence a combination of bulk transport followed by controlled fine positioning, similar to how many small automated lab or printer subsystems manage material flow.

Chapter 7: Software Design

This portion of the report will serve as the visual and structural foundation of the Galvo-based laser printing system's design, transforming concepts and software architecture into tangible, system-level diagrams that illustrate how every subsystem interacts. The goal of this chapter is to clearly define how the microcontroller, communication interfaces, peripherals, and user interaction layers cooperate to achieve real-time laser control and Bluetooth-enabled print operations. The software-hardware interface through multiple diagrams shown below highlights a different dimension of system behavior and design logic. By interpreting flowcharts, case diagrams, state diagrams, class diagrams, data transfer mappings, and data structure representations, this ensures that every component and process in the design is well-defined, traceable, and logically structured.

7.1 Software Architecture Overview

The software architecture of the galvo-based laser printer is designed to provide a robust, modular, and real-time control system that integrates all aspects of hardware control, safety monitoring, and wireless communication. The firmware is developed primarily in C/C++ using the ESP-IDF framework, which natively incorporates FreeRTOS. It is deployed on the ESP32 microcontroller, featuring a dual-core Xtensa LX6 processor –one core dedicated to real-time motion and safety control tasks, and the other for network and Bluetooth communication.

This separation of processing responsibilities enables deterministic timing for the galvo control loops while maintaining uninterrupted BLE communication. The layered software design consists of:

- Hardware Abstraction Layer (HAL) - manages DACs, ADCs, timers, GPIOs, and PWM peripherals via ESP-IDF drivers.
- Control Modules – execute real-time galvo PID loops, laser modulation, and signal filtering.
- Safety and Interlock Modules – monitor emergency stop, enclosure sensors, and watchdog status.
- Communication Stack – based on NimBLE (Bluetooth Low Energy) for wireless job transfer and UART debugging for diagnostics.

This layered structure ensures modularity, portability, and safe concurrency across all system components, enabling high-speed, precision-controlled laser printing.

7.2 Real-Time Task Design

To achieve deterministic performance, the ESP32 firmware utilizes FreeRTOS task management and synchronization primitives. Tasks are assigned priorities based on timing criticality:

- High Priority: Galvo control, laser modulation, and safety monitoring
- Medium Priority: BLE communication and job queue parsing
- Low Priority: Logging, diagnostics, and housekeeping

FreeRTOS synchronization tools –such as queues, semaphores, event groups, and mutexes –ensure thread-safe data exchange and prevent race conditions. The ESP32’s dual-core scheduler allows the system to dedicate Core 0 to control tasks (PID, signal generation) and Core 1 to communication and non-critical operations, minimizing latency in real-time control loops.

7.3 Control Loops and Signal Processing

The heart of the laser printer system lies in its closed-loop control of the galvos. Analog position feedback from the galvo sensors is sampled using the ESP32’s high-resolution SAR ADC, while digital-to-analog control outputs are generated through external DAC channels via SPI or I2S peripheral.

A PID control algorithm computes the difference between desired and actual galvo positions, generating DAC commands that drive amplifier inputs. Signal conditioning includes low-pass digital filters and averaging routines implemented within periodic FreeRTOS tasks.

Hardware timers and DMA are used to schedule sampling and output at consistent frequencies (e.g., 1-10 kHz), ensuring smooth and continuous mirror motion even during complex raster or vector engraving.

7.4 Communication and Protocol Handling

Wireless print job transfer is handled via Bluetooth Low Energy (BLE) using the ESP32’s NimBLE stack, fully integrated into ESP-IDF. A custom GATT service encapsulates commands (e.g., galvo coordinates, laser intensity) and transmits status feedback to the host application (LightBurn or custom PC interface).

Incoming BLE packets are validated, parsed, and queued in FreeRTOS message buffers. A dedicated BLE Task handles connection management, data parsing, and acknowledgement transmission. This separation prevents interference with control operations and ensures that print data arrives predictably even during ongoing motion control.

7.5 Safety and Supervision

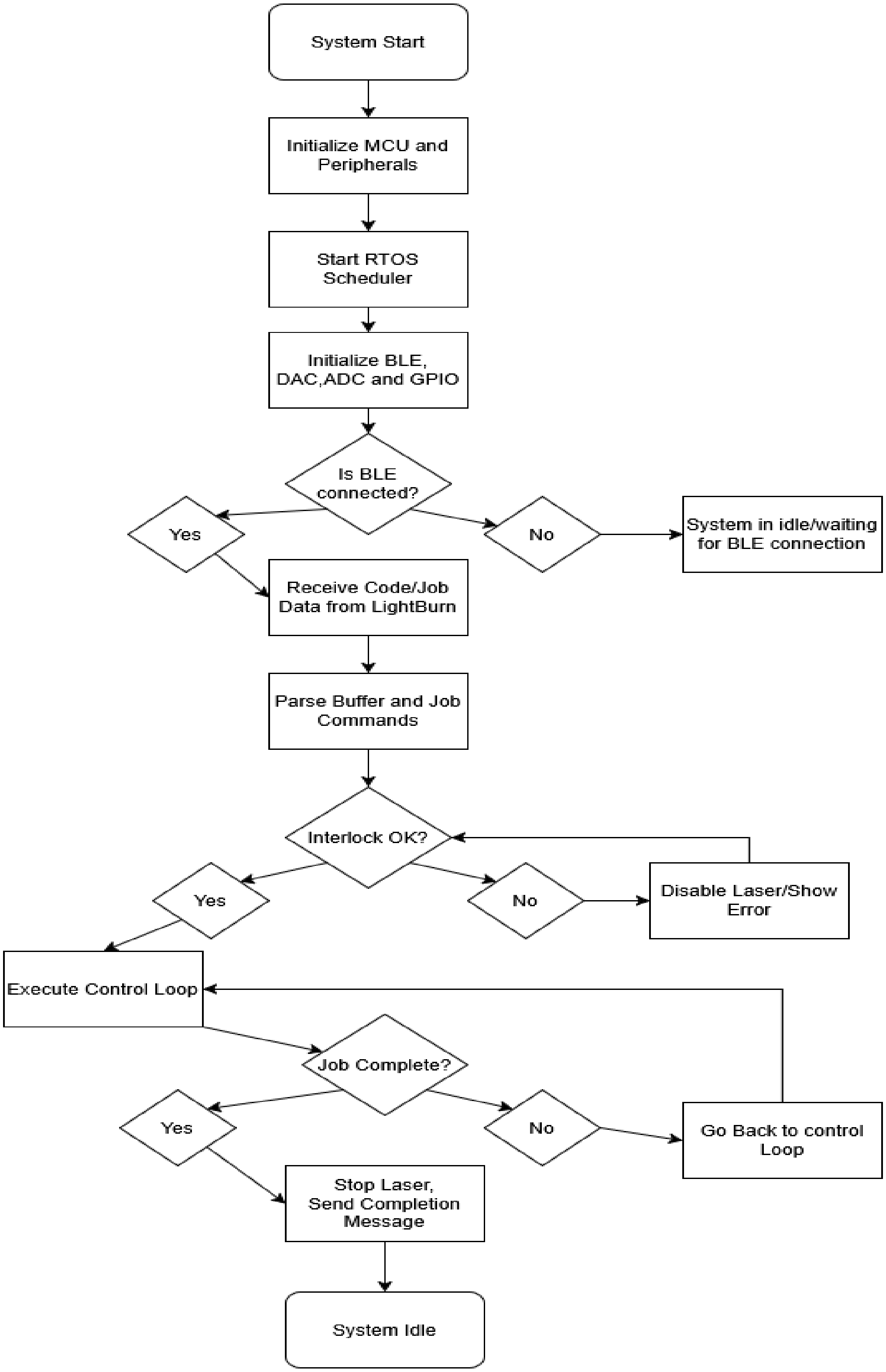
Safety is crucial when operating high-power lasers. The Safety Supervisor Task continuously monitors all hardware interlocks, emergency stop signals, and error flags. Transitions between states are triggered by hardware signals or software commands. For example, if a safety interlock is opened while printing, the state immediately transitions to Fault, disabling the laser, and alerting the BLE interface. Software safety mechanisms include watchdog timers, task timeouts, and priority-based preemption. The integration of hardware and software safety ensures that the system can recover gracefully from faults while maintaining the integrity of ongoing operations. These safety protocols are essential to comply with laser safety standards.

7.6 Software Flowcharts/Diagrams

To effectively convey the structure and behavior of our Galvo-based laser printer system, a series of flowcharts and diagrams have been developed. These visual representations provide a comprehensive view of software operation, task organization, and data flow, helping developers understand the system's functionality and interactions. Each diagram highlights a different aspect of the system, from initialization and real-time operation to user interaction and inter-module communication.

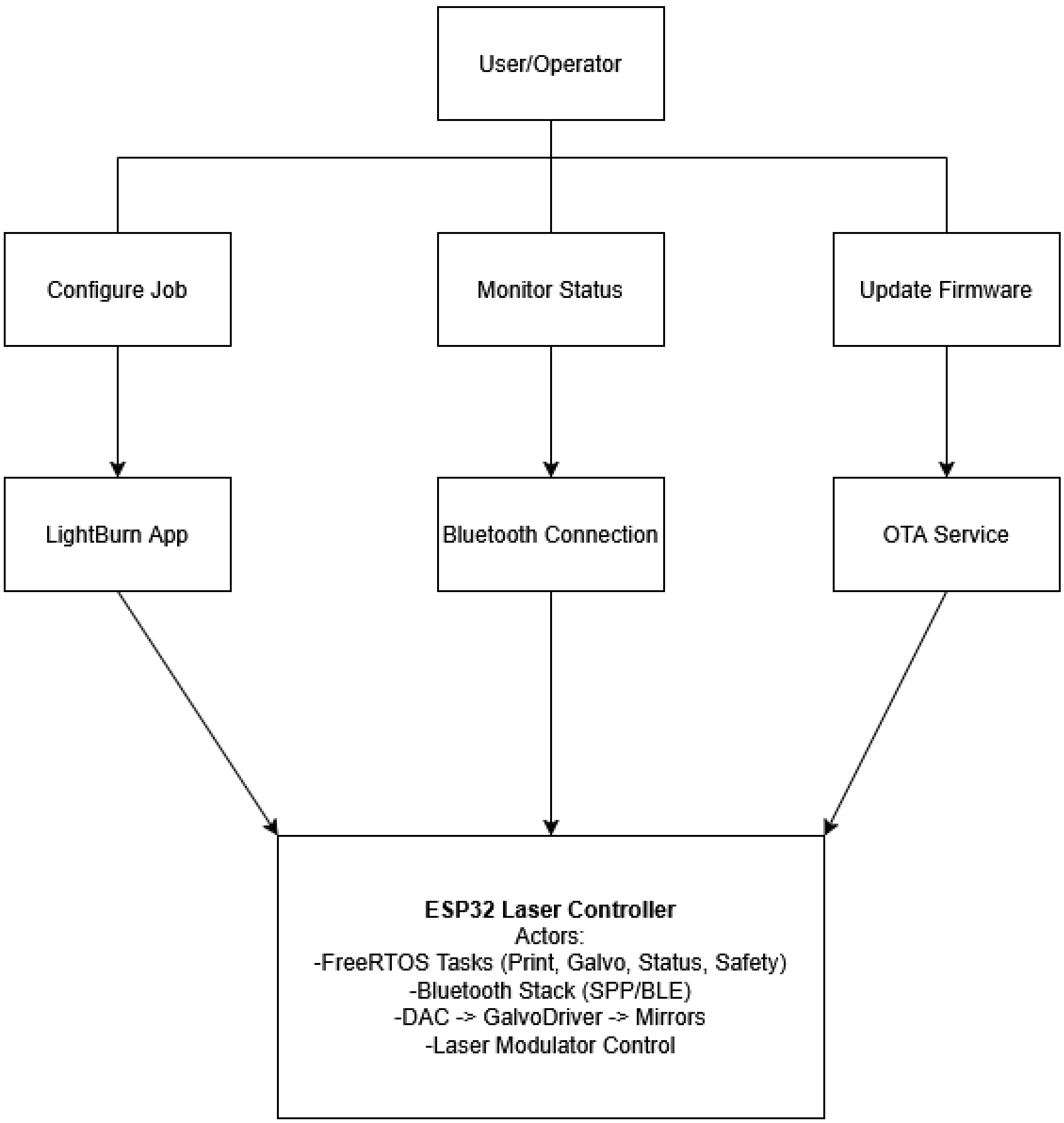
The System Operation Flowchart (below) presents a top-down view of the firmware’s logical sequence. It begins with system startup, followed by hardware initialization, BLE connection checks, and preparation of the galvo control system. Decision points within the flowchart –such as verifying BLE connectivity or interlock status –ensure deterministic real-time performance under FreeRTOS. Loops for waiting on incoming commands and continuous execution of control routines are clearly shown, capturing the operational dependencies necessary to maintain system reliability and fault tolerance. This flowchart serves as the foundation for understanding how the embedded software transitions between tasks and reacts to hardware communication events.

Figure 13: System Operation Flowchart



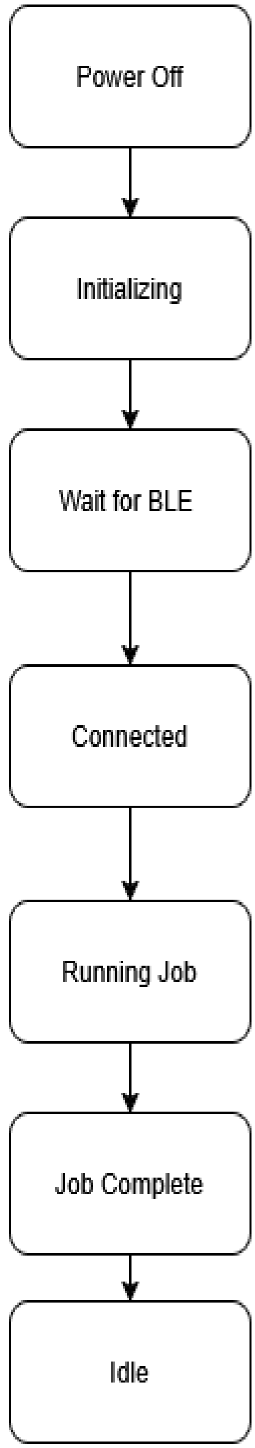
Building on the system flowchart, the Case Diagram below shows how external devices interact with the embedded system. The main actor is the LightBurn PC, which represents the operator controlling the printing process. The PC sends G-code commands to the ESP32 over Bluetooth and receives real-time job status updates in return. Another actor, the Safety Switch (Interlock), reports the system's safety status to the ESP32 before the laser can be activated. This diagram clearly shows how these components communicate and how user inputs and safety checks guide the system's overall operation.

Figure 14: Case Diagram



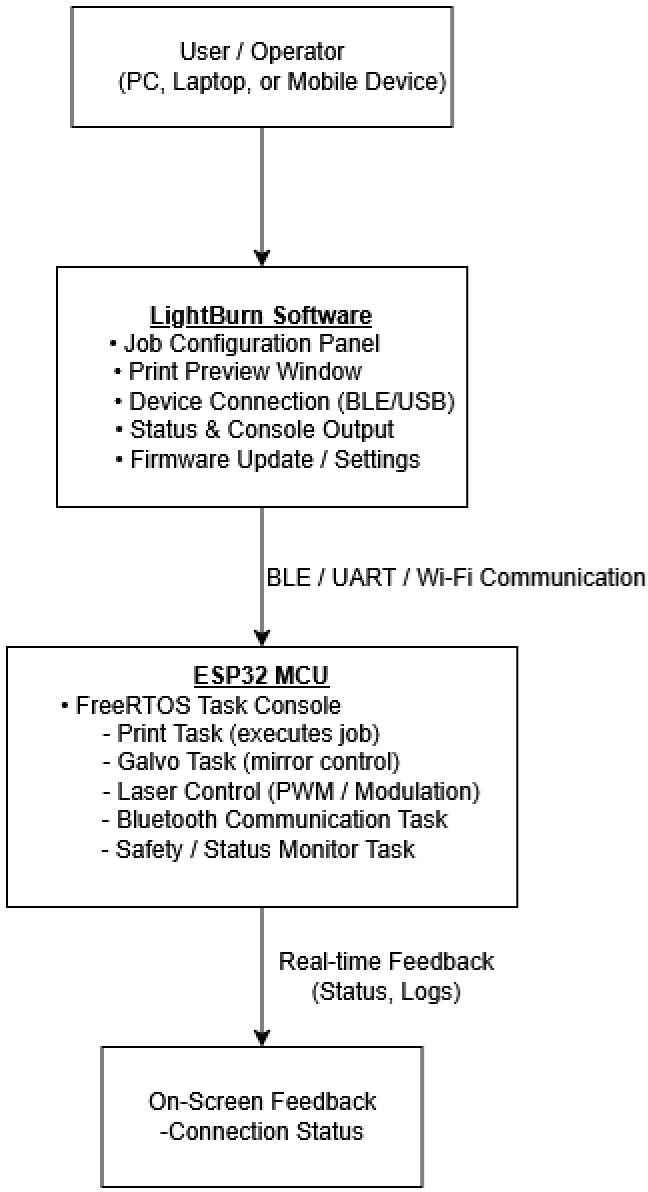
The state diagram below shows the internal behavior and operational modes of our embedded system over time. Each state represents a specific mode of operation (e.g., waiting for BLE, running a job), while transitions represent events or conditions that move the system from one state to another. For “Power Off” the system is inactive, meaning that the MCU is not powered or in reset. “Initializing” state occurs on power-up; the MCU configures clocks, peripherals, BLE stack, and galvo DACs. For the “connected” state it occurs once LightBurn connects; the system is ready to receive job data (G-code). This diagram captures the control logic flow of your firmware at runtime –showing safe startup, runtime control, and fail-safe handling. This is great for providing compliance with real-time safety and control standards, as it visualizes how the MCU gracefully handles state transitions.

Figure 15: State Diagram



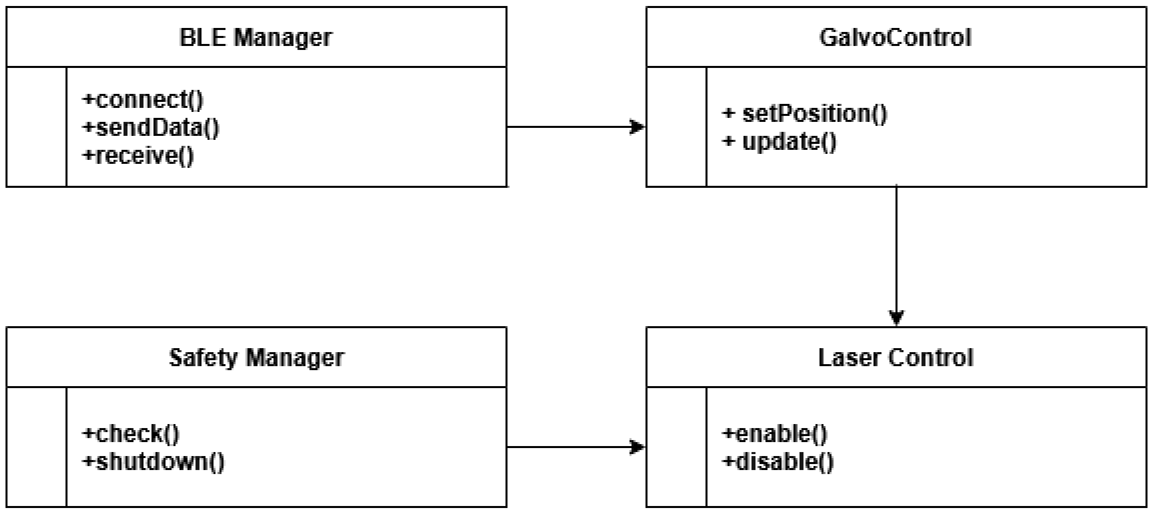
The User Interface Diagram (as shown below) simplifies interaction between the user and the embedded system. It focuses on BLE-based print job submission, queue checking, and feedback acknowledgement. Unlike app-driven or touchscreen interfaces, this diagram emphasizes minimal physical interaction while ensuring reliable communication and confirmation of the job. It shows how user commands enter the system, how they are validated, and how the system responds with status updates, ensuring a clear understanding of how the interface operates in a real-world printing scenario.

Figure 16: User Interface Diagram



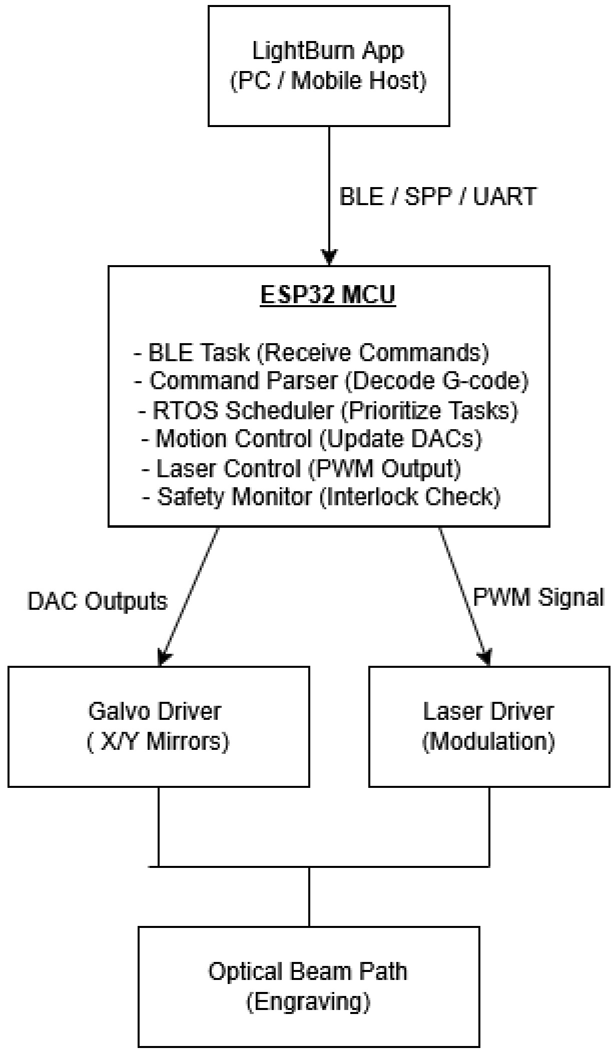
The Class Diagram (as shown below) illustrates the modular design of embedded software. Each FreeRTOS task is treated as a class managing a subsystem, such as BLE communication, laser modulation, or safety monitoring. This design promotes modularity, making debugging and maintenance straightforward. The diagram also clarifies the relationships between subsystems, highlighting how data and control signals flow within a modular real-time architecture. By showing task responsibilities and interactions, the class diagram ensures maintainability and scalability of the firmware.

Figure 17: Class Diagram



The Data Transfer Diagram shown below illustrates the flow of information between software modules, hardware peripherals, and external interfaces. It highlights how print jobs, control commands, and status data move throughout the system—from user input received via Bluetooth to laser output—and how feedback is circulated to ensure safety and precision. For the ESP32-based Galvo laser system, the diagram clearly represents the paths for data input, processing, storage, and output, which are essential for debugging, system optimization, and verifying real-time performance.

Figure 18: Data Transfer Diagram



7.7 Data Structures and Memory Management

Efficient data management is critical for the performance and reliability of the laser printer. Print jobs are stored in structured queues, where each job contains metadata such as resolution, path coordinates, and laser power. Circular buffers are used for galvo command data to ensure continuous motion without stalling. Status logs and system metrics are maintained in RAM with periodic flushes to non-volatile memory for persistent storage.

7.8 Integration Overview

Integration in embedded systems is the process of combining modular software components into a cohesive system, ensuring that each subsystem—communication, control, safety, and user interface—works reliably with the others under real-time constraints. For the ESP32-based Galvo laser printer, software integration focuses on several key areas: synchronization, inter-module communication, peripheral abstraction (DAC, ADC, GPIO, and timers), wireless data handling (through the integrated Bluetooth Low Energy stack), and fault management/safety supervision.

The ESP32's dual-core architecture—featuring one core dedicated to real-time control (PRO CPU) and the other to system and communication tasks (APP CPU)—allows for parallel execution of galvo control and BLE communication without interference. This design ensures deterministic timing for high-priority control tasks while maintaining responsive data transfer with external devices such as the LightBurn PC.

FreeRTOS, which is natively integrated into the ESP-IDF environment, manages all real-time tasks and ensures predictable scheduling. Task priorities are configured such that galvo control and laser modulation preempt non-critical operations like BLE communication or data logging. FreeRTOS queues and semaphores are used to safely exchange information between modules—such as print control, galvo control, BLE communication, and safety monitoring—preventing data corruption or race conditions.

Error handling and safety management are also integrated across modules. The firmware implements watchdog timers, task supervision, and interlock monitoring to detect and respond to hardware or communication faults. For instance, if an interlock is opened, a BLE connection drops, or temperature exceeds a defined threshold, the system automatically transitions to a safe state by disabling the laser and notifying the host interface. Through this tightly coordinated integration, the ESP32 platform ensures both high-speed performance and operational safety in real-time laser printing applications.

7.9 Comparative Interpretation of Software Diagrams

Each diagram presented in this chapter provides a unique perspective on the embedded system, highlighting specific aspects of functionality, control, and interaction. While they share the common goal of illustrating system operation, their focus and granularity differ, making it valuable to consider them comparatively.

The System Operation Flowchart provides a view of the firmware logic. It emphasizes the chronological execution of tasks, loops, and decision points, making it ideal for understanding the operational sequence and interdependencies of system routines. This flowchart is primarily concerned with how the firmware functions over time under FreeRTOS and ensures deterministic real-time behavior across both ESP32 cores.

In contrast, the Case Diagram abstracts the system from the user's perspective. It highlights actors—such as the LightBurn PC, Safety Interlock, and Operator—and their interactions with system functions. This diagram is less concerned with timing and control flow and more focused on who initiates actions and what services the system provides. It is particularly useful for identifying external dependencies and communication pathways influencing firmware design, such as BLE command input or safety signal validation.

The State Diagram bridges operational flow and user interaction by emphasizing conditions and transitions. Each state encapsulates a specific mode of operation (e.g., *Idle*, *Connected*, *Printing*), while transitions define how events trigger changes in behavior. Compared to the flowchart, the state diagram provides a clearer visualization of runtime behavior and safety-critical transitions—making it invaluable for validating control logic, laser enable conditions, and recovery mechanisms on the ESP32 platform.

The User Interface Diagram focuses exclusively on user-system interaction through BLE communication managed by the ESP-IDF NimBLE stack. While the use case diagram shows external actors broadly, the UI diagram highlights data exchange and feedback loops for print jobs, queue verification, and acknowledgment messages. This ensures clarity in user expectations and the reliability of communication protocols when interacting with LightBurn or other host devices.

The Class Diagram shifts attention to modular software design. It emphasizes the encapsulation of real-time tasks into subsystems such as BLE communication, laser control, and safety monitoring. By showing relationships and interactions among these tasks, the diagram supports maintainability, debugging, and future scalability—key benefits of ESP-IDF's component-based architecture.

Finally, the Data Transfer Diagram presents a view of information flow across modules, peripherals, and external interfaces. Unlike the flowchart or state diagram, it does not focus on sequential execution but instead illustrates how data moves between ESP32 cores, peripherals, and wireless interfaces. This ensures safe and accurate operation of real-time tasks while maintaining integrity in communication and control feedback loops. It complements the other diagrams by confirming that data pathways, safety interlocks, and control signals are correctly routed and synchronized throughout the firmware.

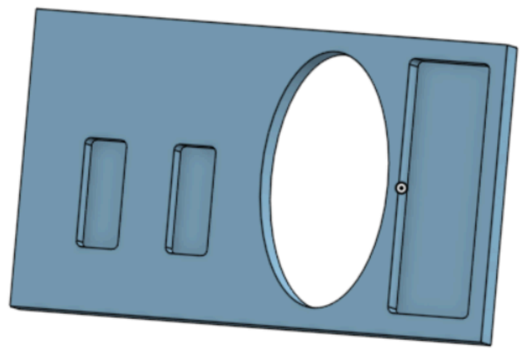
Taken together, these diagrams form a comprehensive understanding of the ESP32-based Galvo laser printing system. When interpreted collectively, they provide a complete blueprint that ensures reliability, maintainability, and safe operation. By comparing them, developers can identify overlaps, gaps, or redundancies in design—leading to a more robust and well-documented firmware implementation optimized for the ESP32 environment.

7.10 Conclusion

The diagrams presented throughout this chapter –ranging from flowcharts to state diagrams to data transfer to user interface diagrams –have a critical role in understanding, designing and validating the software architecture of the STM32WB-based Galvo laser printing system. Each diagram provides a unique perspective on the system: flowcharts illustrate operational sequences and control loops, state diagrams clarify subsystem behaviors under varying conditions, class diagrams define modular software structures, and data transfer diagrams map the flow of information between tasks, peripherals and external interfaces. Collectively, these visual tools not only improve comprehension for developers but also enable rigorous analysis of real-time system constraints, task synchronization, and safety mechanisms. They help identify potential bottlenecks, prevent concurrency errors, and ensure that critical operations –such as laser activation, galvo positioning, and BLE communication –execute reliably and predictably. By providing a structured, layered view of both software and hardware interactions, these diagrams serve as a blueprint for implementation, testing, and future scalability, ensuring the system remains safe, efficient, and maintainable. In essence, they bridge the gap between conceptual design and practical deployment, forming a crucial part for embedded system development.

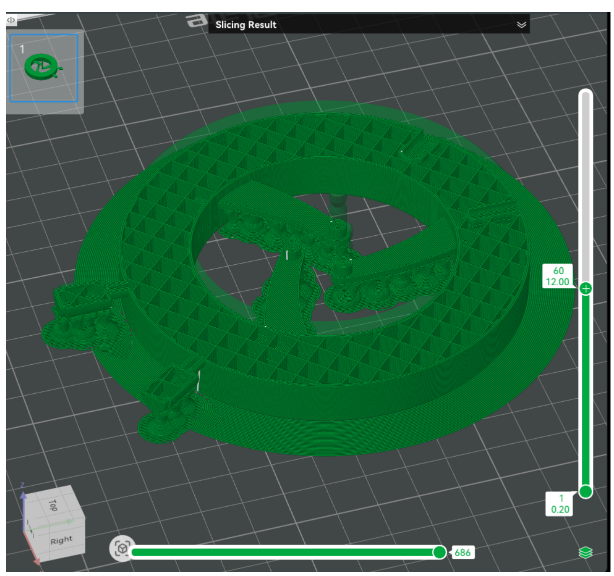
Chapter 8: System Fabrication/Prototype Construction

Initial Prototype Model



Figure[19] Prototype CAD Model

After our initial filament melted due to prolonged use, we switched to a more durable ASA filament. Our prototype was made as shown in the figure above. Additional parts were created for our aspheric lens and laser diode to fit within the smaller rectangular cavities. These cavities allowed for snug fits for our diode, aspheric lens, and galvo. We also tried to print a Newport LCM-2 lens holder, as shown in the figure below, but the CAD file did not include the required mechanical movement spacing. A solid part would be useless for the application we have in mind, so further research would be necessary.



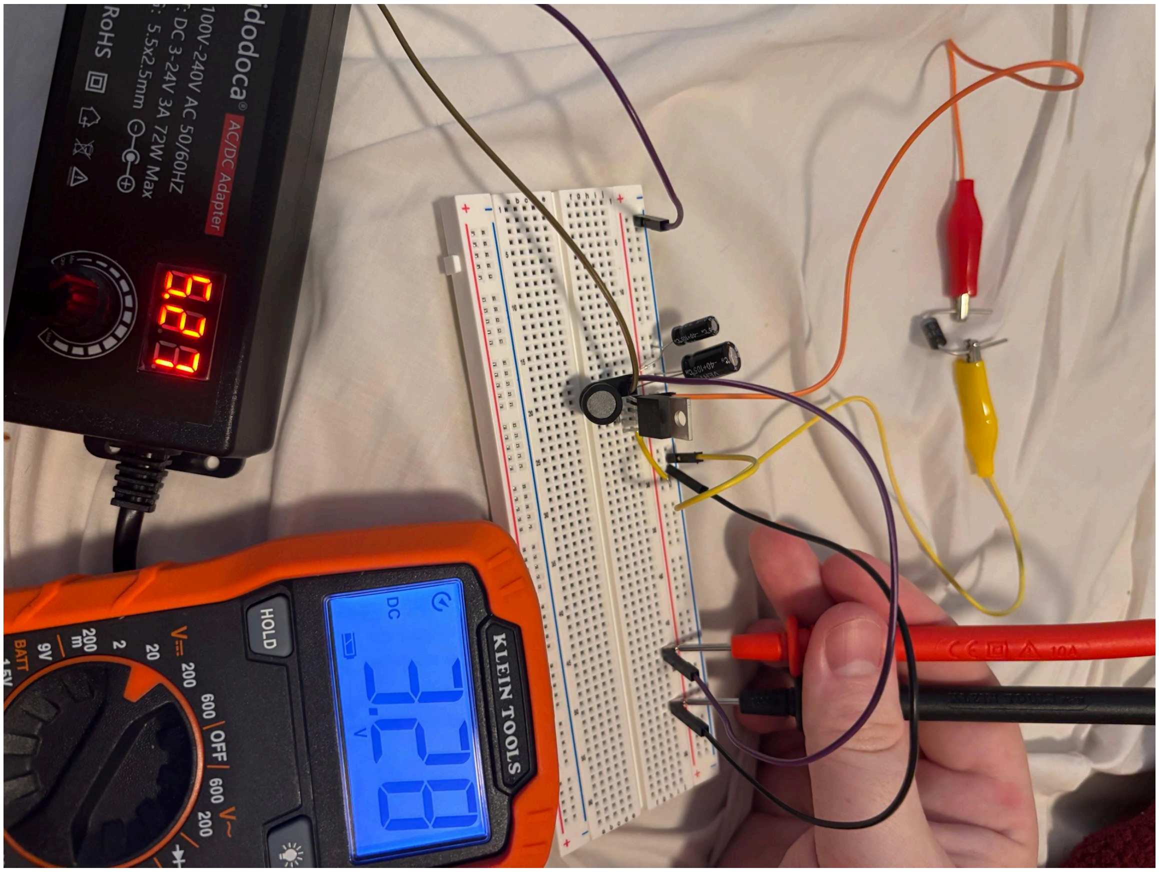
Figure[20] Newport LCM-2 CAD Model

Chapter 9: System Testing and Evaluation

9.1 Hardware Testing

The galvo system was validated by supplying it with a stable AC source using a commercially purchased wall plug matched to the input requirements of the original power supply. The wall plug was connected directly to the supply, allowing the unit to deliver its rated DC outputs to the galvo systemunder controlled conditions. With the system powered as intended by the manufacturer, we verified basic functionality by observing mirror response to standard test signals, confirming that the power path, control electronics, and actuator mechanics operated correctly.

To verify the functionality of the LM2596-3.3 switching regulator, I built a test circuit on a breadboard using the 680uF input capacitor, the 1N5624 Diode and the 33uH inductor as well as the 220uF output capacitor.. A variable bench power supply provided the input voltage, and a digital multimeter was used to monitor the regulated 3.3V output. I adjusted the supply voltage and observed whether the output remained stable under different input conditions. The setup confirmed that the regulator maintained a steady 3.3V output, as shown in the measurement below.



9.2 Optoelectronics Feasibility

In terms of performance, the basics were achieved using the components we had available. There are plans for higher-quality parts, but numerous factors constrained us, and we were unable to test them during Senior Design 1. Powering the system proved reasonably acceptable. We observed the movement of the galvo and the focusing of the aspheric lens. Output was directed toward the hole implemented in the system.

We have much to change going into Senior Design 2. Firstly, installing a cooling system is essential. This would ensure that all mechanical components of the project are cooled, maintaining laser integrity and preventing filament melting. The laser was also not fully centered on the X mirror, so the Y mirror failed to reflect enough of it. We will also implement our high-powered diode. However, we have not received any updates from UPS regarding when it will arrive.

The galvo used in the demo, while useful for its price, is planned to be replaced with a ScannerMax galvo. The pricing is still substantial for our group, but this is still the best option if we wish to have reliable engraving and precise control. Funding it should not be as much of a problem once affairs in the government are sorted out, but this will take time. The galvo used in the prototype could be powered, but several aspects weren't made clear on the product's information page—namely, the mirrors and some extra boards that seem to control the movement.

Regarding the pseudo-f-theta lens we plan to implement, we require further testing for our lens holders. As mentioned in Chapter 8, the file found would be treated as a solid part in our slicer software. Printing smaller parts and assembling them would be the best approach if we wish to implement these holders, but that will require further research and time. Once funding is sorted after the holidays, and the new galvo is purchased, the CAD and software design will require additional adjustment.

Chapter 10: Administrative Content

10.1 Budget

Accounting for today's price changes, the previous group spent around $815 on their final project. Utilizing their documentation to guide our process, we agreed on a target budget of $650 to cover our goal of reducing their project cost.

Table 17: Bill of Materials

Component	Part Number/Number	Quantity	Unit Price
Green Laser Diode	Laser Diode LT-LD-530-1650M-C	1	$130.00
Laser Diode Driver	LDS9 (TL)	1	$107.10
Safety Goggles	EaglePairOD7+ 190nm - 540nm	1	$54.00
Safety Window	Foldable Laser Shield	1	$100.00
Plastic Aspheric Collimating Lens	CAW100-A (TL)	1	$25.93
Glass Aspheric Lens	A260TM-A	1	$105.32
Biconcave Lens	LD2568-A	1	$ 44.81

Achromatic Doublet Lens	AC254-150-A	1	$ 95.34
Positive Meniscus Lens	LE1076-A	1	$ 61.64
Laser Diode Socket	S038S (TL)	1	$5.35
PCB	JLCPCB	1	~$50.00
Raspberry PI	SC0563	1	$26.78
Power Supply	GST25A12-P1J	1	$13.70
Aluminum Rails	B08Y8KL79L	1	$14.99
X & Y axis Motors	17HS16-2004S	3	$12.99
Bolts/Nuts	6259	4	$4.50
Paper Feed motor	NFP-JGA25-370-EN	1	$15.00
Paper	B007JJDTFI	1	$14.96
Total			$Recount needed

10.2 Senior Design Milestones

This project is the final requirement for aspiring engineers at the University of Central Florida. Years of study and examination culminate in the final demo presentation with faculty and reviewers. To ensure our success as a group, planning for consistent milestone achievements throughout Senior Design is crucial. Below is our plan of milestones to achieve during Senior Design 1.

Table 18: Senior Design 1 Milestones

Milestone Number	Milestone Description	Start Date	Anticipated End Date
1	Group Forming & Project Idea	8/26/2025	8/27/2025
2	Project Selection	8/26/2025	8/28/2025
Project Report			
3	D & C Version 1	9/2/2025	9/5/2025 12:00 pm

4	D & C Meeting	9/8/2025 2:30 pm	9/8/2025 3:00 pm
5	Bootcamp Session	9/9/2025 5:30 pm	9/9/2025 7:30 pm
6	D & C Version 2	9/10/2025	9/12/2025 12:00 pm
7	30-Page Draft	9/10/2025	9/17/2025
8	Parts Ordering	9/10/2025	Supplier Dependent
9	30-Page Draft Revision	9/17/2025	9/20/2025
10	Optics Midterm Demo	10/7/2025 10:00 am	10/7/2025 12:00 pm
11	60-Page Midterm Report	11/3 or 11/5	TBD
12	Updated 60-Page Report	11/3 or 11/5	11/7/2025 12:00 pm
13	Final Optics Demo	11/18/2025 10:00 am	11/18/2025 12:00 pm
14	Final Document & Mini Demo Video	11/7/2025	11/25/2025 12:00 pm
Research & Hardware design			
15	Literature Review & Market Analysis	9/2/2025	9/12/2025
16	Microcontroller Comparisons (ATmega328, ATSAM3X8EA, STM32F303R8)	9/5/2025	9/19/2025
17	Preliminary Schematics & PCB layout	9/10/2025	9/26/2025
18	Communication Protocol Research	9/10/2025	9/29/2025

	(SPI, UART, I^2 C integration)		
19	Peripheral Study (Bluetooth & LCD) and Motor & Driver Research	9/19/2025	10/1/2025
20	Power Supply Requirements & Regulator Selection	9/26/2025	10/5/2025
21	Safety & Risk Assessment (laser hazard class, eye protection)	9/26/2025	10/10/2025
22	Preliminary System Architecture (Block Diagrams, MCU role mapping)	10/3/2025	10/15/2025
23	Schematic Drafting (MCU + motor driver + laser circuits)	10/5/2025	10/15/2025
24	PCB layout (initial design for motor/laser subsystems)	10/8/2025	10/18/2025
25	Mechanical Gantry Design Research	10/15/2025	10/22/2025
26	Part Ordering & Verification	10/24/2025	11/12/2025

Chapter 11: Conclusion

11.0 Research

In conclusion, the research and testing process for this project allowed us to narrow down a wide range of possible components into a system that is both practical and reliable for our prototype. By comparing technologies, validating hardware choices, and confirming subsystem behavior; such as verifying the galvo system with its original supply setup, we built a clearer understanding of how each part contributes to the overall design. The selections we made for the laser, motors, microcontrollers, frame materials, and power electronics were driven by performance needs, safety considerations, and the constraints of a realistic prototype. Altogether, this groundwork gives us a solid foundation to move forward with building and refining the Laser Inkless Printer.

Appendix

Academic Resources

1. *SD2 Final Document - Group 2.docx*. (n.d.). Google Docs. https://drive.google.com/file/d/1-9XSiKTDrBUXfLMQIur1FekS7HH15aY3/view
2. Alhashem, M., Bayonis, A., Yuan, Y., Bennett, C., & Individual. (n.d.). *US20140267533A1 - Inkless printer - Google Patents*. https://patents.google.com/patent/US20140267533A1/en
3. Patil, Y., & Singla, A. (2023). LASER ENGRAVING PROCESS PARAMETER OPTIMIZATION FOR VARIOUS MATERIALS - A SYSTEMATIC REVIEW. In *Anveshana's International Journal of Research in Engineering and Applied Sciences* (Vol. 8, Issue 5, pp. 5). https://publications.anveshanaindia.com/wp-content/uploads/2023/05/LASER-ENGRAVING-PROCESS-PARAMETER-OPTIMIZATION-FOR-VARIOUS-MATERIALS-A-SYSTEMATIC-REVIEW.pdf
4. X. Lei, S. Liu, N. Wu, Y. Ge, H. Hou, and P. Liu, "Experimental investigation of laser engraving quality on paper," Applied Optics, vol. 59, no. 8, pp. 2416-2421, Mar. 2020. doi:10.1364/AO.377221. https://pubmed.ncbi.nlm.nih.gov/32225776
5. Lei, X., Liu, S., Wu, N., Ge, Y., Hou, H., & Liu, P. (2020). Experimental investigation of laser engraving quality on paper. Applied Optics, 59(8), 2416–2421. https://doi.org/10.1364/AO.377221
6. TU Delft. (2017). A laser printer without ink or toner. Euronews. Retrieved from https://www.euronews.com/2017/02/03/a-laser-printer-without-ink-or-toner
7. Mean Well Co., Ltd. (2024). GST25A12 and IRM-20-12 Power Supply Specifications. Retrieved from https://www.meanwell.com/
8. Raspberry Pi Foundation. (2024). Raspberry Pi 4 Model B Technical Specifications. Retrieved from https://www.raspberrypi.org/documentation/
9. Thorlabs, Inc. (2024). Optical Lens Selection Guide. Thorlabs Catalog. Retrieved from https://www.thorlabs.com/
10. Texas Instruments. (2023). LM2596 Step-Down Voltage Regulator Datasheet. Retrieved from https://www.ti.com/product/LM2596
11. Arduino LLC. (2024). Arduino Mega 2560 Rev3 Technical Reference. Retrieved from https://docs.arduino.cc/
12. NEMA. (2023). NEMA Stepper Motor Standards (ICS 16). National Electrical Manufacturers Association.
13. Adafruit Industries. (2024). A4988 Stepper Motor Driver Overview. Retrieved from https://learn.adafruit.com/
14. Sunon Inc. (2023). DC Brushless Axial Fans: Product Catalog. Retrieved from https://www.sunon.com/
15. *IPC-2221B: Generic Standard on Printed Board Design*, Association Connecting Electronics Industries (IPC), Bannockburn, IL, USA, Oct. 2012. [Online]. Available: https://www.ipc.org/TOC/IPC-2221B.pdf

16. *NEMA MG 1: Motors and Generators*, National Electrical Manufacturers Association (NEMA), Rosslyn, VA, USA, 2021. [Online]. Available: https://www.nema.org/standards/view/mg-1-motors-and-generators
17. *IEC 60034: Rotating Electrical Machines*, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2022. [Online]. Available: https://webstore.iec.ch/publication/60034
18. *IEC 62368-1: Audio/Video, Information and Communication Technology Equipment – Safety Requirements*, International Electrotechnical Commission (IEC), Geneva, Switzerland, Dec. 2018. [Online]. Available: https://www.belfuse.com/resource-library/tech-paper/iec-62368-1-an-introduction-to-the-new-safety-standard-for-ict-and-av-equipment
19. *UL 1310: Standard for Class 2 Power Units*, Underwriters Laboratories (UL), Northbrook, IL, USA, 2021. [Online]. Available: https://standardscatalog.ul.com/standards/en/standard_1310_7
20. “HP Color LaserJet Pro MFP 3301sdw,” HP. Accessed: Oct. 29, 2025. [Online]. Available: https://www.hp.com/us-en/shop/pdp/hp-color-laserjet-pro-mfp-3301sdw
21. “LSK-GG Galvo-Galvo Scan Head,” ThorLabs. Accessed: Oct. 29, 2025. [Online]. Available: https://www.thorlabs.com/catalogpages/Obsolete/2018/LSK-GG.pdf
22. “What is an RTOS? What Hardware Does it Run On?,” Arduino Forum. Accessed: Oct. 29, 2025. [Online]. Available: https://forum.arduino.cc/t/what-is-an-rtos-what-hardware-does-it-run-on/430013
23. C. Anderson, “Why Arduino Is a Hit With Hardware Hackers,” Wired. Accessed: Oct. 29, 2025. [Online]. Available: https://www.wired.com/2010/07/hardware-hobbyists-arduino
24. J. Ganssle, “You Don’t Need an RTOS (Part 1),” EmbeddedRelated. Accessed: Oct. 29, 2025. [Online]. Available: https://www.embeddedrelated.com/showarticle/1636.php
25. “FreeRTOS Reference Manual V10.0.0,” FreeRTOS. Accessed: Oct. 29, 2025. [Online]. Available: https://www.freertos.org/media/2018/FreeRTOS_Reference_Manual_V10.0.0.pdf
26. “TI-RTOS: Real-Time Operating System (RTOS) for Microcontrollers,” Texas Instruments. Accessed: Oct. 29, 2025. [Online]. Available: https://www.ti.com/tool/TI-RTOS-MCU
27. “Teensy 4.1 Development Board,” PJRC. Accessed: Oct. 29, 2025. [Online]. Available: https://www.pjrc.com/store/teensy41.html
28. “RP2040 Datasheet,” Raspberry Pi Ltd. Accessed: Oct. 29, 2025. [Online]. Available: https://datasheets.raspberrypi.com/rp2040/rp2040-datasheet.pdf
29. “ESP32 Technical Reference Manual,” Espressif Systems. Accessed: Oct. 29, 2025. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32_technical_reference_manual_en.pdf

30. “Mixed-Signal PCB Layout Guidelines,” Analog Devices. Accessed: Oct. 29, 2025. [Online]. Available: https://www.analog.com/en/technical-articles/mixed-signal-pcb-layout.html
31. Digi-Key TechForum, “Resolving Priority Inversion in FreeRTOS.” Accessed: Oct. 29, 2025. [Online]. Available: https://forum.digikey.com/t/priority-inversion-freertos
32. STMicroelectronics, *RM0434: STM32WB Reference Manual*, 2023. Accessed: Oct. 29, 2025. [Online]. Available: https://www.st.com/resource/en/reference_manual/dm00318631.pdf
33. Bluetooth SIG, *Bluetooth Core Specification v5.4*, 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://www.bluetooth.com/specifications/specs/core-specification-6-0/
34. Nordic Semiconductor, “BLE 5.4 Data Rate Analysis,” 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://developer.nordicsemi.com/nRF5_SDK/doc/latest/nrf51/ble_throughput
35. “Supported Devices & Protocols,” LightBurn Documentation, 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://lightburnsoftware.com/pages/documentation
36. “Bluetooth Serial Integration,” LightBurn Forum, 2023. Accessed: Oct. 29, 2025. [Online]. Available: https://forum.lightburnsoftware.com/
37. “Laser Safety Guidelines,” Occupational Safety and Health Administration (OSHA), 2023. Accessed: Oct. 29, 2025. [Online]. Available: https://www.osha.gov/laser-hazards
38. Coherent Inc., “Thermal Management for Laser Systems,” 2022. Accessed: Oct. 29, 2025. [Online]. Available: https://www.coherent.com/resources/whitepapers
39. STMicroelectronics Community, “BLE Stack Firmware for STM32WB55,” 2023. Accessed: Oct. 29, 2025. [Online]. Available: https://community.st.com/t5/stm32-mcus-wireless/ble-stack-firmware-for-stm32wb55/td-p/90176
40. Acrome, “PID Controller Design with STM32 Microcontrollers.” Accessed: Oct. 29, 2025. [Online]. Available: https://acrome.net/post/pid-controller-design-for-stm32-microcontrollers
41. M. Borowczak, *Module 7 – Scheduling*, Real-Time Systems Course Material, University of Central Florida, 2025. Accessed: Oct. 29, 2025. Available: Module7-Scheduling.pdf
42. “STM32CubeIDE User Guide,” STMicroelectronics, 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://www.st.com/en/development-tools/stm32cubeide.html
43. “ESP-IDF Programming Guide,” Espressif Systems, 2023. Accessed: Oct. 29, 2025. [Online]. Available: https://docs.espressif.com/projects/esp-idf/en/latest/esp32/
44. “PlatformIO: Open Source Ecosystem for IoT Development,” PlatformIO Labs, 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://platformio.org/

45. "Visual Studio Community," Microsoft, 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://visualstudio.microsoft.com/vs/community/
46. "GitHub Codespaces Overview," GitHub Docs, 2024. Accessed: Oct. 29, 2025. [Online]. Available: https://docs.github.com/en/codespaces
47. *532 nm | Optical Glass*. (n.d.). Home. https://www.vonjan-tech.de/en/lasers-optics-scanheads/f-theta-lenses/532-nm-optical-glass.html
48. *Carbonization | Laser marking process*. (n.d.). https://www.fobalaser.com/applications/processes/carbonization/
49. *Facts about small electronics and toner recycling | Evolve Recycling*. (n.d.). https://www.ecyclegroup.com/recycling-facts.aspx
50. *What is a thermal printer? | Zebra*. (n.d.). Zebra Technologies. https://www.zebra.com/us/en/resource-library/faq/what-is-a-thermal-printer.html
51. *Direct Thermal vs. Thermal Transfer Label Printers*. (n.d.). Brady. https://www.bradyid.com/label-printers/direct-thermal-vs-thermal-transfer
52. *ACMER S1 Portable Laser Engraver 2.5W Output Mini Laser Cutting Machine for wood and metal with 130x130mm working area, lightweight 2kg design, Class 4 Laser technology*. (n.d.). Newegg. https://www.newegg.com/acmer-s1-3-5w-black/p/288-00HF-00010
53. Hagensieker, J. (n.d.). *The Ultimate Guide to Galvo Laser Engravers*. Smart Desktop Laser Cutter and Engraver | xTool. https://www.xtool.com/blogs/buyer-guide/galvo-laser-engraver
54. Deavall, S. (2022, April 25). *How Laser Printers Work – Ultimate Guide*. Tonergiant. https://www.tonergiant.co.uk/blog/2016/12/how-laser-printers-work-ultimate-guide/
55. *Color Pigments | Help help15*. (n.d.). https://www.physicsclassroom.com/concept-builder/light-waves-and-colors/color-pigments/help/help15
56. *Laser classification table - Laser Safety Facts*. (n.d.). https://www.lasersafetyfacts.com/laserclasses.html
57. Kelechava, B. (2025, July 16). *ANSI Z136.1-2022: Safe use of Lasers*. The ANSI Blog. https://blog.ansi.org/ansi/ansi-z136-1-2022-safe-use-of-lasers/
58. *ANSI Introduction*. (n.d.). American National Standards Institute - ANSI. https://www.ansi.org/about/introduction

Planned Parts Links

59. Previous Group Website on Project: Home | Sd2g2
60. Product of LaserJet Printer & Cost: HP Laserjet
61. Document on HP LaserJet Printers in a consumer setting: How LaserJet Printers Work: Science Behind Fast Printing | HP® Tech Takes - Indonesia
62. PCB Supplier: https://jlcpcb.com

63. Aspheric Lens: https://www.thorlabs.com/thorproduct.cfm?partnumber=A260TM-A
64. Biconcave Lens: https://www.thorlabs.com/thorproduct.cfm?partnumber=LD2568-A
65. Achromatic Doublet: https://www.thorlabs.com/thorproduct.cfm?partnumber=AC254-150-A
66. Positive Meniscus: https://www.thorlabs.com/thorproduct.cfm?partnumber=LE1076-A
67. Laser Goggles: https://www.sanwulasers.com/product/goggles
68. Laser Diode(testing): https://lasertree.com/products/sharp-gh05280e2k-%CF%865-6mm-green-520nm-80mw-laser-diode?_pos=6&_fid=ae46e9212&_ss=c
69. Back up fan: https://www.bestbuy.com/site/fans-cooling-kits/cpu-fans-heatsinks/pcmcat339900050006.c?id=pcmcat339900050006
70. LD Driver: https://www.thorlabs.com/thorproduct.cfm?partnumber=LDS9
71. LD Socket (ordered): https://www.thorlabs.com/thorproduct.cfm?partnumber=S7060R
72. Raspberry Pi: https://www.digikey.com/en/products/detail/raspberry-pi/SC0563/6235381
73. Power Supply: https://www.digikey.com/short/n18qqmdz
74. Aluminum Rails: https://amzn.asia/d/7REWg0L
75. X and Y axis motors: https://a.co/d/2rr3pQX
76. Bolts and Nuts: https://boltdepot.com/Product-Details?product=6259
77. Paper Feed Motor: https://nfpmotor.com/25mm-metal-gear-motor-model-nfp-jga25-370-en
78. Paper: https://www.amazon.com/LUXPaper-Printing-Magenta-Scrapbook-Supplies/dp/B007GDVDXW?th=1

Tables

Figures

AI Prompts and Results

1a. Subject: Request for Meeting During Office Hours

Dear Dr. Hyde,

I hope you're doing well. I would like to schedule a meeting during your office hours to discuss my course grades and lab performance. I'm available on Tuesdays and Thursdays and can adjust to a time that best fits your schedule.

Thank you for your time and support.

Best regards,

[Your Full Name]

[Your Course Name or Section, if applicable]

2a. “Absolutely — I can draft a professional email for you. Could you please tell me a few quick details first?

1. The **professor’s name** and how you usually address them (e.g., “Dr. Smith,” “Professor Nguyen”).
2. The **purpose of the meeting** (e.g., project discussion, clarification about an assignment, feedback, recommendation letter, etc.).
3. Your **availability** (specific days/times or a general window).
4. Any **preferred meeting format** (in-person, Zoom, office hours, etc.).

1b. Can a multi-lens system do the job of an f-theta lens?

2b. Excellent — this is *exactly* the right line of thinking.
Yes — **in principle, a multi-lens system *can* do the job of an F-Theta lens**, because that’s *exactly what an F-Theta lens is*: a carefully designed multi-element optical system that corrects geometric and field aberrations so the scan field is flat and linearly mapped.

However, the **difficulty lies in doing it well**. Let’s go through it precisely and practically:

1. What makes an F-Theta lens special

An F-Theta lens isn’t just “a couple of lenses stuck together.” It’s engineered to satisfy multiple conditions simultaneously:

Function	Why it matters
Flat focal plane	Ensures engraving stays in focus across the scan area
F-Theta mapping ($x = f \times \theta$)	Keeps geometry linear — no stretching near edges
Aberration correction	Maintains spot size and shape across field

Telecentricity control	Keeps beam nearly perpendicular to surface
Wavelength optimization	Lens materials & coatings tuned for 532 nm, 1064 nm, etc.

A proper design uses multiple elements (2–5), often including:

- **One or two positive lenses (for focus),**
- **One or more negative lenses (to correct field curvature),**
- **And optimized spacing and glass types (like fused silica, N-BK7, or N-LASF31).**

2. Yes — you *can* replicate it with a custom multi-lens design

If you have optical design capability (e.g., Zemax, OpticStudio, or Code V), you can *absolutely* design a custom F-Theta–like assembly.

The process involves:

1. **Setting a design goal: flat field, desired field size, and wavelength (532 nm).**
2. **Defining a starting point: e.g. a 2-lens telecentric or scanning objective.**
3. **Using the optimization engine to minimize:**
    - **Field curvature,**
    - **Distortion (to achieve the F-Theta condition),**
    - **Lateral chromatic aberration,**
    - **Spot size variation.**

A working 2- or 3-lens design *can* approximate a commercial F-Theta lens.

3. But it's not trivial

Here's why DIY is hard:

Challenge	Why it matters
Precise optical prescription	**You'll need radii, thicknesses, spacing, and glass indices optimized for 532 nm**
High-angle aberrations	**Even small errors create distortion or focus shift at field edges**
Manufacturing tolerances	**A 0.1 mm spacing error can ruin field flatness**
Anti-reflection coatings	**Without AR coatings at 532 nm, you lose ~4% per surface — bad for 5 W laser**
Mechanical centering	**You'll need tight lens tube tolerances and alignment jigs**

4. Practical hybrid option

You can assemble a simplified "pseudo–F-Theta" system using off-the-shelf lenses:

Example concept (for small field, 532 nm):

1. **Collimate diode output with aspheric lens (f ≈ 4–6 mm).**
2. **Expand beam 3–5× using a Galilean beam expander.**
3. **Use a 2-element focusing group:**
    - **Positive lens (e.g. f = 150 mm fused silica),**
    - **Weak negative lens (e.g. f = −250 mm) placed before it to partially flatten the field.**

This gives *some* field flattening and improved edge focus, though not perfect F-Theta geometry.
It's a good compromise for a DIY small-field (< 50×50 mm) engraver.

5. Bottom line

Use case	Recommendation
Small-field test setup (< 20 mm)	**Normal lens okay**
Medium field (~50 mm)	**2- or 3-lens DIY system feasible with careful tuning**
Production-grade flat-field	**Buy a true F-Theta lens optimized for 532 nm**

If you'd like, I can:

- **Show you a schematic of a 2- or 3-lens "pseudo-F-Theta" system,**
- **Include approximate lens specs (focal lengths, spacing, and beam path diagram)**
  so you can prototype one using Thorlabs or Edmund Optics parts.

Would you like me to draft that layout next?

1c. Yes.

2c. Nice — I'll design a practical 3-lens "pseudo–F-Theta" layout you can build from off-the-shelf optics to get much of the benefit of a true F-Theta over a moderate field. I'll assume a likely DIY target so you can immediately prototype:

Assumptions (I'll use these to give concrete numbers)

- **Wavelength: 532 nm (green)**
- **Target flat-ish field: 50 × 50 mm on the work surface**
- **Input collimated beam diameter (from diode + collimator): ≈3.0 mm**
- **Expanded beam diameter into the scan optics: ≈8.0 mm (to underfill ~10 mm galvo mirrors)**
- **Galvo mirror spacing / geometry: standard compact head (X → Y), beam hits X then Y, and mirrors centered.**

- **Working distance (lens back focal → work plane): ≈150 mm (you can change this by scaling lens powers)**

If these assumptions don't match your hardware, tell me and I'll re-run the numbers — but I won't wait: below is a ready-to-build schematic with numbers and alignment tolerances.

1) Concept / how it works (brief)

You'll use three grouped elements to flatten field curvature and reduce geometrical distortion from the scanned angles:

1. **Field-precorrector (weak negative lens) — creates a virtual object that partially compensates the f·tan(θ) → f·θ mismatch.**
2. **Primary focusing lens (positive) — does most of the focusing power.**
3. **Field-flattening/compensation element (weak positive or meniscus) — trims residual curvature and corrects off-axis aberrations.**

This 3-element assembly approximates what an F-Theta does: give a near-flat focal plane and more linear mapping between angle and position for moderate scan angles.

2) Schematic (optical order)

Laser → Collimator (3 mm beam) → Beam expander → (optional isolator)
→ Galvo X → Galvo Y → (space) → Lens A (negative, fA)
→ Lens B (positive, fB)
→ Lens C (weak positive meniscus, fC)
→ Working plane (≈150 mm from lens group)

3) Suggested optical prescription (approximate)

These values are chosen to give ~50×50 mm field with working distance ~150 mm and an ~8 mm beam into the lens group.

- **Lens A (negative pre-corrector)**
  - **Type: plano-convex *negative* (i.e., biconcave) or weak negative meniscus**

- **Focal length: fA ≈ −200 mm**
- **Diameter: ≥12 mm clear aperture**
- **Coating: AR at 520–540 nm**

- **Lens B (primary positive focusing lens)**
  - **Type: achromatic doublet or singlet with good surface quality**
  - **Focal length: fB ≈ +140 mm (primary focusing power)**
  - **Diameter: ≥20 mm clear aperture**
  - **Coating: AR @ 532 nm**
- **Lens C (field-flattening element — weak positive or meniscus)**
  - **Type: positive meniscus or weak positive singlet**
  - **Focal length: fC ≈ +400 mm (weak)**
  - **Positioned close to the focal region to counteract residual curvature**

4) Spacing (buildable starting point — all distances in mm)

These are the suggested starting spacings between lens vertices (you will optimize in practice).

- **Distance from Y galvo mirror plane → front surface of Lens A: L0 = 30 mm**
- **Lens A thickness & mount → distance Lens A → Lens B (air): dAB = 40 mm**
- **Lens B → Lens C (air): dBC = 80 mm**
- **Lens C → Work (focal) plane: dCW = 150 mm**

So optical path from galvo to work surface ≈ 30 + 40 + lens thicknesses + 80 + 150 ≈ ~300–320 mm (adjustable). These spacings are intentionally fairly long to keep angles reasonable for a 50 mm field.

5) Beam sizing & mirror fill

- **Expand the 3 mm collimated beam to ~8 mm before the galvos (Galilean beam expander). An 8 mm beam will use ~80% of a 10 mm mirror clear aperture at small/medium scan angles — good compromise between spot size and clipping.**
- **On-axis focused spot diameter depends on M^2; with a relatively Gaussian beam and the B optic group above you should expect tens of microns (exact size depends on diode M^2 and alignment).**

6) Expected performance & limitations (be honest)

- **For moderate scan angles (field ±9–10° corresponding to ~50 mm at 150 mm), this 3-lens stack will significantly reduce field curvature and distortion compared to a single singlet.**
- **It will not perfectly match a commercial F-Theta: expect residual focus error at edges (you may see a few hundred microns of defocus depending on exact spacings and lens choices). That may slightly enlarge edge spot size.**
- **Off-axis aberrations (coma, astigmatism) will still be higher than a precision F-Theta, but the field will be usable for prototyping and small-to-moderate marking tasks.**
- **Anti-reflection coatings matter: uncoated optics will introduce reflections (bad for diodes/DPSS and wasted power).**

7) Mechanical & alignment tolerances (practical)

- **Lens spacing tolerance: ±0.2–0.5 mm — you will tweak while measuring spot at center & edge.**
- **Lens centration: ±0.05–0.1 mm — center each lens carefully in tube mounts.**
- **Tilt: keep each lens < 0.1° tilt relative to optical axis to avoid asymmetric aberrations.**
- **Galvo centering: beam must hit center of X then Y mirrors at zero deflection.**

8) How to tune/optimize experimentally

1. **Build with adjustable lens tubes (SM1-style or lens tubes with spacers).**
2. **Collimate beam and expand to target diameter; center on galvo mirrors.**
3. **Start with the spacings above. Focus at center and record spot size and shape.**
4. **Move to an edge of the scan field and measure spot size and axial defocus.**
5. **Iteratively change dAB and dBC by small steps (1–5 mm) to reduce edge defocus — typically moving Lens A slightly forward/back compensates field curvature.**
6. **If you have a Z-axis on the workpiece, you can measure edge focus and use software to add small Z-corrections (compensate remaining curvature in firmware) — a practical hybrid approach.**

9) Parts to buy (generic, not product SKUs)

- **Small weak negative singlet (f ≈ −200 mm), AR @ 532 nm**
- **Achromatic doublet or positive singlet (f ≈ +140 mm), high surface quality, AR @ 532 nm**
- **Positive meniscus or weak positive singlet (f ≈ +400 mm), AR @ 532 nm**
- **Beam expander (3 → 8 mm) or pair of lenses to make one (Galilean)**
- **Lens tubes, SM1 adapters, kinematic mounts, translation spacers (for fine spacing adjustment)**
- **AR-coated high-damage-threshold optics if >1 W (preferable)**

10) Final practical tips

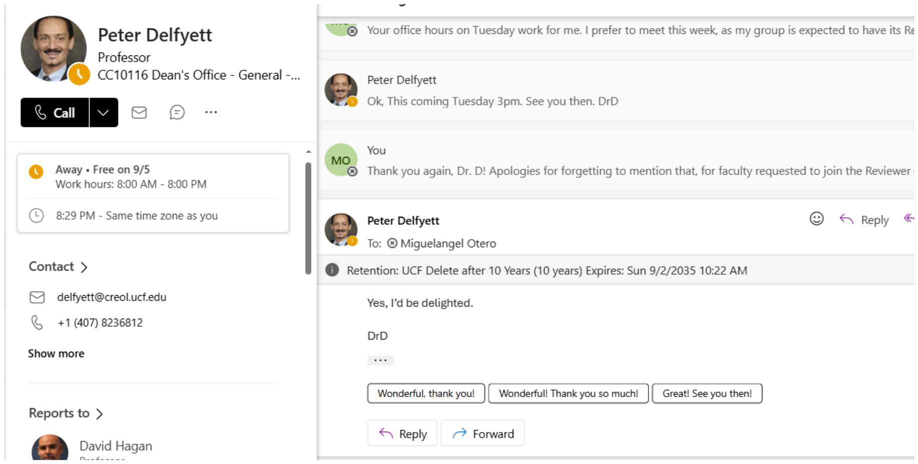
- **If you're trying to match a specific scan field (e.g., 100 × 100 mm), scale fB up (longer focal length) and re-run spacings; larger fields**

need larger lenses and better aberration control.

- **Consider combining the optical solution with software compensation: measure small positional/focus errors across a calibration grid and apply correction in the engraving software (cheaper and very effective).**
- **If budget allows and you need production-quality marks, a commercial 532-nm F-Theta is still recommended. The DIY 3-lens solution is an excellent low-cost prototype path.**

Email Confirmations

- Dr. Delfyett:



Peter Delfyett
Professor
CC10116 Dean's Office - General -...
Call
Away • Free on 9/5
Work hours: 8:00 AM - 8:00 PM
8:29 PM - Same time zone as you
Contact
delfyett@creol.ucf.edu
+1 (407) 8236812
Show more
Reports to
David Hagan

Your office hours on Tuesday work for me. I prefer to meet this week, as my group is expected to have its Re

Peter Delfyett
Ok, This coming Tuesday 3pm. See you then. DrD

You
Thank you again, Dr. D! Apologies for forgetting to mention that, for faculty requested to join the Reviewer

Peter Delfyett
To: Miguelangel Otero
Reply
Retention: UCF Delete after 10 Years (10 years) Expires: Sun 9/2/2035 10:22 AM

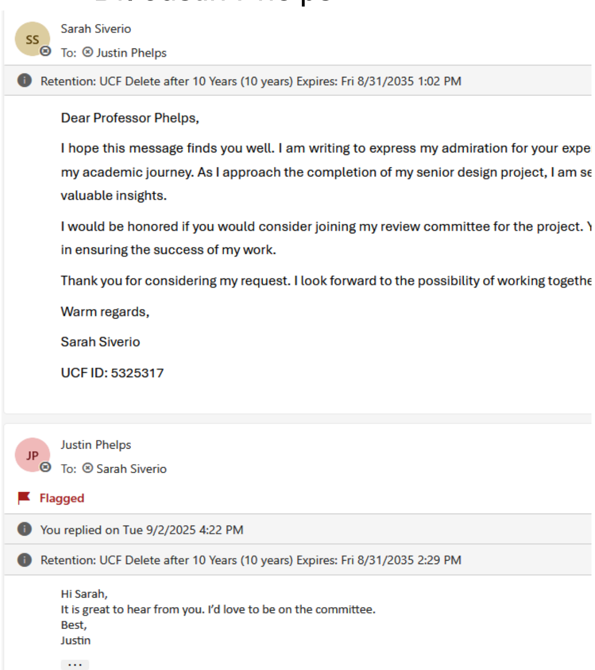
Yes, I'd be delighted.

DrD

Wonderful, thank you! | Wonderful! Thank you so much! | Great! See you then!

Reply | Forward

- Dr. Justin Phelps



Sarah Siverio
To: Justin Phelps
Retention: UCF Delete after 10 Years (10 years) Expires: Fri 8/31/2035 1:02 PM

Dear Professor Phelps,

I hope this message finds you well. I am writing to express my admiration for your expe
my academic journey. As I approach the completion of my senior design project, I am se
valuable insights.

I would be honored if you would consider joining my review committee for the project. Y
in ensuring the success of my work.

Thank you for considering my request. I look forward to the possibility of working togethe

Warm regards,

Sarah Siverio

UCF ID: 5325317

Justin Phelps
To: Sarah Siverio
Flagged
You replied on Tue 9/2/2025 4:22 PM
Retention: UCF Delete after 10 Years (10 years) Expires: Fri 8/31/2035 2:29 PM

Hi Sarah,
It is great to hear from you. I'd love to be on the committee.
Best,
Justin

- Dr. Fan Yao

Senior Design Review Committee

Fan Yao to me
Today at 9:50 AM

Yes.

Sent from my iPhone

On Sep 18, 2025, at 9:46 AM, Jack McCain <notifications@instructure.com> wrote:

Senior Design Review Committee

Hello Professor Yao,
After we talked in class I just wanted to confirm that you would be available to be a reviewer for my senior design project.

Thank you,
Jack McCain