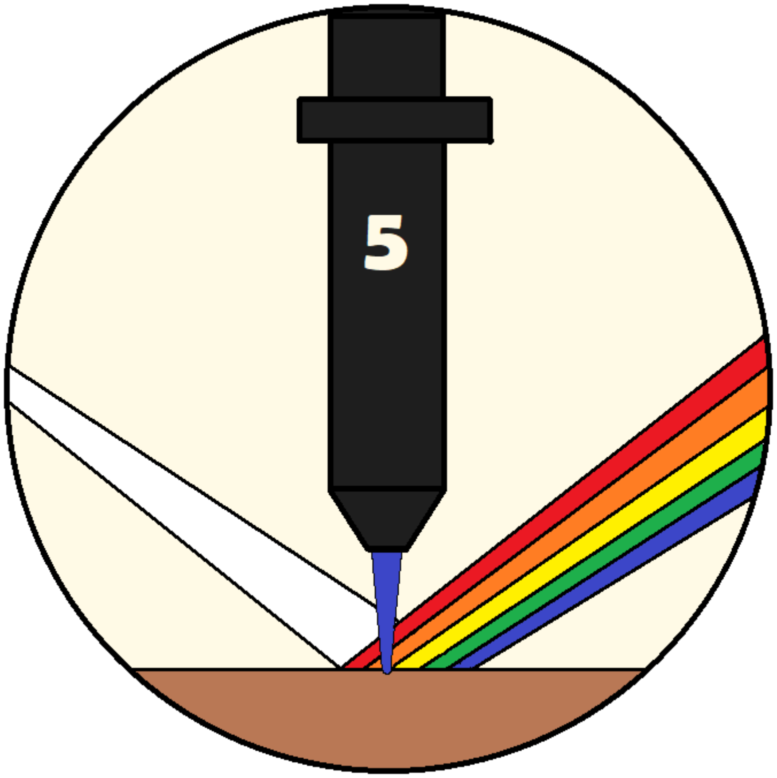
Automated Parameter Adjusting Laser Engraving System (APALES)

ECE Senior Design Group 5



Group Members:
Felipe Mosquera - Computer Engineering
Aly Megahed - Computer Engineering
Kavinaash Jesurajah - Computer Engineering
Jackson Gilliland - Photonics Science and Engineering
Nolan McGinley - Photonics Science and Engineering
Amir Mohd - Mechanical Engineering

Reviewers:
Dr. Hao Zheng
Dr. Peter Delfyett
Dr. Mark Maddox
Dr. Jeffrey L. Kauffman

Table of Contents

1 Executive Summary

Engravings have been an integral aspect of human history dating back thousands of years to the Paleolithic era. Sharpened rocks and bones were used to etch designs into cave walls and animal bones. It was man's earliest form of art and culture. Engraving tools slowly became more sophisticated over the millennia; ranging from hard tools on clay tablets in ancient Egypt to the Greeks using advanced engraving tools on coins and other metal pieces to achieve intricate artisanal designs. Recent history has vastly improved the art of engraving with the invention of motorized engravers and laser engravers. This project aims to improve engraving technology even further by implementing a material detection component to allow for easier and more user-friendly use. Artists who laser engrave multiple mediums must change the laser power settings and engraving speed depending on the material and maintain record of which powers and engraving speeds work best with each material, and this process can be a burden. Our goal is to streamline the process and reduce the necessity of manually changing the laser parameters for each material.

Multiple Senior Design projects in the past have attempted and conquered the challenge of laser printing or laser engraving, but none have implemented an automatic material detection component. There currently needs to be products on the market that employ this technology, as many industries could be reinvigorated using said technology. One such implementation could be the textile industry, allowing from either a large manufacturing lens to the individual consumer to design their own prints and have them be engraved onto their article of choice. The same can be said for other industries depending on the materials, such as engraving your own logo onto your product, or creating advertisements to be engraved onto multiple objects. Another aspect of our project is that we also aim to make laser engraving more accessible to the public. Implementing an automatic parameter adjustment in a laser system will streamline the laser engraving process for household use as well. Our primary goal is to optimize the laser engraving process by removing the necessity of manually changing laser parameters between materials.

Our laser engraver will be a continuous-function engraver, eliminating the line-by-line function of other laser engravers and printers. Our secondary goals are to incorporate an autofocusing component for the laser with an automatic adjustment of the z-stage, this is an industry standard, and our other secondary goal is to be able to detect saved materials with an accuracy of 80% or higher. While not within our current goals, this project also introduces the possibility of future potential, as it envisions a community full of laser engravers with open source to share design. Over the course of this research paper we combined the various disciplines of mechanical, computer, and photonics engineering to create a multi faceted project opening up a new section in laser technology, with a goal to promise material detection that is adaptable, safe, reliable, and a new hallmark in our current field of research and undergraduate study.

2 Project Description

This section serves to provide the motivation that inspired our team to develop a laser engraving system equipped with automatic material identification along with a brief history of other technologies that guided the evolution of our project. Furthermore, this section provides explanations and details pertaining to our project's goals and objectives. Lastly, the requirement specifications of the project are presented to obtain the proposed goals and objectives.

2.1 Motivation

Laser engravers/cutters currently exist in many forms on the market and are increasingly available for consumers with even the smallest budgets. When engraving, users must keep track of each material as well as the laser requirements for each material (power and scan speed). In a cluttered environment, it can be easy to forget the identity of each material and even easier to forget the required laser specifications associated with the material. Some laser engraver owners have resorted to using QR codes to keep track of engraving material information which can waste part of the material's surface area and increase the time and effort needed to keep track of all of the materials. Our project will focus on creating a solution to this problem by linking each material's spectral fingerprint with its name and laser preferences. Our project will automate the material identification process and remove the need for physical labels such as QR codes to keep track of each material.

Currently, there are no laser engravers on the market equipped with the capability to identify the material it is engraving. The responsibility of keeping track of not only the identity of each material but also the laser requirements lies on the user of laser engravers. Users with an abundance of different materials can find it difficult to remember all of the information associated with each material which can cause users to need to go through the diagnostic process again which involves wasting a section of material in order to find the right pairing of power and speed. Our project aims to save all of this information using spectroscopy and have a quick solution to material identification.

2.2 Project Goals and Objectives

This section will outline the goals and objectives associated with our project. Goals and objectives are an essential part of any project because they act as a blueprint for us to follow and ensure our project is continuing properly and on time. Goals represent the overarching targets that are fundamental to the project, like how easily a product can be operated. The objectives indicate the path and processes needed to achieve those goals. These goals and objectives give the project direction and drive, and provide an outline for the team to follow and pursue. We identified the core, advanced, and stretch goals of APALES that suit the project. The objectives required to complete those goals are discussed in detail to provide a clear and straightforward path to success.

2.2.1 Goals

Core goals:
C1.0: Engrave quality patterns on wood, leather, and cardboard
C2.0: Identify wood, leather, and cardboard with >85% accuracy
C3.0: Focus the laser to create linewidths on each material less than 0.40 mm wide
C4.0: Make material prediction in less than 5 seconds

Advanced goals:
A1.0: Recognize wood, leather, and cardboard with >90% accuracy
A2.0: Focus the laser to create linewidths on each material less than 0.25 mm wide
A3.0: Make material prediction in less than 2 seconds

Stretch goals:
S1.0: Make APALES function as a laser cutter for wood, leather, and cardboard

2.2.2 Objectives

(C1.0) To ensure APALES will be operable by a wide audience of minimally trained consumers, we took steps to ensure our system has safety precautions to keep users out of harm's way while operating the laser. we did enclose the engraver with a hood to prevent eye and tissue damage from near UV wavelengths. We included a set of fans for circulation to prevent the buildup of toxic gas. We adhered to regulations pertaining to the use of class IV lasers.

(C2.0) APALES will be able to engrave basic patterns on materials including wood, leather, and fabric. Basic patterns include a simple dot, square, and circle. These patterns do not require much precision or modulation of the laser. Engraving these patterns will be the first step toward creating a fully-capable engraving system.

(C3.0) To ensure APALES can appeal to the market as a valuable product, we did aim to keep the price as low as possible while still accomplishing our goals. To keep the device price to a minimum, we did use cost-effective components such as readily available electronics and metal beams. Upon selection of each component, a cost analysis will be done to ensure the cheapest part will be selected which still meets all of our requirements.

(C4.0) As part of the central goal of our project, our device shall be equipped with the capability to differentiate wood, leather, and fabric. The ability to differentiate between the three will lie in the quality of the spectrometer. We did use high-quality optics as well as ensure proper alignment between components and the camera sensor to obtain consistent data. The camera sensor will be high resolution (minimum 720p) and will cover the visible spectrum. The diffraction grating will have a line density of 1000 lines/mm which should sufficiently break the white light into each unique spectrum.

(A1.0) In order to obtain detailed designs for engravings, it is imperative to have a small spot size for the laser. The spot size will be determined by the ability to focus the diverging light beam from the laser diode with optics and accurate placement. By using lens simulation software such as Zemax, we did optimize lens placement and selection in order to obtain a spot size of under 0.5 mm in any direction.

(A2.0) While the main goal of our system is to create a laser engraver, laser cutters have similar functionality and do not require any additional hardware. Cutting through materials as opposed to engraving them requires more power but will be less sensitive than engraving. Having dual functionality will be done through adding features within the user-interface to switch between engraving and cutting which will change the laser power and scan speed accordingly with the identified material.

(A3.0) An additional feature that will be explored within our engraving system will be adding a feature to detect the distance from the laser to the material surface. Naturally, as various items will be placed under the laser, not all will be of equal height. As the laser beam converges and diverges, the spot size will be unequal at different depths which will make it impossible to engrave consistently without adjustment. By creating a time-of-flight mechanism composed of an LED and photodiode, the z-depth will be read which will enable the adjustment of the laser height to compensate for differences in material thickness.

(A4.0) While the basic goal of our system will be to differentiate wood, leather, and fabric, an advancement will be to expand this to 5+ materials including aluminum, and glass. The ability to detect these materials will lie in the accuracy of the spectroscopy system and will be accomplished by using quality components and accurate alignment. If within budget, we did use a higher quality camera sensor and diffraction grating to increase the resolution of the obtained spectrum.

(S1.0) To be competitive with industry standard laser engravers/cutters, we seek to focus the laser to a spot size of below 0.1 mm in any direction. In order to accomplish this, we did use optical simulation software to determine the right lens and placement to acquire the smallest spot size possible. Additionally, if within budget, more expensive lenses will be used in order to improve the performance of our system if necessary.

(S2.0) Going along with the previous objective, we want to obtain the z-depth distance and use that information to automatically adjust the laser height. The laser mount within the CNC system will have a motor which will move the laser up/down to adjust for the material thickness. we did use a stepper motor to precisely control the laser height in accordance with the measurements obtained using the time-of-flight sensor.

(S3.0) To be on par with similar technology such as the SensiCut, our device should be able to differentiate over ten different materials including different types of wood, leathers, fabrics, metals, and plastics. For this to be done, the highest quality optical components will be used including a high resolution camera sensor, a high performance diffraction grating, and a system of lenses within the spectrometer to focus light to the grating and to the camera sensor.

2.3 Requirements and Specifications

To have a successful project, defining our requirements will help ensure a smooth process going through the pipeline of investigation, development, to building a final product. In this section, we did highlight the various specifications that we did strive to include for the laser engraver, including dimensions, laser wavelengths, and safety features.

Photonics/Optics Engineering General Requirements:

- The system will be able to focus the laser to a spot size of less than 0.3 mm
- The laser system will be able to engrave on wood, leather, fabric, and cardboard.
- The system should be able to adjust its z-distance to control the laser spot size to allow the user to have more/less engraving detail
- The laser should be able to operate within safe optical power limits and has good laser power conversion efficiency.

- The laser system must include an emergency stop

Mechanical Engineering General Requirements:

- The system should have dimensions not exceeding 1 m x 1 m x 1 m.
- The system's weight should not surpass 25 pounds (6.8 kg).
- Ventilation will be managed by automated fans, activating during engraving and ceasing after the process ends.
- Enclosed within a casing, the system will isolate itself from background light and shield users' eyes from harmful UV light.
- The laser temperature should remain between 40-60°C.
- Design the CNC platform's overall structure.
- Integrate the laser module, material sensors, and focusing system seamlessly into the mechanical frame.
- Develop appropriate linear motion systems like belts, linear guides, and ball screws.
- Implement a mechanism for easy material loading/unloading.
- Create a durable and robust safety enclosure ensuring proper ventilation and cooling.
- Construct a stable base housing the platform bed to minimize excess vibrations.

Computer Engineer General Software Requirements:

- The user interface must contain a simple menu to verify CNC is ready and begin the engraving process with user inputs taking less than 1 second.
- Software must be able to process data from the reflection spectroscopy system and classify material with an 80% accuracy rate.
- UI must include confirmation of classified material after receiving data from the spectroscopy system.
- Microcontroller software must be able to interface with laser engraving software on a PC.

Computer Engineering General Hardware Requirements:

- The main PCB must be compact enough to fit onto the side of the CNC machine
- Microcontroller unit must have the ability to interface with the user via LCD display and pushbuttons
- LCD display must be compact but also visible to the user
- The Microcontroller platform must have the ability to interface with the laser and stepper motors of the CNC machine
- The microcontroller must be able to control laser power, through PWM (pulse width modulation) or otherwise
- The microcontroller must be able to interface with the reflection

spectroscopy system to classify the current material being engraved
- CNC machine must include X and Y limit switches to identify the (0,0) position on the board
- CNC laser must be able to engrave intricate patterns/images on each of the material types
- Laser must conform to safety standards (power limitations, fire prevention)

Project Specific Quantitative Requirements:

No.	Specification	Requirements
1	**Laser wavelength:**	450 nm
2	**Laser power:**	4 W
3	**LED power:**	5 W
4	**Diffraction grating:**	600 lines/mm
5	**Bed Size:**	220mm x 220mm (X and Y Axes)
6	**Precision Accuracy:**	±0.01mm
7	**Stepper Motors:**	3
8	**Spectrometer Actuator:**	110mm
9	**Safety Enclosure:**	220mm x 220mm
10	**Material Selection/Compatibility**	Paper, Cardboard, Wood, Leather
11	**Laser System:**	Spot Size < (0.3mm x 0.3mm)
12	**Real-Time Material Detecting:**	Over 85% accuracy
13	**Compatibility Testing:**	Windows, macOS, Linux
14	**User Interface Responsiveness**	Takes < 3 second
15	**Real-TimeControl Latency**	100 milliseconds
16	**File Compatibility:**	DXF, SVG, etc.
17	**User-Interface Screen:**	2.5in x 2.5in
18	**PCB and Microcontroller:**	2.0in x 0.7in

Table 01: Project Specific Quantitative Requirements

2.4 Hardware Block Diagram

The hardware block diagram serves the purpose of visualizing how the hardware of our system works together. The system has a process flow which follows the arrows of our hardware block diagram. The engraving process begins at the external computer when the desired image is converted into g-code by a universal g-code sender, which then is read by the GRBL

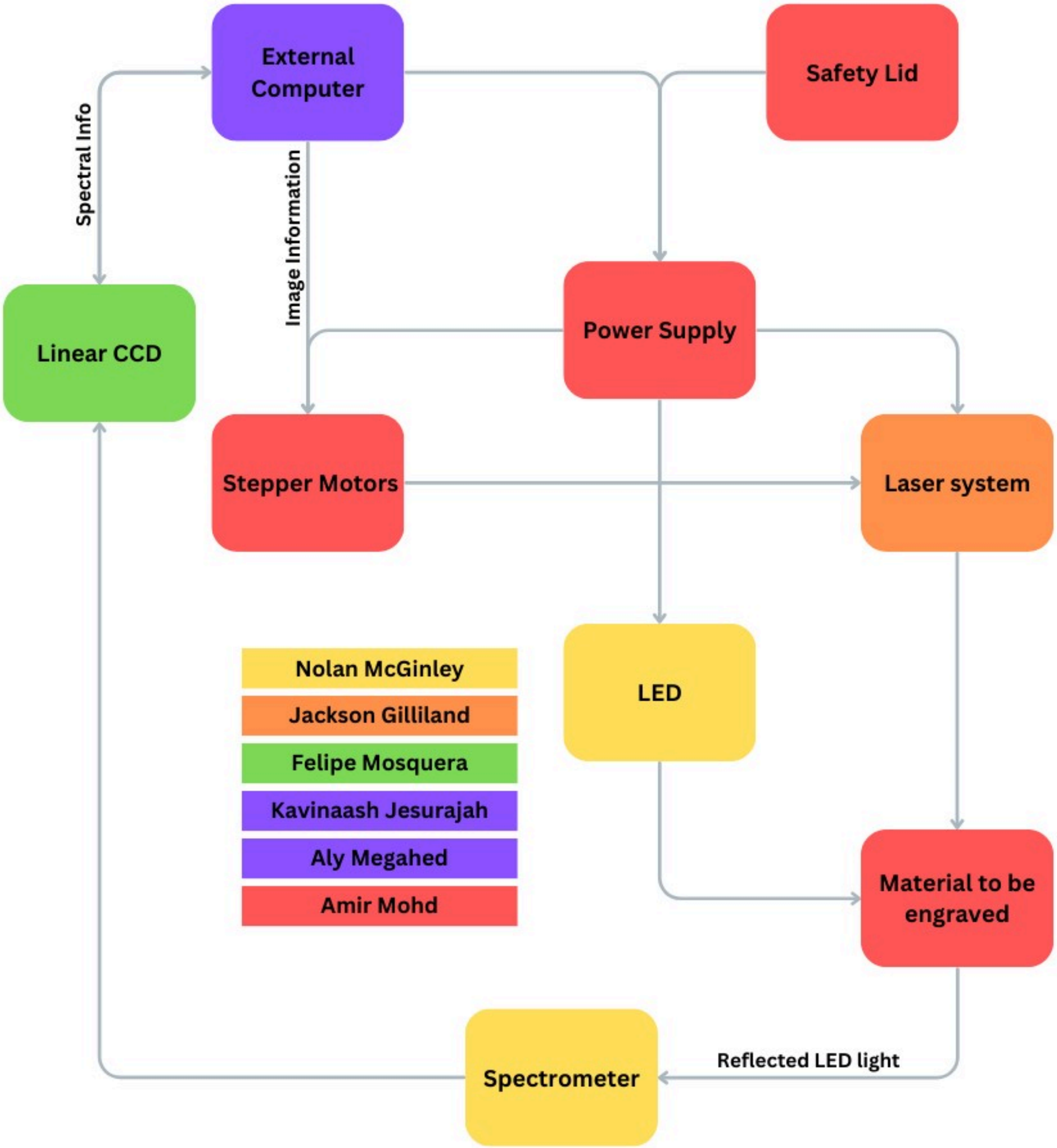


Figure 01: Hardware block diagram and process flow

2.5 Product Investigation

The purpose of this section is to give a brief explanation on the final portion of creating a product, which includes its selling towards a customer base. we did focus on how to find a target audience, and finding the correct way to sell it, as well as looking at other aspects of product manufacturing, such as its quality and the sustainability of the product for a long period of time.

2.5.1 Target Audience and How to Sell

The grace of this project is its ability to be able to adapt to any market, regardless of age or group. Our focus is to create a product that will be able to express your creativity with no bounds, allowing artists to transform any simple material into their own personalized experience. Not only does this product etch designs designs for the user, but completely shifts the paradigm to include any person regardless of their background. While we want this project to be able to hit as many markets as possible, we want our priority to be with people who want to innovate and create. Those who have the ability to be either professional or hobbyists and create the engravings for a multitude of reasons, such as jewelry, custom art, or even gifts to others. This further gets pushed to other markets such as having it be a great tool for those who own small businesses, with the ability to make promotional products, or unique branding to each customer. We also want this to be a good stepping stone for innovation, and can be used at scholar institutes such as schools or colleges for educational purposes. We want this to be further used by any skill level, and for specific applications such as engraving on materials like wood, metal, or leather.

2.5.2 Quality and Ease of Use

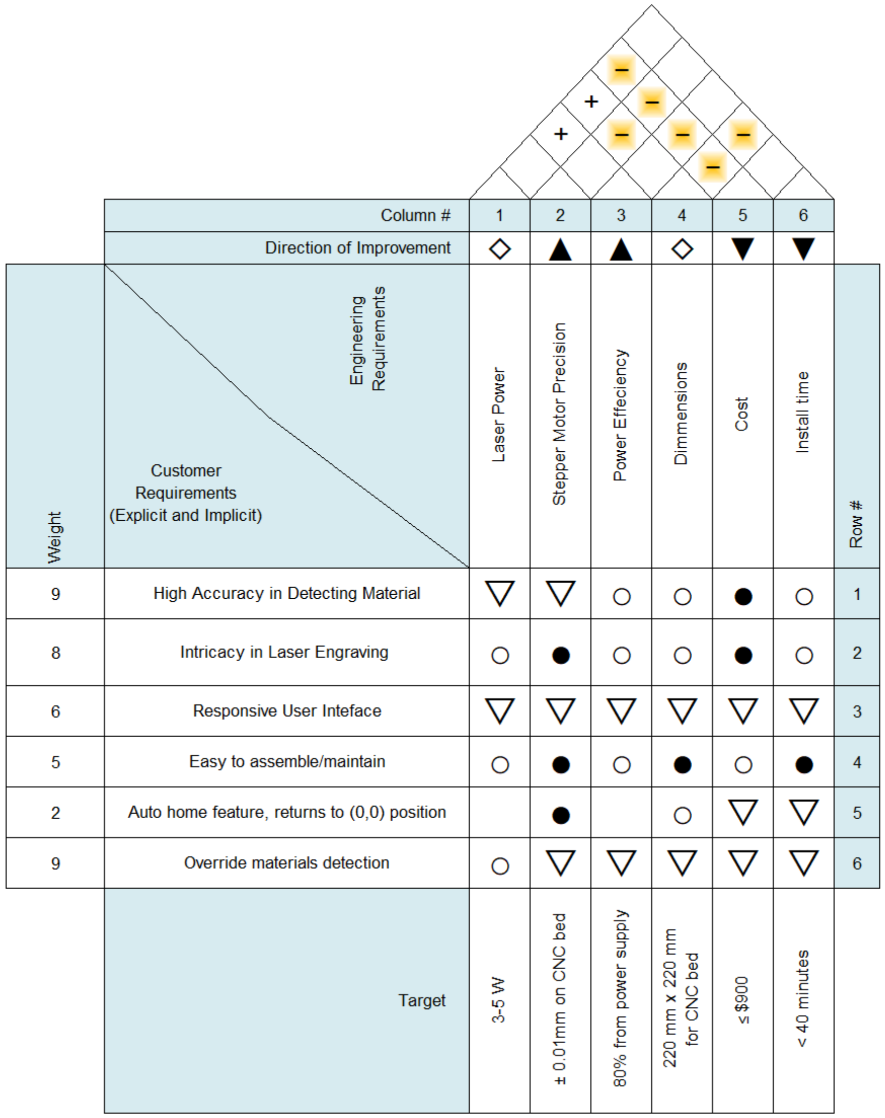
To ensure the success of this project, we want to ensure the ability of offering a quality product that will resist things that degrade it such as wear and tear. The laser will offer precise designs for etching, with the detailing being reproduced as faithfully as we can. Having a product that will end in these types of results is a defining aspect of a quality system. Consistency and durability will be at the forefront of our project, as time progresses we want to continue having the same quality of products from now to a few years from now. Another important regulation to maintain is how easy it is to use. we did have the engraving system use a UI that is friendly for use. This is enhanced by the fact that we are using softwares that has various libraries and a multitude of online resources to further ease the experience.

2.5.3 Sustainability and Regulatory Compliance

If we want to offer a product that ensures sustainability, one of the key aspects to keep in mind will be its efficiency in energy consumption. One step we are taking to keep this is the type of hardware we use, such as the MCUs that use LPM (Low Power Mode). we did also try to build it using materials that can be durable and long lasting, such as its aluminum rails. It also offers a compact design allowing for easy use for transportation. Besides the material used to construct it, we are focused on having reduced emissions. To reduce our footprint, we are going to create the proper systems for ventilation, as well as filtration so it can capture any fumes that could be hazardous.

2.6 House of Quality

The house of quality shown below represents the relationship between customer/market requirements and engineering requirements. There is a strength associated with the relationship of each pair of requirements. These values are shown in the “main room” section (center square) of the house. For example, the intricacy in laser engraving has a strong relationship with the stepper motor precision. Additionally the house of quality shows positive or negative relationship between every pair of engineering requirements. These values are shown in the roof section (top triangle). For example, a higher laser power means a higher cost, there is a negative relationship since we aim to reduce cost.



Weight	Column #	1	2	3	4	5	6	Row #
	Direction of Improvement	◇	▲	▲	◇	▼	▼	
		Laser Power	Stepper Motor Precision	Power Effeciency	Dimmensions	Cost	Install time	
9	High Accuracy in Detecting Material	▽	▽	○	○	●	○	1
8	Intricacy in Laser Engraving	○	●	○	○	●	○	2
6	Responsive User Inteface	▽	▽	▽	▽	▽	▽	3
5	Easy to assemble/maintain	○	●	○	●	○	●	4
2	Auto home feature, returns to (0,0) position		●		○	▽	▽	5
9	Override materials detection	○	▽	▽	▽	▽	▽	6
	Target	3-5 W	± 0.01mm on CNC bed	80% from power supply	220 mm x 220 mm for CNC bed	≤ $900	< 40 minutes	

Correlations		Relationships		Direction of Improvement	
Positive	+	Strong	●	Maximize	▲
Negative	−	Moderate	○	Target	◇
Correlation		Weak	▽	Minimize	▼

Fig 02: House of quality chart

3 Technology Investigation

The technology investigation section serves to provide a background on similar products, a review of relevant technology, and some necessary theory to understand the functionality of our project. It is imperative to understand the state of the market surrounding laser engravers and material identification technology to get a picture of the problem our project seeks to solve.

3.1 Similar Products

Laser engravers are a fairly abundant technology available on the market even for the most cost-restricted folk. A quick search on Amazon will find the cheapest laser engravers available for little more than one hundred dollars. What is more rare is to find a laser engraver with the ability to detect the material being engraved. The majority of laser engravers leave it up to the user to adjust the laser parameters to fit with the material being used. In order to find the right power and scan speed, laser engraver users have to go through a diagnostic process in which a new material has a grid engraved where in each square of the grid, the laser power and scan speed are changed slightly in order to show how variable setting affects the material’s appearance. Users can save their preferences manually in an external source but have no way to automatically set the laser parameters by identification alone.

There are currently no commercial laser engravers that have a material detection feature, but there have been a couple of independent projects done in the past that have sought to achieve a similar goal.

3.1.1 SensiCut

SensiCut is a material-sensing platform for laser cutters that can identify thirty different materials using an optical technique known as “speckle sensing” (MIT News). Speckle sensing identifies materials by analyzing their microstructure using a laser light source. SensiCut can differentiate many materials that appear very similar visually but have different structures at the microscopic level. SensiCut captures images of the reflection from the laser bouncing off of the material. As materials have various surface patterns and roughnesses, light will reflect differently depending on the microstructure. Additionally, as laser light is coherent, the reflected light will interfere with itself either positively or negatively resulting in a speckle pattern which is captured by a sensor on the SeniCut module. The captured image runs through a machine learning algorithm that compares the captured speckle pattern to those already in the database and finds the most likely match.

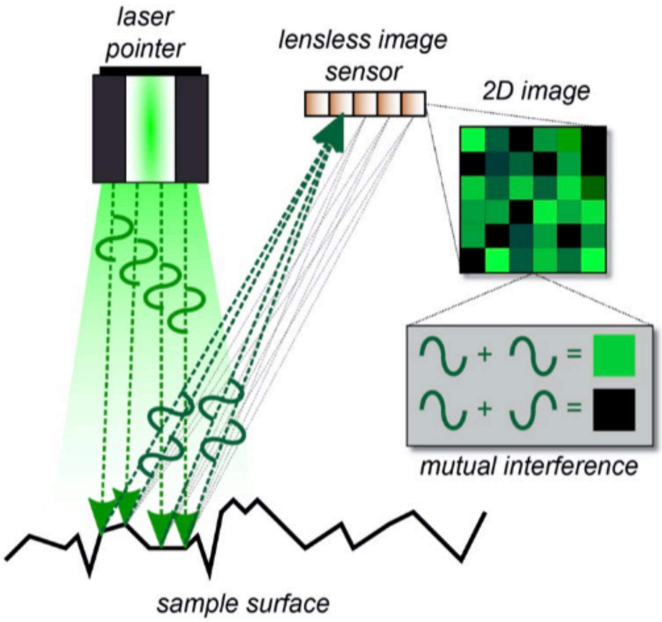


Figure 03: Diagram of speckle-sensing technology that SeniCut uses to identify materials (MIT News)

SensiCut boasts an accuracy of over 98% and claims that its module can identify materials unsafe for engraving/cutting. SensiCut comes with its own database of material speckle patterns which allows new users to seamlessly identify their own materials without the need for a diagnostic process. It should be noted that SensiCut is not an all-in-one device for laser cutting/engraving, it is an accessory that can be attached to a running system. SensiCut aims to achieve a very similar goal to our project, which is to automate the material identification process in laser engraving. Our project is achieving the same goal and integrating the optics-based material identification process into a fully working laser engraver.

3.1.2 Boss Laser

Boss Laser is an industrial laser cutter/engraver with a large cutting space and high cutting power. Boss Laser proves a range of different size laser cutters and a range of powers as well. These laser systems do not have automatic material detection but they do implement a high power laser for engraving and cutting. Boss Lasers implement CO2 lasers at a wavelength of 10.6μm and powers upwards of 55W. Laser systems of this size are useful in a wide array of applications and industries like industrial manufacturing, auto manufacturing, electronics, and medical devices. The wide range of powers makes this laser able to cut metals or only slightly engrave wood. Boss Laser uses a large laser engraving system and the entire engraving surface is enclosed by a hood, and if the hood is breached then the laser immediately cuts off, eliminating the necessity for safety goggles during use. This technology is different from ours because of the high powered applications like cutting metals, and Boss Laser lacks any material detection capabilities, but it is similar to our theorized technology because of the clear CNC like operation of the machine. Boss Laser has a very unique design compared to our design because they station the laser on the side of the engraver and use mirrors to direct the beam to the engraving head. This is a very expensive method of beam direction because of the cost of the mirror system. They most likely get the optics for cheaper because they buy them in bulk and implement them into numerous machines. Boss Laser also requires the user to input the laser cutting parameters like power and engraving speed on every job.

3.1.3 Glowforge

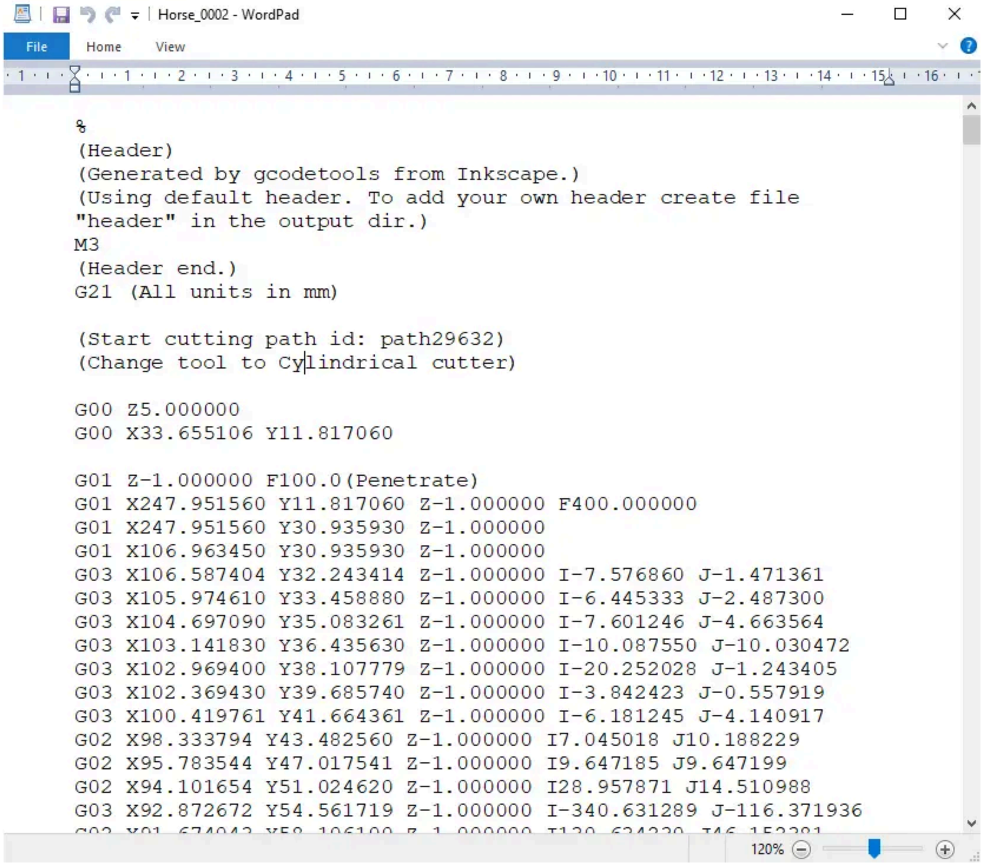
Glowforge is a laser engraver/cutter that is used for at home applications, and aligns closer to our applications more than an industrial laser system like Boss Laser. The Glowforge systems are compact CO2 laser systems that have decent cutting bed size and high output optical power. Glowforge also implements a stationary laser with an array of mirrors directing the beam to the engraving head. They can cut many materials to relatively large thicknesses upwards of ten millimeters thick. Their design houses the entire system in an enclosure and eliminates the need for safety goggles during use. This enclosure also eliminates dangerous fumes and smoke that are created during the cutting or engraving process. This design is similar to ours because it is an enclosed at home use laser engraver/cutter, but the machine lacks material detection capabilities and the user must enter laser engraving power and speed parameters on every material every time.

3.2 CNC Software Components

Understanding motion control software is imperative for the CNC design of this project. CpE needs to have a good understanding on how to interface the microcontroller with the CNC system and how to interface the PC with the microcontroller. We must know how to take a raster or vector image on the PC and prepare it to be sent to the laser engraver. This process requires some system of conversion into commands that the MCU can understand.

3.2.1 G-code Introduction

G-code is a programming language that’s commonly used for CNC machines. It stands for “geometric code”. The commands in a G-code file tell the machine where and how to move: at what speed and the path to follow. The following is an example of a g-code file generated from a vector graphics app called Inkscape. The example was supplied from howtomechatronics.com.



```
%
(Header)
(Generated by gcodetools from Inkscape.)
(Using default header. To add your own header create file
"header" in the output dir.)
M3
(Header end.)
G21 (All units in mm)

(Start cutting path id: path29632)
(Change tool to Cylindrical cutter)

G00 Z5.000000
G00 X33.655106 Y11.817060

G01 Z-1.000000 F100.0(Penetrate)
G01 X247.951560 Y11.817060 Z-1.000000 F400.000000
G01 X247.951560 Y30.935930 Z-1.000000
G01 X106.963450 Y30.935930 Z-1.000000
G03 X106.587404 Y32.243414 Z-1.000000 I-7.576860 J-1.471361
G03 X105.974610 Y33.458880 Z-1.000000 I-6.445333 J-2.487300
G03 X104.697090 Y35.083261 Z-1.000000 I-7.601246 J-4.663564
G03 X103.141830 Y36.435630 Z-1.000000 I-10.087550 J-10.030472
G03 X102.969400 Y38.107779 Z-1.000000 I-20.252028 J-1.243405
G03 X102.369430 Y39.685740 Z-1.000000 I-3.842423 J-0.557919
G03 X100.419761 Y41.664361 Z-1.000000 I-6.181245 J-4.140917
G02 X98.333794 Y43.482560 Z-1.000000 I7.045018 J10.188229
G02 X95.783544 Y47.017541 Z-1.000000 I9.647185 J9.647199
G02 X94.101654 Y51.024620 Z-1.000000 I28.957871 J14.510988
G03 X92.872672 Y54.561719 Z-1.000000 I-340.631289 J-116.371936
```

Figure 04: Gcode example for cylindrical cutter (HowToMechatronics.com)

We can see that each of the lines start with “G##” followed by a set of numbers. Each of these lines represents a g-code command and its parameters. The first three parameters in a given command represent the cartesian coordinates, XYZ. Notice each of the Z values are set to 1, this example is working with a 2D plane. In addition to the cartesian coordinates, some commands contain an F parameter, which is the feed rate or how fast the move will be done.

Each of the g-code commands represents some action or configuration that the CNC machine must perform. The G00 command rapidly moves the machine to some position without cutting. All axes are moved at the same time, so the machine moves in a straight line from the previous coordinate to the new one.

The G01 command tells the machine to move linearly from the previous position to the end position specified as its parameters. It includes a feed rate to indicate the speed of the movement. It is a cutting/engraving movement. The machine controller interpolates the in-between points for the straight line to travel through. It must perform thousands of calculations per second to complete the movement.

In addition to linear movements, circular movements may be performed using G02 and G03. The former is used for clockwise circular interpolation while the latter is used for counterclockwise interpolation. In addition to the end position, a G02 (or G03) command requires an offset parameter to indicate the center of the arc. Let’s use the following set of commands as an example:

```
G01 X6 Y14 F200
G02 X12 Y8 I0 J-5
```

The start position for the G02 command is the end position of the G01 command. The G02 command places the center point of the arc -5 units below the (6,14) coordinate. This is used to perform the clockwise arcing cut, which ends at position (12,8) according to the G02 command. In practice, the G00 command is used to set-up some starting position, while the G01, G02 and G03 commands are used for the cutting/engraving of some shape.

Besides these movement commands, there are configuration commands for unit selection. G20 sets the g-code units to inches while G21 sets them to millimeters. Since the feed rate is in units/min, if the code is set to G20 the feed rate is in inches/min while if it's set to G21 the feed rate is in mm/min. There is also a home position command, G28. This returns the tool/laser to its reference point.

Typically this g-code won’t be produced manually to engrave the desired shape or pattern. We’ll be using some software to convert an image to a g-code file, which can then be interpreted by our machine.

3.2.2 GRBL

GRBL is a free and open source software that functions as motion control for a microcontroller. It facilitates the operation of a CNC machine via an Arduino board. GRBL is typically used with the Arduino Uno board, which uses the ATmega328P microcontroller. This is the MCU family that GRBL is designed to run on. Shown below is the GRBL pinout for the Arduino Uno board courtesy of Koert van der Veer via the GRBL GitHub.

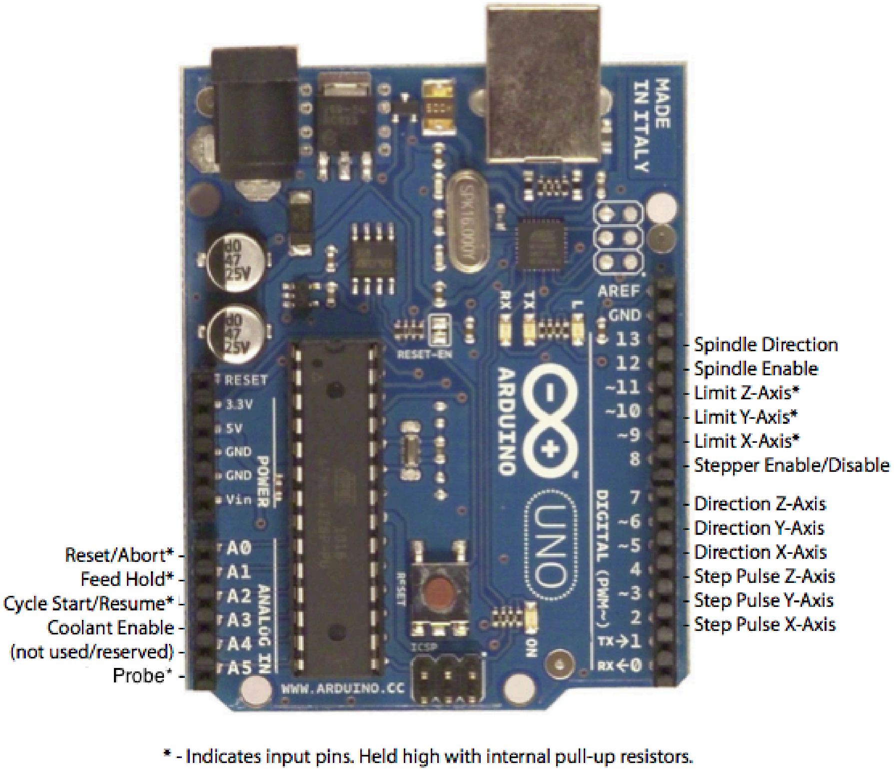


Figure 05: Arduino UNO with GRBL pin-out indicating signals (github.com).

The software was initially released in 2009. It was first created by Norwegian developer Simen Svale Skogsrud and since 2011 has been maintained by American developer Sungeun K. Jeon. GRBL isn't an acronym, it's actually a stylised spelling of the word “gerbil”. Skogsrud named it after a bigger version of a computer mouse. It is a free software released under the GPLv3 license. GRBL has been adopted as the motion control software of choice by several companies such as Inventables and Carbide3D. It was primarily designed for milling machines (subtractive manufacturing), however it has been used for all kinds of CNC projects including laser engraving.

GRBL accepts the files generated by CAM software, which contains the g-codes. It converts those g-code instructions into signals which can be received by the stepper motors. GRBL supports outputs for most mechanical requirements of a given CNC project. The developers have targeted the Arduino based ATMega328 series chips, which makes the software well optimized for this low cost hardware.

After converting the image or vector graphic via some CAM software, the g-code file is ready to use with GRBL. The g-code can be streamed via a USB port to the microcontroller board on which GRBL is installed. A g-code compatible software such as Universal G-code Sender (UGS) may be used from the host computer. GRBL supports all standard g-codes, however it does not support macros, which can be handled by the g-code sender instead.

A helpful feature of GRBL is its “look ahead” approach for controlling machine accelerations. It can see upcoming g-codes and make sure that the machine produces smooth conversions between motions. Since GRBL is a free motion control software with well optimized performance, it’s a major consideration to be used in our project. The only limitation is that it requires the use of the ATMega328 chips.

3.2.3 Inkscape

Inkscape is a free and open source software (FOSS) for editing vector graphics files. It is compatible with Windows, macOS and GNU/Linux. Inkscape can be used for both technical and artistic drawings: logos, clip art, typography, flowcharts, diagrams and more. Since it uses vector graphics, it allows for sharp printouts and renders at any resolution. This is unlike raster graphics, which is limited by a finite pixel resolution. It uses the SVG file format, which is supported by many other apps. Inkscape is also extensible; it supports many add-ons to expand its functionality.

For our application, Inkscape can be very useful since it supports bitmap (raster) to SVG conversion. We can take existing logos or pictures and convert them into a vector format. This vector format can be modified on Inkscape in accordance with our dimensional constraints. We can add or remove shapes and lines as well as modify the thickness of certain areas. Inkcape facilitates the preparation of the images/logos for engraving.

Inkscape also supports an extension called Gcodetools, which converts the vector image into a g-code file. It operates with a function called “Orientation points”, which looks at the existing points associated with the vector graphics image. The image/model can be scaled according to the desired size. The tool size can be set, which will be the laser spot size we’re working with. Additionally, the feed rate can be specified. These parameters will generate the g-code accordingly.

While Gcodetools can be useful, it is designed for general purpose CNC applications. There is an Inkscape extension more tailored to laser CNC applications called Inkscape Lasertools. It supports parameterisation of the laser on/off command, laser speed, and PWM among other things. As with the Gcodetools extension, this parameterisation is used to generate the g-code. Which extension to consider will depend on ease of use and the compatibility of generated g-codes with the GRBL firmware.

3.2.4 Universal G-code sender

Universal g-code sender (UGS) is a g-code platform used to communicate with motion control software like GRBL. It’s a cross-platform Java application with support for Windows, macOS, Linux and Raspberry Pi. It features a 3D Gcode visualiser including color coded line segments and real-time feedback for the tool/laser position.

To use UGS, the user imports the g-code file from the CAM software (Inkscape) and connects the machine/microcontroller with the motion control software installed. The firmware and port must be set, for example GRBL on Arduino Uno using port 3. The user must find the zero position on the board/slab being cut into and set the tool/laser accordingly. The physical position must match the g-code, UGS supports position feedback through the controller state option. After setup is complete, the user can then begin the engraving process. This is where UGS begins sending the g-codes to the microcontroller. Using the controller state feature, the user can track the current position of the tool/laser during the engraving process.

An advantage of using UGS is the support for the manual movement of the machine. Rather than using an imported g-code file, the user can interact with a GUI that controls the tool/laser position. This can be very useful for testing the mechanical design of the CNC platform. UGS allows us to set some step size (in mm) for the machine to move. Moving the machine a certain number of steps and then manually measuring the distance traveled lets us test the accuracy of the stepper motors as well as the vibrations.

3.2.5 LaserGRBL

An alternative to using UGS and Inkscape is LaserGRBL, an all-in-one software package that can take a raster image as input and send the g-codes to the GRBL microcontroller. LaserGRBL is a free and open source software tailored for laser CNC machines using GRBL v0.9 and GRBL v1.1 standards.

Similar to UGS, LaserGRBL supports a load and preview option for g-code files. The user is able to see what the engraving job will look like ahead of time. It also supports manual control of the laser through user defined buttons. These custom buttons are configured to execute a set of g-codes in order to test the CNC machine. There is an option for “TwoStateButton” which executes some configured action on the first click and a different action on the second click. This is typically used to test the laser on/off functionality. Another useful feature is the GRBL import and configuration. Through LaserGRBL the user is able to flash the Arduino board with the GRBL firmware.

LaserGRBL supports the import of raster images directly (jpg, png, or bmp). Images can be resized according to the engraving dimmensions. Raster images can then be converted to grayscale or black and white and then a conversion tool can be used to produce the g-code. One of the conversion tools, Line-to-line, produces g-codes designed to work with the PWM output of the laser. It can simulate the “shades of gray” on the material engraving.

As with UGS, once the g-codes are generated and are ready to be sent to the microcontroller the engraving process can be started. LaserGRBL supports job-time preview as well as realtime projection. The advantage of using LaserGRBL over UGS is that it’s tailor made for laser applications. The conversion tools for raster images may be easier to work with than in Inkscape. Since the g-codes are generated for laser applications it may produce a clearer engraving on the material.

3.3 Microcontroller Usage

To understand the implementation of a microcontroller into our project, first there needs to be an introduction to the concept of embedded systems as a whole. In its simplest terms, an embedded system is hardware that includes the use of a microcontroller within its components. That means that something like a vending machine may be considered an embedded system, as it includes a microcontroller to input signals, collect cash, and the dispensing mechanism. The microcontroller we decide to use will become the focal point for this entire system, so great consideration will be given to the one chosen, Many things need to be included for this laser engraving system such as: CNC Motors, the ability to read and store data from the position of the motors, control the laser, read the data from the sensors,, and have communication with software on the computer to read and display data.

To be in accordance with our own requirements, within our research, we saw the requirements of good communication with the computer, several GPIO pins to allow connection for various uses, and store data from the sensors. One important feature of our project is the ability to be able to detect the material being presented, allowing it to run at various speeds depending on the depth of engraving and material type. Because of this, it is imperative our microcontroller is able to process data at various speeds allowing it to run at the same time as our laser, so it won’t run any trigger for safety issues. We also want to have our microcontroller have easy access to transmitting information to a software running on a computer, so this is important to take note of when deciding what kind of microcontroller to have installed. We want to have the microcontroller communicate with software that can interface with laser engraving software on a PC. The following sections will begin to highlight a variety of microcontrollers from the past 50 years that are commonly used microcontrollers, so we can compare the features used in them to combine to have the features desired.

3.3.1 AVR Microcontroller

The AVR Microcontroller is a family of 8-bit microcontrollers that were developed in the late 1980's by two Norwegian students, with its first microcontroller being released in 1997, known as the AT90S8515. The AVR continues to be a legacy product, being implemented and used in various projects developed in the 21st century. Some of the key features of the AVR is offering low power mode, clock speed up to 32 MHz, and several built in functions such as UART and I2C.

One of the more popular microcontrollers of the AVR family is the ATmega16, being introduced in the early 2000s. This was created by Atmel for its second generation of microcontrollers. It was then succeeded by the ATmega16, 32, 64, etc. These included further memory and quality of life inclusion. Below the specs of the ATmega16 are highlighted:

Processor Core	**Memory**	**Functions**	**Clock**	**LPM**
8-Bit 1 MHz-16 MHz	Flash: 16 KB SRAM: 1KB EEPROM: 512 Bytes	32 Pins ADC UART SPI I2C PWM	RC Oscillator 8 MHz	Yes

Table 02: Specs included in the ATmega16

Several important things are included in the datasheet for this microcontroller we highlighted, such as its several functions and various amounts of pins. When designing the PCB that will be embedded into our project, these are just some of the key features to keep in mind.

As far as microcontrollers that are commercially available and easily accessible for us in this project, one of the possible choices for our decision would be the ATmega32. There are several reasons for this being the one chosen. Given that this is part of the AVR family of microcontrollers, it offers many of the same benefits done in the previous iteration, the ATmega16. The board can be developed using either C or C++, allowing easy use for developing code, as there are various tutorials, examples, and basic documentation online. Other basic features that are included are 32 KB of flash memory, 32 pins for I/O use, multiple timers, and it has serial communication protocols such as UART, SPI, I2C, and ADC as well. When keeping this all in mind, the ATmega32 becomes a very enticing choice as the MCU, thanks in part to its several features such as its versatility, variety of features, easy programming using the Arduino IDE, and tons of support for it online.

3.3.2 8051 Microcontroller

Another popular microcontroller important to emphasize is the 8051 microcontroller, developed in the 1980s by Intel, which garnered attention as being forward thinking as one of the first microcontroller families. Similar to the AVR MCU (microcontroller unit), it is also an 8-bit core, with 128 bytes of memory. Despite this MCU being one of the oldest of its kind, it's been able to stand the test of time by still being implemented, resulting in extensive research done, including numerous libraries and resources in relation to them. Despite its age, the 8051 includes much historical significance as it continues to be a valuable platform for many projects. Some of the specs included are highlighted below:

Processor Core	Memory	Functions	Clock	LPM
8-Bit 1 MHz-33 MHz	Flash: 64 KB RAM: 128-256 Bytes EEPROM: N/A	32 Pins ADC UART SPI I2C PWM	RC Oscillator 12 MHz	Yes

Table 03: Specs included in the 8051

3.3.3 MSP Microcontroller

The last MCU family I want to emphasize in the decision of features to implement, is the MSP. The MSP (Microcontroller Super Lower Power) family was developed by Texas Instruments in 1993, which started with the release of its first edition, known as the MSP430. There are various version of the MSP that have been created, but the MSP430 has been able to outshine as being one of the most popular choices for embedded systems, due to much of its customizability, and ability to have low power consumption as well as high performance in relation to embedded systems.

The MSP430 uses a 16-bit design, with the MCU I want to show importance to is the MSP430FR6989 in particular, being that I have prior experience using this board for creating an embedded system. This specific board was used in an educational setting prior to taking this course, as a means to get a grasp on the general concept of embedded systems. Through labs with real world applications, I was able to Below is some of the specs for this board:

Processor Core	**Memory**	**Functions**	**Clock**	**LPM**
16-Bit 8 MHz-16 MHz	Flash: 128 KB FRAM: 2 KB EEPROM: N/A	64 Pins ADC UART SPI I2C PWM	RC Oscillator 12 MHz	Yes, LPM3 LPM4

Table 04: Specs included in the MSP430

3.3.4 Comparisons of Microcontroller

When developing our project, we had to have careful consideration in the selection of our microcontroller. Various elements were observed and taken respectfully in our final decision. We did take a look at various MCUs that are all from different families, with each having distinct features that can be applicable for a wide variety of scenarios. Some of the key aspects we kept in mind is the energy efficiency of MCUs such as the MSP430, or how the 8051 has a much easier usage for simple hobbyist projects. But for us, the final choice does ultimately depend on the restraints in our project's requirements, with the amount of power and memory needed.

When considering these MCU options, the one that truly fits the necessities of our project is ultimately the ATmega 32. It comes out on top as being the most compelling choice for its higher memory capacity compared to the ATmega16. This allows for us to have an abundance of space not just for the code itself, but to store data, such as the various materials and their respective information in our databases. Being one of the more popular choices in the MCU community as well as in large industry designs just shows its effectiveness in providing a reliable product. For our project that requires a larger memory storage device, as well as a low power mode, and its large amount of pins, and its communication with several software components, it makes ATmega32 a very valuable choice for our laser engraver.

3.3.5 Functions for Communications

Regardless of the MCU that will be chosen, it is essential to have a grasp and general understanding on the various communications that the MCU will have with its interface. In this situation, the PC, which will be able to display the data being done. Generally speaking, the way the two pieces of hardware communicate with each other is through the hardware itself rather than software. Several forms of communication are essential in any form of embedded system, such as gathering data from sensors, machine interfaces, etc. Many times when using these communication functions, code will have to be written and configured onto the microcontrollers hardware as a way to communicate to and from each other.

3.3.5.1 PWM

PWM (pulse width modulation) is a standard communication protocol used in many electronics/embedded systems that include the use of a microcontroller. Typically it works by having a voltage applied to, in our case, motors, by having it be turned on and off incredibly quickly, as a means to control the intensity of the motor. This process involves generating a series of pulses, during which when its on and off is referred to as on-time and duty cycle. To get a specific measure, we did use both on-time and duty cycle to determine an average voltage used. One certain limitation to this protocol is that it can create electrical noise, which becomes stronger as the frequency of the PWM increases. To overcome this, some form of filtration may be used.

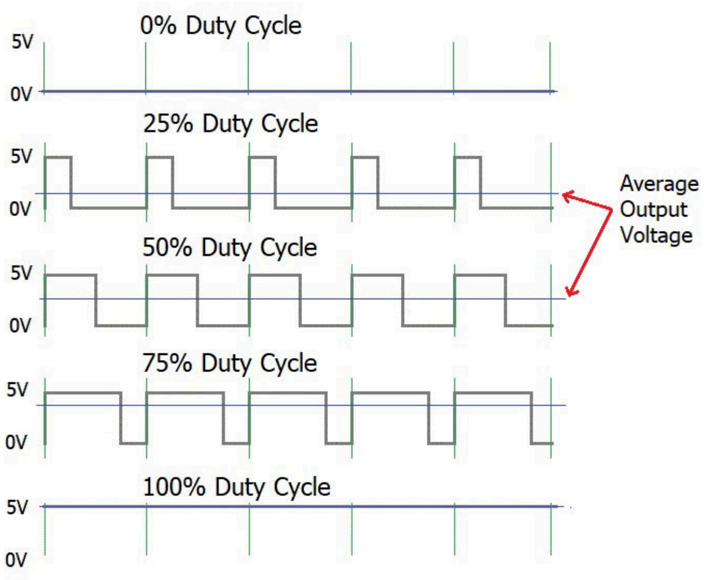


Figure 06: PWM representation at various duty cycles

What makes the MSP430 such an enticing microcontroller is its ability to control the PWM through the use of its own timer module. As the MCU uses a 16-bit register, it allows us to initialize one of these as a clock timer, allowing for precision in doing specific measurements for the PWM. There are several of these including the master clock, MCLK, submaster clock, SMCLK, and auxiliary clock, ACLK. You can start and stop them using the corresponding registrs in relation to the MCU, as well as use the interrupts that can handle certain events. For our scenario, we can have interrupts set up that can be raised when a certain safety risk has been raised, or if the positioning of the diode laser has been moved from its origin. PWM can be used in tandem with several other protocols such as I2C, UART, or SPI, depending on the requirements for this project. Those communications will be delved into with further detail in sections below.

3.3.5.2 I2C

I2C (Inter-integrated Circuit) is a commonly used protocol which is designed for transferring data between circuits. Originally developed in the 1980s by Phillip Semiconductors, I2C has now been able to simplify the way we communicate between microcontrollers. I2C runs on a two-wire bus system, meaning that it uses both serial data and serial clock. Serial clock being the that synchronizes the data being transferred, and serial data is where the data is actually transmitted. I2C operates on a concept using master and slave, meaning the master sends a start and stop condition to its slaves to transfer data.

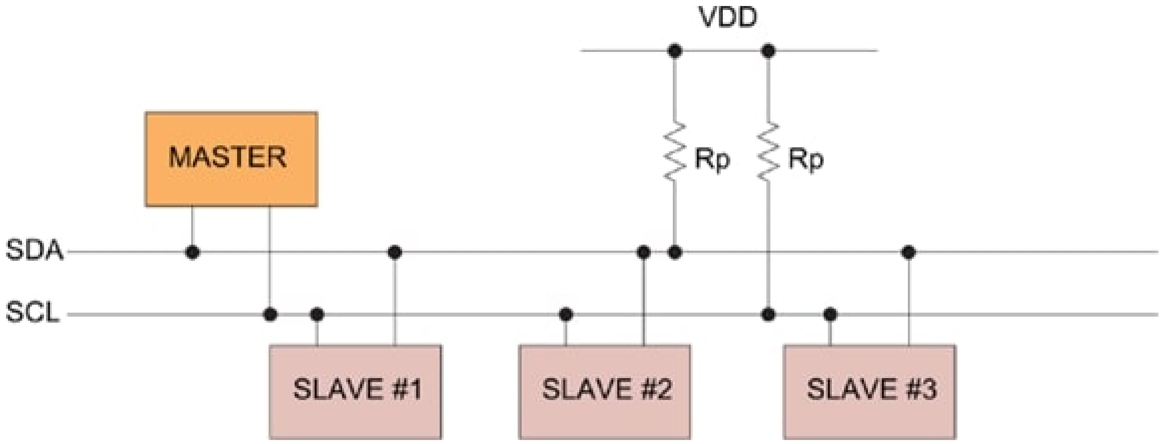


Figure 07: I2C master with multiple slave devices

As shown in the figure above, there are two wires being used to transfer in relation to its master sending to the numerous slaves. I2C also has the functionality of ACK/NACK, meaning when something is not acknowledged (NACK) there is an issue that has occurred.

3.3.5.3 UART

UART (Universal Asynchronous Receiver/Transmitter) is one of the oldest forms of communication in computer history seeing its origins rooted as early as the 19th century with telegraph systems using Morse code to transmit data over long distances. It started to take modern shape in the early 1970s, when UART started to get its first chips designed to handle serial communication. What sets this protocol apart is its use of both a transmitter and a receiver.

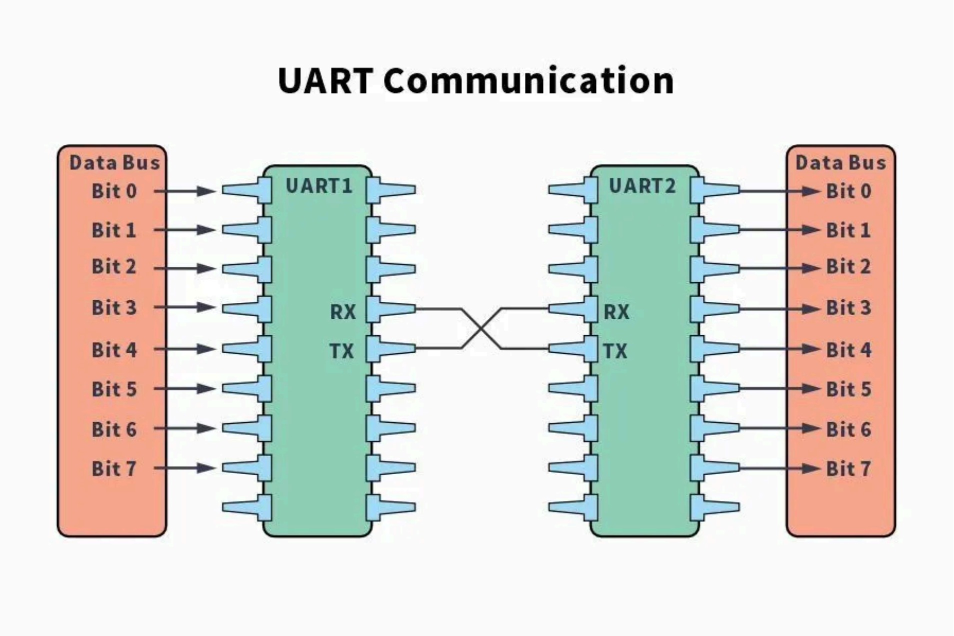


Figure 08: UART Communication between two devices

UART uses a frequency called baud rate, which is measured in bits per second. This is used in finding the data for the speed of transmission. It communicates by sending data in a serial format, typically having a start and stop bit at the beginning and end of the data. Typically UART runs asynchronously, meaning that both the receiver and transmitter must have the same baud rate, sending information from the least significant bits of data first. One of the most common rates being used is at 9600, with another typical rate being 115200 as well.

3.3.5.4 SPI

SPI (Serial Peripheral Interface) varies from other communications such as UART, as it runs synchronously. Originally developed in the 1980s, SPI has its origins in the company Motorola, as it was created because there was a necessity for a method to connect microcontrollers to external devices. SPI runs very quickly without the need for frames as a way to package data. As a result of this, it has the capability to transmit data quickly between a master and its slaves. SPI runs using four primary configurations for its communication, MISO, MOSI, SCK, and CS. The first two being used to transmit to and from the master and slave data. Similar to I2C, there is a master slave relationship, with one master having several slaves attached to it. Because the master is responsible for having the signal for the clock, it therefore has full control in signaling to the slaves. One of the largest disadvantages of using SPI in comparison to other similar protocols such as UART or I2C, is SPI relies on further complex wiring, needing four rather than the smaller two wires.

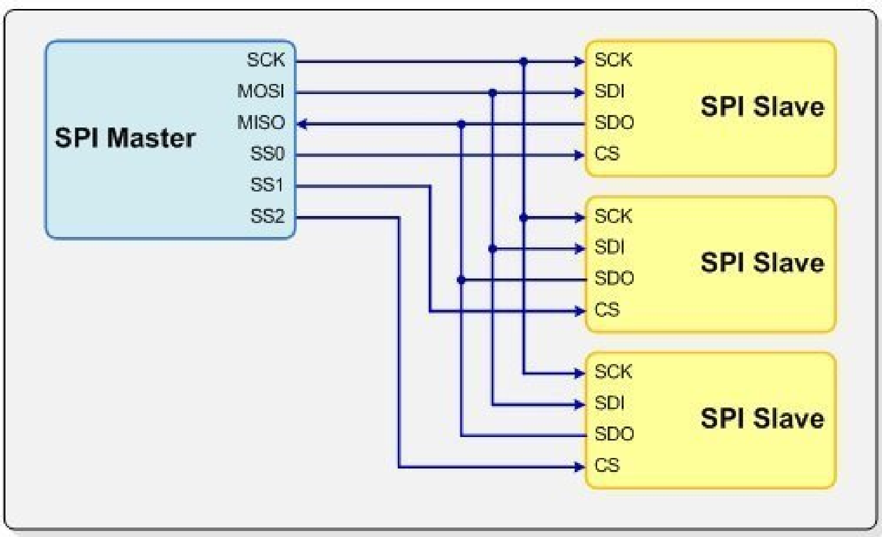


Figure 09: SPI with one master and multiple slave devices

SPI offers many quality of life improvements in comparison to other protocols, such as its slaves having its own unique slave select line, which allows for more complex configuration for our devices. It also allows for low latency, making it very quick to respond to specific issues when a quick reaction time is needed. Another aspect to keep in mind is that due to it being synchronous, it has a smaller chance of data becoming corrupted due to the simplicity of its communication. While there's many aspects that improve it such as its speed, it does come with its own limitations that cause further decision making needed before its usage, such as its limited capabilities in checking for errors.

3.4 Laser System

This section will address multiple factors of the laser system. we did discuss laser fundamentals, types of lasers, laser specifications and functions, beam optics, laser safety, and laser engraving materials. Understanding all aspects of the laser system will enable us to implement the right laser with the right functions for our project. We know we cannot use a laser that is too big because it needs to be able to move freely above the engraving platform and it must be easily moved by the CNC motor system. Based on previous Senior Design projects regarding laser printers or engravers, we know that diode lasers perform exceptionally well regarding beam profile and power output, but diode lasers are also very affordable. This section will weigh the many options and varieties of lasers to ensure our design uses the best laser for our system.

3.4.1 Laser Fundamentals

When designing a laser system, it is crucial to understand all of the fundamentals of laser operation and the foundation of which lasing occurs. The following sections will discuss stimulated emission, gain, and the Fabry-Perot etalon, which together provide a basic understanding of laser operation.

3.4.1.1 Stimulated Emission

The word “laser” comes from an acronym, LASER, which means Light Amplification by Stimulated Emission of Radiation. This means lasers exhibit amplification of light through the stimulated emission of photons. This emission occurs at an atomic level, and is brought about by electrons exciting and relaxing across the energy bandgap of a material. These electrons are excited via a method called “pumping.”

Pumping is the method of getting energy in the gain medium, and is often referred to as the power source for lasers. Often for solid state lasers the pumping method is through absorption of ultraviolet photons from a source. Electrons absorb the photons and excite to a higher energy state. The electrons will then relax to a slightly lower state known as the “metastable state,” where the electrons stay for a small period of time. After a short time, the electrons go through an “emission transition” from the metastable state to either a lower lasing level state or the ground state. During the emission transition, a photon is released from the change in energy state, and this photon is of energy equal to the difference between the two energy states. This is the basis for stimulated emission.

Stimulated emission occurs when a population inversion is achieved through enough pumping in the gain medium. When a photon collides with an excited electron, it results in two photons of the same polarization, phase, and energy. These reactions happen over and over again until enough threshold power is generated, then the system begins to laser.

3.4.1.2 Gain

Gain is very much related to stimulated emission. It is essentially how much stimulated emission there is stimulated compared to spontaneous emission. Gain is characterized by the laser system’s free spectral range (FSR). The FSR is the range of wavelengths that experience gain in the laser cavity, and is determined by the length and refractive index of the gain medium. Complementary to the FSR is the gain profile. The gain profile determines the shape of the allowed lasing modes. By multiplying the gain profile (Gaussian or Lorentzian shape) by the FSR, we obtain a graph which highlights the gain characteristics of the laser system.

3.4.1.3 The Fabry-Perot Etalon

The Fabry-Perot etalon, or Fabry-Perot resonator, is a cavity between two highly reflective mirrors separated by a specific distance. This cavity can be vacant and filled with light oscillating in air, which will allow the device to be used as an interferometer; or the cavity can have a gain medium, which will enable the construction of a population inversion and therefore lasing. The distance at which the mirrors are separated determines which wavelengths of light resonate within the cavity, and therefore the gain characteristics. The Fabry-Perot etalon was invented by Alfred Perot and Charles Fabry in the late 1800’s, well before the first laser system, the MASER (Microwave Amplification by Stimulated Emission of Radiation), but the impacts of the Fabry-Perot etalon are experienced until today.

3.4.2 Laser Types

When designing a system using a laser, it is important to consider the vast array of lasers which are available. This section will discuss the characteristics and applications of each type of laser. Implementability and ease of use were huge factors in designing our laser system. There are some clear frontrunners in terms of optical power and size, but we must weigh all options to have a full understanding of the best option for our system.

3.4.2.1 Solid-State Lasers

Solid-state lasers are a subset of lasers which, as the name suggests, use a solid material as the gain medium. This solid material can either be a crystal, glass, or a ceramic. They are highly versatile, with a vast array of different output powers and wavelengths, ranging from milliwatts to kilowatts, and from infrared to ultraviolet.

Solid-state lasers are capable of creating incredible quality beams because of the vast amount of cavity engineering which can be done for these systems. First, the system of resonating mirrors has many different options like plane parallel, concave-plane, confocal, and concentric just to name a few. This cavity shape determines a large amount of characteristics of the laser, chiefly the resonator length and cavity mode variety as we discussed in Section 3.4.1.1. Mirror configuration is also crucial for maintaining a stable lasing sequence. The reflected stimulated emission must remain inside the lasing cavity to preserve the quality of the beam, or if ultra-high powers are required, a diverging beam system could be used but the beam will be very imprecise. For our purposes, we need as precise of a beam as possible, so if we were to utilize the solid-state laser, we would need a meticulously aligned confocal or plane mirror configuration. The reflectivity of the mirrors as well as their configuration affects the output coupling capabilities of the laser system. A higher reflectivity mirror raises the threshold intensity (and therefore gain) required for lasing in the system.

Solid-state lasers have a wide variety of applications, ranging from the medical field to the automotive manufacturing industry. These lasers have proven that they are capable of intricate manipulation and can facilitate minute details because of their great beam quality. In the medical field, solid-state lasers are used for numerous minimally invasive surgical operations, from dermatology use to tattoo removal. In the manufacturing industry, solid-state lasers are used for welding, high-power material cutting of metals and alloys, and part assembly machines.

3.4.2.2 Gas Lasers

Gas lasers operate with a gain medium in gaseous form, which is different from solid-state and dye lasers. Some of the most common gas lasers, and this goes for lasers in general, use carbon dioxide (CO2) and helium neon (HeNe) in the resonator cavity. The gas gain medium is usually pumped by setting a voltage across the cavity, and the electrons are excited to create stimulated emission.

The gas laser, more specifically the HeNe was the first continuous beam laser and has continued to prove its vast utility. Currently, the carbon-dioxide laser is one of the most widely used lasers in the world, with many applications including the laser cutting and manufacturing industries. The output power range of gas lasers is from milliwatts to kilowatts, so there is no shortage of powers to choose from. Gas lasers are generally very large and bulky. In the optics labs during undergrad, 633 nanometer HeNe lasers are used for simple geometric optics experiments, and these lasers are quite bulky. They would not be easily implemented in the design of a low powered engraving system like our project. The company Boss Laser, which is referenced in Section 3.1.2, is a leading manufacturer of industrial CO2 laser cutting systems capable of generating hundreds of watts for incredible cutting power.

Gas lasers have a very low laser conversion efficiency (see Section 3.4.3.3) and require high wattage to operate because of the nature of exciting a gas with a voltage. Excimer lasers are another class of gas lasers which are used primarily in medical applications, such as LASIK eye surgery. While gas lasers have vast applications in general, a gas laser would not be optimal for our system because of their high input power and large size.

3.4.2.3 Dye Lasers

Dye lasers are very unique systems in that they have a liquid gain medium as opposed to a gas or solid-state gain medium. The dye is pumped with either a voltage or high energy light source (UV LED will suffice) to an excited state to achieve population inversion, and then the dye is ripe for stimulated emission or lasing to occur. These systems are made of many components and would likely be too intricate for our application.

These lasers are unique and useful in another way because they are usually tunable across a wide range of wavelengths, making it a great tool for many different research applications, but does not suit our needs because we want to keep a constant wavelength for consistent laser engraving. The wavelength tunability could be incredibly useful for another type of laser engraving system where different materials have different quality of engraving based on wavelength due to different absorptions of materials. A dye laser could be a great choice for another engraving system that changes multiple parameters like wavelength, laser power, polarization, etc., but since we only have only one parameter to change for our system, power, we would not find dye lasers useful in our applications.

3.4.2.4 Fiber Lasers

Fiber lasers were heavily considered for this project because of their incredible implementability, durability, and small space. These lasers turn the optical fiber core into a gain medium with doping. In fiber lasers, the optical fiber core is doped with certain rare ions like neodymium or yttrium with a high enough density to allow for a large generation of stimulated emission. These doping atoms have electrons that are excited by energy in the form of electricity or, more commonly, high energy photons. Fiber lasers are very durable and have great longevity of use.

Optical fibers are made using a thermal drawing process, which turns a short and thick preform into a very long and very thin optical fiber. Optical fiber lasers are different from normal optical fibers because the preform is doped with the rare ions. The entire optical fiber acts as the resonating cavity with help from a reflective coating on the ends of the fiber. As light travels through the fiber, it collides with excited electrons and begins to lase.

Optical fiber lasers are implemented in many different laser cutting and engraving devices across a multitude of applications. Fiber lasers are a great design choice for laser engravers because of their flexibility and ease of implementation with CNC moving parts. This would be a great option for our laser engraver because the end of the fiber can be easily placed on the moving platform and the excess fiber can be routed easily along moving head above the engraving stage. The pumping mechanism is coupled to the input side of the fiber and that can be easily placed along with our spectrometer components. The main drawback of fiber lasers is their cost, which is upwards of a thousand dollars at the cheap end. This is unrealizable for our project, therefore fiber lasers are not a viable option of laser device for our laser engraver.

3.4.2.5 Diode Lasers

Semiconductor diode lasers are some of the most compact and powerful lasers on the market today, and it shows because they are one of the most implemented lasers in compact laser engraving machines. There are countless laser engraving systems for sale on Amazon which all utilize laser diodes as the engraving medium, this proves their ease of use and effortless implementation.

Diode lasers are uniquely small, the smallest of all laser systems. The diode itself is only a small pin, but when connected to drivers and placed in a housing with a fan they bulk up slightly but are still incredibly small compared to most other laser systems. Their working principles are based in semiconductor physics, and the operation of a laser diode is very similar to that of an LED, with a very broad spectrum. A laser diode behaves as an LED until its threshold current is achieved, then its linewidth shrinks dramatically and lasing occurs. This function enables laser diodes to function well with varying current. A DC current just below the threshold current is applied, then a pulse width modulator (PWM) is used to send a square wave with variable duty cycle and modulate the laser diode between LED function and laser function. The laser diode’s fast on/off times allow it to function at high efficiency and engrave very intricate designs with fast speeds.

The diode laser is an excellent component to include in a laser engraver design because of its vast advantages. The major drawback of the diode laser is its characteristic beam divergence as referenced in . The lasing gain medium in a laser diode is a semiconductor slab. The height of the slab is very small compared to the width, and this causes a large aspect ratio, and therefore a notable difference in the beam divergence. The beam diverges much faster in the vertical direction compared to the horizontal direction, and this must be accounted for using optics. Another disadvantage of the laser diode which results from the not-ideal aspect ratio is the laser spot. The laser spot and beam profile are in the shape of a rectangle

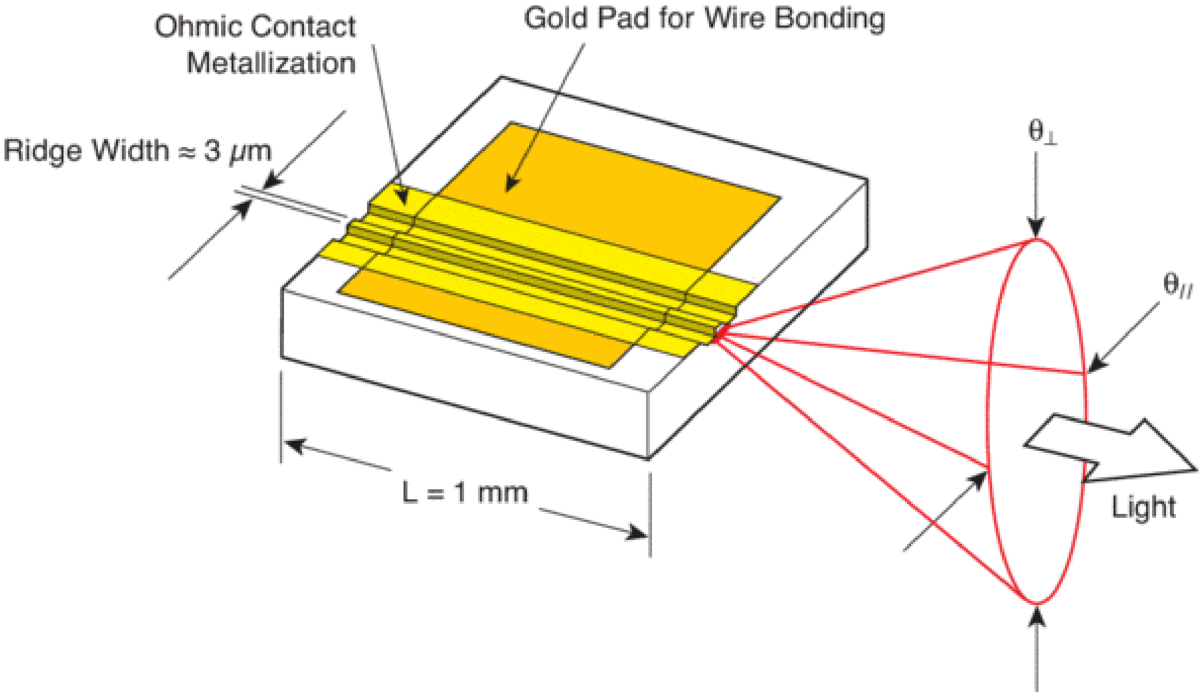


Figure 10: Elliptical beam divergence for laser diode, from MKS Newport [46]

3.4.2.6 Laser Design

Selecting a laser system for this project was difficult because we wanted to weigh all the pros and cons of each viable laser system. First we had to rule out which lasers would simply not fulfill our needs, and those are the solid-state laser, CO2 laser, and dye laser. Our design involves moving the entire laser system for engraving because it involves fewer optics. Lenses and mirrors are expensive optical components and we want to minimize the number of optics used to cut back on costs as much as possible.

A solid state would be much too heavy for the system. As the stepper motors move the laser around, the large weight and mass of the laser system means there is a lot of inertia, which causes vibrations in the system. Vibration from the moving laser system greatly reduces our resolution and engraving/cutting quality and must be reduced as much as possible. This means the only viable way to implement a solid-state laser into our engraving system would be to make the laser stationary and focus with mirrors, which is not congruent with our design. The same weight factor applies for CO2 and dye lasers. CO2 lasers need a large resonance cavity, and dye lasers need lots of mechanical components to function properly, so the volume, size, and weight of these laser systems make them not viable options for our design.

We heavily considered using a fiber laser for this project. A fiber laser would be a great option because it fits our design constraints while still being a relatively large laser system. The power source and pumping source are too much weight to have on the moving engraving head, but it fits our design because those components of the laser can be made stationary while still not using other optical components. The fiber itself is coupled to the pump source, then the other side of the fiber is connected to the engraving head. The optical fiber needs to be maintained in an optimal cutting position but also need to be able to accommodate for the full area of the engraving platform. This challenge is difficult to face because it is very easy to damage the laser power output and beam quality by improperly situating the fiber length. With this issue paired with the tremendous cost of fiber laser systems, we decided the fiber laser would not be a suitable choice for our project.

This left us with the diode laser module. Diode lasers are very compact and can deliver very high power outputs, ranging to the tens of watts. This is beyond our power needs for our laser engraving applications, so the abilities of the diode laser go above and beyond our needs. The laser diode can be easily mounted to the engraver head, and will not cause abundant vibrations in the system because of its light weight. The laser diode also does not require many optics, only a lens or two for collimating and focusing. Another huge advantage for the laser diode is the options for PWM use. This makes it very easy to control with a square wave plus a DC current input to control the lasing state and LED state of the laser diode, thus enabling us to have precise laser control and high speed. The laser diode is the perfect option for our applications.

3.4.3 Laser Power

This section will discuss the specifics of laser power. It is necessary to understand the flow of energy through the laser system from the wall plug to the laser emission.

3.4.3.1 Laser Electrical Power

The electrical power in a laser system is often quite high due to the energy required to excite so many electrons and promote stimulated emission. The amount of electrical power needed is related to the designed optical output power and changes from laser to laser. If the laser is designed for milliwatts (mW) of output power, then the input electrical power may also be in mW or up to a few watts (W) or more depending on the power conversion efficiency. The electrical power is used by the pumping source for most lasers, and for diode lasers it is absorbed in the active region of the semiconductor.

A major issue with the consumption of electrical power is the high temperatures generated from the electricity flow. The reduction of electric power efficiency is discussed in its respective section. Traditional lasers must have a cooling system for their pumping medium and the gain medium. In our case, diode lasers are best cooled by a fan that can operate on the same circuit.

3.4.3.2 Laser Optical Power

The optical power in a laser system is the amount of power that emits from the stimulated emission end of the resonance cavity, or in the laser diode's case, the active layer of the semiconductor diode. This power is affected by many factors including input electrical power, gain medium, pumping source, threshold gain, and many more. Optical power is usually measured in mW or W and it is very important to know this metric accurately because of the purpose for this laser. We must be able to tailor the optical power of the system in order to precisely engrave and cut materials at safe parameters and not cause fires. Each different material will burn at different temperatures and it is important to know how much optical power is coming out of the laser in order to not focus too much energy onto the material which will cause the fire.

3.4.3.3 Laser Power Conversion Efficiency

The laser power conversion efficiency is a ratio of the absorbed electrical power to the output optical power, where both are measured in mW or W. This is a very important metric because it is an indicator of overall laser performance, and efficiency is necessary in a machine such as ours. There are many electrical components to our system, including the PCB and array of stepper motors and drivers, and the added electrical power of the laser, if not monitored, can overwhelm the system and cause power shortage.

One of the most important factors in laser power conversion is we need a high conversion efficiency for the temperature regulation. If the power conversion efficiency is very low, then that is more energy that is being transferred as heat and not as usable energy. In addition to becoming a fire hazard, the laser diode requires more power as the temperature increases, which tumbles and overheats the system until failure. It is paramount to have a laser diode system with a higher laser power conversion efficiency to minimize excess heat energy because the fan can only regulate so much heat. For understanding the laser power conversion efficiency, we can use an electric power meter and an optical power meter to measure the powers and compare using a ratio of the electric and optical power respectively. Laser power conversion efficiency values greater than 60% are acceptable. For our implementation.

3.4.4 Laser Beam Characteristics

This section will discuss the desirable beam characteristics for our laser system. Since we are using a diode laser in our design, we did mainly discuss diode lasers, but we did include discussion on traditional laser systems which use a resonator.

3.4.4.1 Beam Waist

The beam waist (ω) of a laser is also referred to as the spot size of the beam. This component of the laser is crucial to understand alongside the use of optics because the laser beam must focus to a very small spot size in order to be able to focus enough energy and burn a material and engrave or cut.

Inside the laser resonance cavity, or active layer of the semiconductor device for a diode laser, there is a point which can be considered the origin of laser propagation, this point is known as the minimum beam waist (ω_0). The minimum beam waist can be in the center of the resonator, or active layer, or be moved to one side depending on the geometry of the reflectors in the cavity. The beam waist is associated with a characteristic of the wavefront of the laser, known as the radius of curvature (R) which is important to beam propagation and is discussed further in the Rayleigh Range section.

Our goal is to achieve the minimum spot size possible to ensure the greatest quality engraving. The smaller the spot size, the greater the resolution of the engravings or cuts. The beam waist is modified by other optics like lenses, of course, but using geometric optics and ray tracing knowledge we can find the minimum beam waist and spot size in order to perform the best laser engraving as we possibly can.

3.4.4.2 Rayleigh Range

The Rayleigh range of a laser system is a very important factor to take into consideration when designing a system with other optics. The Rayleigh range of the laser is known as the point where the radius of curvature reaches a minimum because R is equal to infinity at ω_0 and at infinite distance from the origin, therefore taking a derivative of the behavior of the Rayleigh range with respect to distance from the beam waist we can find the minimum where the rayleigh range is located. The important factor about the Rayleigh range is that if its value is comparable, meaning on the same order of magnitude, to the focal length of the lens being used, then the beam will not focus at that lens' focal length. This Rayleigh range is known as the crossing point between the near-field and the far-field, and if the beam is in the far-field, it will be very difficult to focus. Luckily, the Rayleigh range of most laser diodes is relatively large compared to the EFL of the lens we did be using.

3.4.4.3 Beam Profile

The beam profile is very important in our design because this is the shape of the spatial intensity of the laser beam itself. If the beam is not uniform like a traditional laser's Gaussian beam or an elliptical beam like that of diode lasers, then the engraving or cutting will lose resolution and the beam may not be able to engrave if it is not focused. The laser's beam profile is one of the most important aspects of laser engraving.

The laser system design consists of the laser diode and two focusing lenses, one for collimating and one for focusing. These optics will work together in order to produce the minimum spot size possible which will produce the best quality engraving that is possible for our team. Ideally, the beam would be a uniform Gaussian, circular beam, but due to the physical constraints of a diode laser, the beam profile is slightly elliptical due to the different divergence angles of the horizontal and vertical propagation of the electromagnetic wave. This divergence happens because of the different sizes of the height and length of the active layer of the semiconductor diode, and is a slight inconvenience but is a manageable issue to deal with.

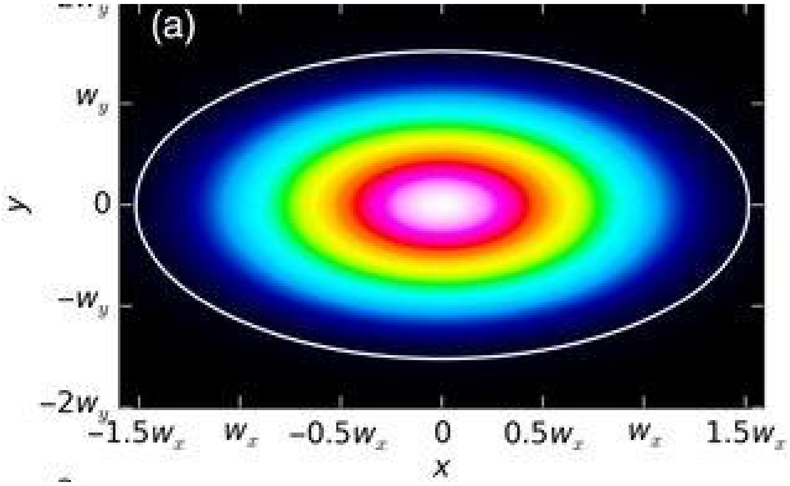


Figure 11: The desired elliptical Gaussian beam profile for laser diodes, from Hofer et al. [47]

3.4.5 Laser Optics

This section will discuss using lasers with other optical elements, chiefly the focusing behavior of lenses with laser energy distributions. The nature of laser light is that it is composed of highly coherent and monochromatic light. The power propagation electromagnetic behavior of laser light is very different from that of normal incoherent light from most daily light sources, and these minute details must be taken into consideration when designing a sensitive system.

3.4.5.1 Laser Lens Behavior

As mentioned in the Rayleigh range section, the laser beam does not focus at the effective focal length of a lens if the Rayleigh range is comparable to that effective focal length. Semiconductor laser diodes have a Rayleigh range on the order of a few meters, reminding that the Rayleigh range is where the radius of curvature of the beam is at a minimum, not the beam waist. The beam of a semiconductor laser diode is diverged greatly due to the small height of the opening on the emitting side, and therefore the Rayleigh range is larger. Our desired focal length for the laser is on the order of a few centimeters at most. Since these values are not comparable for our system, we do not need to worry about this issue. Our laser beam will focus approximately to the effective focal length of the lens we select.

Convex-concave (meniscus) and plano-convex lenses are the best focusing lenses, and are readily available from Edmund Optics and other competing optics companies. These lenses will be discussed further in 3.4.5.3 Focusing Lenses.

3.4.5.2 Damage Threshold

When dealing with laser systems, especially medium to high power systems, the damage threshold of the optics is a huge concern because of the high power of laser beams. The power of the laser beam is generally in the range of watts, but can be as high as kilowatts (kW) or even megawatts (MW) for some very high power applications.

A main concern about damage threshold for our system is that we are using a laser in the blue/UV range of the electromagnetic spectrum, and generally optics have a lower damage threshold in this range than other parts of the spectrum. This should not be a huge issue though because our system will only be emitting 5W of power at a maximum. An issue could arise if the laser is emitting power for a very long continuous time, like for a long engraving time, but the laser turning on and off while printing should be enough time to let the optics cool down. Our laser diode is capable of 5W of output power, which translates to upwards of 8kW/cm^2 for a short pulse, which can damage certain optics at 450 nm, but for our purposes this should not be a huge issue.

3.4.5.3 Focusing Optics

This section will discuss the huge range of different focusing elements we can use for our system. The main types of focusing elements are lenses, and we did discuss the use of plano-convex lenses, meniscus lenses, and aspheric lenses for this application. Some very important factors to be aware of when talking about lenses are focal length, refractive index, Snell’s Law, and radius of curvature, as all of these impact the quality of the focus in the lens. For our application of laser engraving, there are specific design characteristics in mind which dictate the characteristics of the lens we want. We are focusing the beam of a small semiconductor laser diode which has large beam divergence and relatively high power that must be in relatively close proximity to the engraving material in order to create the best resolution possible. Therefore we want a lens with a small diameter, short focal length, and made of a high damage threshold material to best suit our application. In addition to lenses, this section will also discuss axicons used for focusing high powered beams for cleaving purposes.

3.4.5.3.1 Plano-Convex

Plano-convex lenses are some of the most common lenses used for focusing light. Not only are these lenses used in laser focusing, but they are used in focusing light in cameras and telescopes. These are very helpful lenses due to their multiple characteristics that help focus the light. The thickness of the lens, the refractive index, and the radius of curvature of the convex side all contribute to the focusing power of the lens.

A plano-convex lens is made of 2 different lens styles per side, a completely flat side (plano) and a curved outward side (convex) which enables us to focus light how we want. These lenses allow huge variations of the aforementioned characteristics, enabling us to create a focusing lens for many different applications. In order to use a plano-convex lens for our project, we must consider the desired lens characteristics references in the introduction paragraph. The ideal plano-convex lens for our application would be small with a short focal length, around 1-2cm in order to get the resolution we need.

3.4.5.3.2 Meniscus Lenses

Meniscus lenses are a type of lens that is created from combining a concave face with a convex face. These lenses are known to have a higher optical power than their normal plano-convex counterparts, and this is due to a few factors. Meniscus lenses have different thicknesses at the center than at the edges of the lens, which creates a powerful optical effect depending on the desired light manipulation. Meniscus lenses have different radii of curvature for each curved-side face.

There are positive meniscus lenses and negative meniscus lenses. Positive meniscus lenses have a shorter radius of curvature on the convex side and a longer radius of curvature on the concave side; they also have edges that are thicker than at the center. Due to the difference in thickness from the center to the edges, a tighter beam focus can be created and therefore a smaller spot size. Negative meniscus lenses have a shorter radius of curvature on the concave side and a longer radius of curvature on the convex side. The center of the lens is thicker than its edges, making the beam diverge or expand much better. This type of lens is frequently used in beam expanding applications. A positive meniscus lens would be a great option to use in our project by being very optically powerful, as well as being thinner than other types of focusing lenses.

3.4.5.3.3 Aspheric Lenses

Another option considered for focusing the laser beam is an aspheric lens. Aspheric lenses are very powerful lenses because they are made for specific applications and do not behave like other lenses. An aspheric lens bends light unlike other lenses because its surface is curved in a specific way that is not like a sphere. One incredibly powerful aspect of aspheric lenses is that they manipulate light in such a way that it can reduce a multi-optic system down to a single lens. We could use an aspheric lens to reduce the focusing system from two lenses to a single lens system, which would reduce the size of the laser focusing system. A bad aspect about aspheric lenses is that they are usually very expensive because of the large amount of labor and design required to manufacture these lenses, they are much more difficult to make than traditional flat or curved lenses. Due to their incredibly high price, aspheric lenses are not a viable option for our project.

3.4.5.3.4 Axicons

Axicons are incredibly powerful and useful optical elements that have been found to be very useful in material cutting and manufacturing. Axicons are not like normal lenses due to their special shape. These optical elements have a flat side, and instead of the other face being spherical, the face is a cone. The conic shape of the axicon enables a phenomenon which is profoundly useful in cutting and cleaving. There are also reflective axicons, which use two different reflecting surfaces at designed angles in order to create a Bessel like beam, but those will not be useful in our current design for a laser engraver.

The conic shape of the face allows the light entering to momentarily behave like that of a Bessel function shaped light beam. What this does is create not a focal length from the lens, but instead it creates a line along the optical axis which the Bessel beam interferes with itself in such a way to create a line of high intensity. This high intensity line enables us to cut through materials as if the beam were like a lightsaber from Star Wars. We could have perfectly flat cuts on thick materials, but this type of lens is not likely to be very helpful in our application, because we only wish to engrave instead of cut. Another reason these optics would not be useful to us is their very high price, therefore axicons will not be a viable option for APALES.

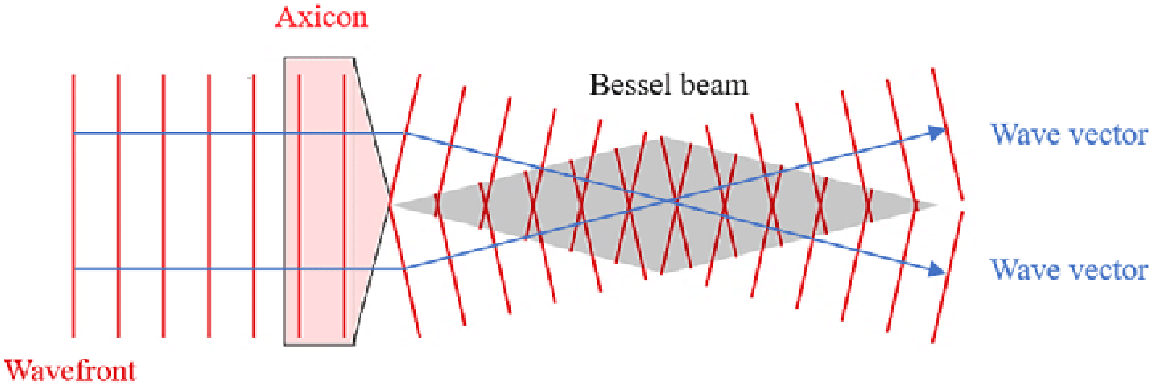


FIgure 11: Axicon and Bessel-like beam [56]

3.5 CNC Hardware Components

In terms of the fundamental structure, here are some essential elements of the CNC machine that are crucial to comprehend in order to grasp the operation of various machine types more effectively.

3.5.1 Input Device

The input devices facilitate the accurate input of the part program into the CNC machine. Typically, three primary input devices are utilized in industries, namely the punch tape reader, magnetic tape reader, and computer through RS-232-C communication. However, the selection of these devices may vary depending on the unique objectives and requirements of each company.

CNC machines have evolved significantly in terms of their control systems over the years. Early on, punch tape readers were employed, utilizing a long strip of paper with punched holes that encoded instructions for the CNC machine's operations. This method provided a tangible and straightforward means of relaying commands. Another advancement in CNC technology came with the introduction of magnetic tape readers, functioning much like tape players but specialized for reading magnetic tapes that contained coded instructions. This innovation offered a more compact and efficient way to communicate with the CNC machine. In more contemporary setups, CNC systems have embraced computer integration through the RS-232-C communication protocol. This approach enables seamless collaboration between the CNC machine and a computer, facilitating the exchange of precise instructions in a standardized language. This evolution reflects the continual refinement of CNC technology, from physical punch tapes to magnetic media and, finally, to sophisticated digital communication protocols for enhanced precision in manufacturing processes.

Considering the needs for our project we plan to opt in for a computer with RS-232-C communication as the input unit for our small-scale laser engraver, considering its potential to facilitate seamless communication between our material detection system and the CNC setup. Given the intricate nature of material detection and potential real-time adjustment requirements, leveraging the computational power and adaptability of a computer seems like a promising choice. Furthermore, the standardized RS-232-C communication protocol could ensure reliable data transfer and efficient coordination between the computer and the CNC system, potentially enhancing the overall precision and control of our engraving process."

3.5.2 Machine Control Unit (MCU)

The main control unit, often referred to as the MCU, serves as the machine's central hub, earning its nickname as the 'heart' or ‘brain’ of the system. It plays a crucial role in overseeing and executing the primary operational tasks exhibited by the CNC machine.

- Interpreting the encoded information input
- Deciphering the encoded data
- Executing sophisticated techniques like interpolation to create commands for axis motion
- Receiving feedback signals related to the position and speed of each drive axis (Important for our application of real time data interpretation and execution)
- Managing additional control functions such as coolant, spindle activation, tool changes, and more.

The Arduino Uno (MCU) board supports the use of GRBL, which is a motion control software that takes the g-codes and outputs the signals. To interface with the driving system, there is an add-on board called a CNC shield. This connects the Arduino board to the driver circuits which then connect to the stepper motors.

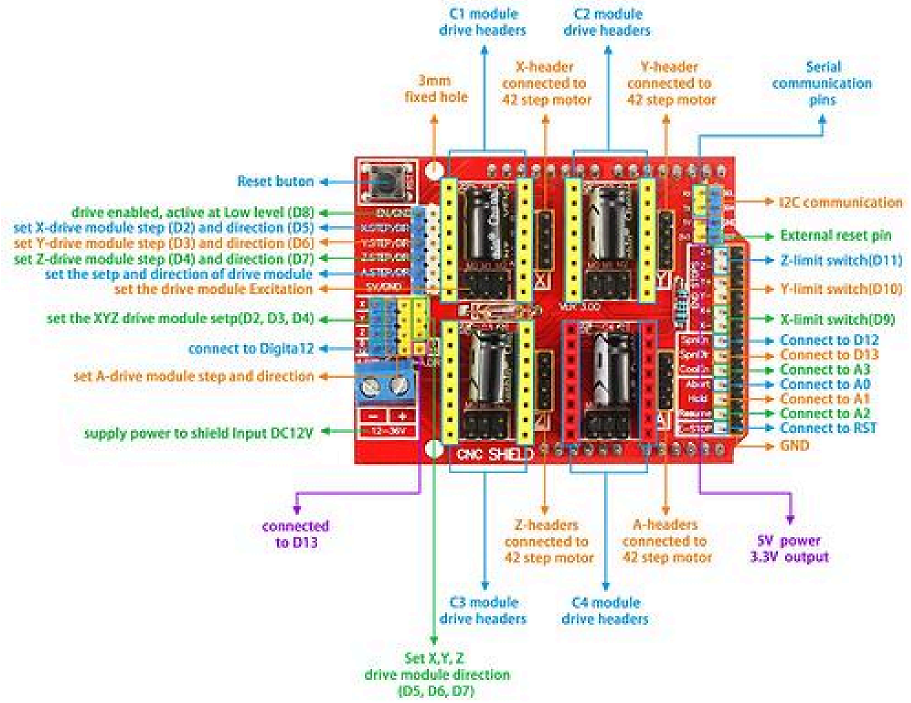


Figure 13: Arduino CNC shield diagram (forum.aduino.cc)

3.5.3 Driving System

➢ ***Driver Circuit:*** These are circuits that take the electrical signal from the microcontroller and convert it to the required output for the stepper motor. They are current limiting circuits regulating the amount of current drawn by the stepper motor. The selected driver circuit must have an output current at or below the rated current of the stepper motor. The circuit takes the DC power (VMOT and ground pins required to drive the motor. It also takes the logic pins from the microcontroller to step the motor and in what direction.Below are some stepper motor drivers that we are considering implementing in our laser engraving CNC system:

- <u>*Trinamic TMC2208:*</u>
    - Cost effective and easy to control amongst many different platforms.

  - Potential resonance at higher speeds.

- *Geekcreit DRV8825:*
  - Adjustable current limits and microstepping capabilities.
  - Low cost relative to other stepper motor drivers.

- *Leadshine ACS606:*
  - Exceptional precision, especially at higher speeds.
  - Generally more expensive relative to other motor drivers.

- *Leadshine DM542S:*
  - Reduced motor heat,better torque at higher speeds.
  - Higher cost compared to open-loop motor drivers.

The selection of the Geekcreit DRV8825 stepper motor driver for our CNC platform is grounded in our need of strategic performance, paired with its availability and cost effectiveness. Known for its previously mentioned adjustable current limits and micro stepping capabilities, it offers exceptional control over the stepper motors aligning with our overall need for precision and accuracy in our laser engraver CNC system. Its budget friendly nature also makes it an optimal candidate for our project, providing a well-rounded solution without compromising any of the necessary features.

- ➢ ***Stepper Motors:*** These motors provide precise control over the movement of the laser head along the X and Y axes, ensuring accurate positioning and precise material removal. They offer cost-effective and reliable motion control, making them a popular choice for our small-scale CNC system.

Some specific varieties for the stepper motors include NEMA 17, NEMA 23, and Integrated Stepper Motor varieties were considered for their size, torque, and cost-effectiveness.

NEMA 17 Stepper Motor (Stepperonline Nema 17 Bipolar):

- Compact size that is suitable for low to moderate torque applications.
- Widespread availability and integration amongst various CNC platforms.
- May show some sign of resonance at higher engraving speeds.

NEMA 23 Stepper Motor (Stepperonline Nema 23 Bipolar):

Higher torque output comparative to the NEMA 17, suitable for larger loads

Larger dimensions, weight, and overall, physical size contribute to more weight to the system.

Integrated Stepper Motor (OMC Hybrid Servo Stepper Motor):

- Serves as a bridge between stepper and servo motors, hence the hybrid name.
- Provides a decent amount of torque, and offers great precision.
- Higher cost comparative to traditional stepper motors.

Considering the specific requirements of our small-scale laser engraver, the Nema 17 stepper motor seems to be the most suitable choice. The fact that it is moderately cost-effective and easy to obtain is essential.as It also offers a balance between compact size, precise control, and moderate torque, making it ideal for the controlled and accurate movements required for the X and Y-axis operations in the CNC system. Its widely recognized compatibility with small-scale applications and its ability to ensure precise positioning make it a reliable option for our material detection laser engraver.

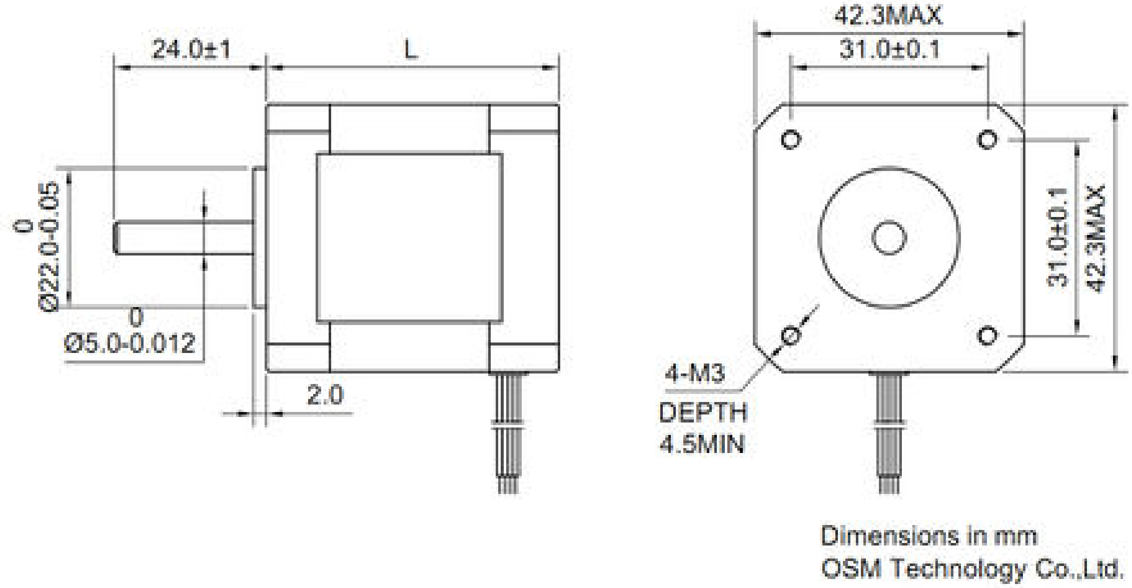


Figure 14: Nema 17 stepper motor diagram from OSM Technology Co.

- ➢ ***Linear Actuators:*** By converting rotational motion into linear motion, linear actuators facilitate the controlled movement of the laser head, ensuring smooth and precise engraving operations. Their compact design and high precision make them suitable for applications requiring accurate and consistent motion control.

In terms of linear actuators, the ‘Thomson Electrak’ HD Actuator could be a suitable option. Its robust design and high load capacity would ensure the reliable and precise linear motion control necessary for controlling the movement of the laser head during the engraving process. This would contribute to the overall stability and consistency of the material removal process based on the identified material properties.When considering this choice of a linear actuator, it is essential to consider maintaining stability during the material detection and engraving process, as excessive vibrations can negatively impact the accuracy and quality of the engravings.

Choices such as the THK Ball Screw, Misumi Precision Lead Screw, and Misumi Rack and Pinion serve as viable options to consider. The ‘THK Ball Screw’,well known for its high efficiency and low friction, comes at a higher cost relative to lead screw setups. While the Misumi Precision Lead Screw does come in at a lower cost, it is suitable for the level of precision we need, but can have some problems with higher friction. Lastly, the Misumi Rack and Pinion provides exceptional high-speed linear motion, but may have more backlash compared to screw based actuators.

- ➢ ***Belt Drive Systems:*** Utilizing belts and pulleys, belt drive systems offer an efficient and cost-effective solution for driving the movement of the laser head. They provide smooth and reliable motion along the designated axes, ensuring consistent engraving quality and accuracy.

Considering the belt drive systems, the Gates PowerGrip GT, BEMONOC GT2 Timing Belt, and BIQU Steel Core GT2 Timing Belt were among the belts analyzed for their torque transmission and flexibility.The Gates PowerGrip GT offers high torque transmission, ideal for precision, but may exhibit backlash in certain conditions. The BEMONOC GT2 Timing Belt, known for low backlash, is balanced against slightly lower torque transmission compared to timing belts. The BIQU Steel Core GT2 Timing Belt enhances strength and durability but may be slightly less flexible than standard GT2 belts. The DRV8825, a stepper motor driver, provides a cost-effective solution for controlling stepper motors with adjustable current limits.

- ***Ball Screw Mechanisms:*** With their ability to convert rotational motion into linear motion with minimal friction, ball screw mechanisms enable precise and smooth movement of the laser head. They are known for their high accuracy, making them a suitable choice for applications demanding precise positioning and motion control.

- *POM Wheels:*

  When diving into POM wheels, we explored choices like the OpenBuilds V-Wheel, Dual V-Wheel, and Miniature POM Wheel. The OpenBuilds V-Wheel takes the spotlight for its stability and exact movements, although it demands occasional TLC to keep debris at bay. Then there's the Dual V-Wheel, stepping up with added load-bearing prowess and stability, but it's a bit of a high-maintenance player due to its intricate design. On the flip side, the Miniature POM Wheel suits snug setups but might not flex its muscles as much when it comes to heavy lifting compared to its larger counterparts.

- *Limit Switches:*

  We took a close look at various limit switches, such as the Omron D4MC-5020, Honeywell HOA1887, and Cherry DS Series Magnetic Proximity Switch, to understand their play in our laser engraving CNC platform. The Omron D4MC-5020 keeps it simple and budget-friendly, but there's a catch—it might wear down faster, demanding more regular check-ins. Now, the Honeywell HOA1887 is our smooth operator, offering non-contact action and a longer lifespan. Yet, it has a vulnerability—it can be a bit touchy with external light, so we need to keep an eye on that. Lastly, the Cherry DS Series Magnetic Proximity Switch is our tech marvel, operating without any physical touch. It's super reliable, but we've got to be mindful of its sensitivity to external interference. Even though each switch brings its unique take to the CNC system, the traditional mechanical Omron D4MC-5020 switch seems most likely in our selection.

Machine Tools:

In our material detection laser engraver project, machine tools are vital. Their control is focused on the X and Y axes, ensuring precise material selection based on the identified material properties.

3.5.4 Motion Type CNC

- Contouring Systems: Machines following the material's contour, like milling and lathe machines, utilize simulated tool and work movements for precise control.
- Point-to-Point Control Systems: Machines like drilling and boring machines maintain fixed positions for both the workpiece and the tool, ensuring accurate and safe operations.

Opting for contouring systems, we aim to ensure that our laser engraver precisely follows the intricate contours and material properties during the engraving process. By leveraging simulated tool and work movements, we can guarantee the high level of control necessary for achieving detailed and accurate engravings.

3.5.5 Loop Control CNC Systems

- Closed-Loop Systems: Feedback from the control system enhances precision and power, allowing for extensive monitoring and increased accuracy in servo-based CNC systems.
- Open-Loop Systems: Instructions are converted to signals, which are then utilized by servo amplifiers to power the motors.

In the realm of CNC systems, closed-loop systems excel due to their continuous feedback mechanism, ensuring heightened control over critical parameters during the engraving process. Through real-time data collection and analysis, these systems can swiftly detect and rectify any deviations, maintaining the desired accuracy and minimizing the likelihood of errors. On the other hand, open-loop systems, although efficient in executing commands, lack the crucial monitoring and correction features that are integral in achieving intricate engraving designs with utmost precision.

Therefore, the integration of closed-loop systems not only guarantees seamless operations but also establishes a robust foundation for delivering impeccable and intricate engraving outputs, aligning seamlessly with our project's core focus on precision and high-quality results.

Selecting closed-loop systems aligns perfectly with our project's focus on accurate material detection and precise engraving. These systems offer extensive monitoring capabilities, enabling us to maintain the necessary precision and achieve consistently high-quality engraving results, thereby minimizing errors throughout the engraving process.

3.6 Mechanical Design and Integration

In this section, we did be focusing on some of the software applications that will be used in this project, including Solidworks in the creation of various mounts on the laser engraver. we did also highlight some of the potential materials that will be included in the material detection of the laser.

3.6.1 3D Modeled Mounts

SolidWorks Application in 3D Modeling

The 3D mounts for the laser and spectrometer play a critical role in ensuring stability and precision within the CNC system during the engraving process. In the development of the laser engraving CNC system, the application of SolidWorks plays a pivotal role in the precise and efficient 3D modeling of essential components, particularly those intended for Fused Deposition Modeling (FDM) printing. SolidWorks' comprehensive suite of tools and features offers a tailored approach to design development, accommodating the specific requirements and material characteristics of FDM printing materials, such as polycarbonate, ABS, and PEI. This section focuses on the strategic utilization of SolidWorks in the 3D modeling process for the laser mounts within the CNC system, emphasizing the software's capabilities in facilitating detailed parametric modeling, seamless integration with CNC system components, structural analysis and design optimization, as well as advanced visualization and prototyping. By harnessing SolidWorks' advanced functionalities, the section aims to underscore the significance of precise 3D modeling in ensuring the seamless integration and optimal performance of the laser mounts within the CNC system, thereby contributing to the overall efficiency and functionality of the laser engraver.

For the custom 3D mounts and models, it is advisable to opt for sturdy and heat-resistant materials suitable for Fused Deposition Modeling (FDM) 3D printing, such as high-quality polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) filaments. These materials offer the necessary structural robustness and effective heat dissipation, maintaining the laser's stability and optimal performance during engraving. Leveraging the flexibility of FDM 3D printing, incorporating adjustable features within the mounts, such as fine-tuning mechanisms for focal point and alignment, ensures precise control over the engraving process, enabling the production of intricate and high-quality designs.

Possible Material Selections

Polycarbonate Based (PC)

Strength and Toughness: Polycarbonate is known for its high impact resistance and toughness, making it suitable for producing sturdy and durable laser mounts that can withstand mechanical stress and potential impacts during operation.

Heat Resistance: Has good heat resistance, enabling it to maintain structural integrity and dimensional stability under elevated temperatures. Having a Vicat softening point of up to 114°C. The material is flame retardant with a UL 94 rating of V2, making it ideal for electrical and electronic equipment. This property is crucial for ensuring the laser mounts can withstand the heat generated during the engraving process without deformation or degradation.

Material Properties

Density: 1210 kg/m^3
Melt volume rate: cm^3/10 min
Vicant softening temperature: 112 ℃
Young’s Modulus xy-direction: 2010 MPa
Tensile strength xy-direction: 63 MPa
Elongation at break xy-direction: 4%
Impact strength yz-direction: 64kJ/m^2
Burning behavior: V2

The above information is provided by Covestro (formerly DSM Additive Manufacturing) for 3D printed test samples of Addigy® GPC 3D 1000.

Acrylonitrile Butadiene Styrene (ABS)

Mechanical Strength and Durability: ABS offers good mechanical strength and durability, making it a suitable choice for producing robust and reliable laser mounts that can withstand repetitive operational demands and environmental stresses.

Heat Resistance and Dimensional Stability: ABS material exhibits notable heat resistance and dimensional stability, allowing it to maintain its form and structural integrity even when exposed to moderate temperatures during the engraving process. This feature ensures the laser mounts remain stable and reliable throughout the CNC system's operation.

Material Properties

Tensile Strength: 29.6 - 48.0 MPa
Tensile Modulus: 1,790 - 3,200 MPa
Elongation at Break ≅ 53%
Elongation at Yield ≅ 5.5%
Flexural Strength: 60.6 - 73.1 MPa
Flexural Modulus: 1,600 - 2,400 MPa
Glass Transition Temperature ≅ 108°C
Heat Deflection Temperature (1.8 MPa): 70°C - 89°C
Hardness ≅ Shore D 100
Density: 1.01 - 1.20 g/cc

The above information is provided by Covestro (formerly DSM Additive Manufacturing) for 3D printed test samples of Addigy® GPC 3D 1000.

Considering the unique requirements of our laser engraving CNC system, polycarbonate emerges as the prime candidate for the construction of our laser mounts. Its exceptional impact resistance, superior heat resistance, and lightweight yet robust nature ensure the durability and stability of the mounts within the system. Furthermore, the material's transparency and optical clarity allow for precise laser alignment, contributing to the accuracy and quality of our engraving operations. Polycarbonate's resilience against various chemicals and environmental factors also guarantees the longevity and reliability of the mounts, solidifying its position as the most suitable material choice for our project

Material Detecting Component Accommodations

Considering the design itself we must accommodate all the hardware and photonic devices that are necessary for the laser engraver project. This includes a central laser mount that can house our chosen laser snug and securely with an attachment for the lens right below the laser head. Additionally, the mount has to also accommodate the led light that is going to be shooting down at the laser engravers bed on one side, while the optics fiber cable being mounted on the adjacent side directed towards the bed as well (to collect the materials information).

Another benefit of making the mount an “all-in-one” housing system is the wire and cable management. From the laser head itself having a wire powering, to the fiber cable needed for the spectrometer it will all be compact in one singular harness connected to the hardware box on the side of the system. The laser mount design, optimized for FDM printing with polycarbonate, features a streamlined and adjustable structure. SolidWorks simulations ensure that the design accounts for the material's high impact resistance and heat resistance, allowing for seamless adjustability while maintaining structural stability during the engraving process.Taking the lead to create the 3D model for the centralized mount in solidworks considering all these needs, it should allow a compact unit where all material detection scanning can be initialized and the laser can begin the engraving process subsequently.

Below is a version of the mount keeping into account all the considerations previously mentioned.

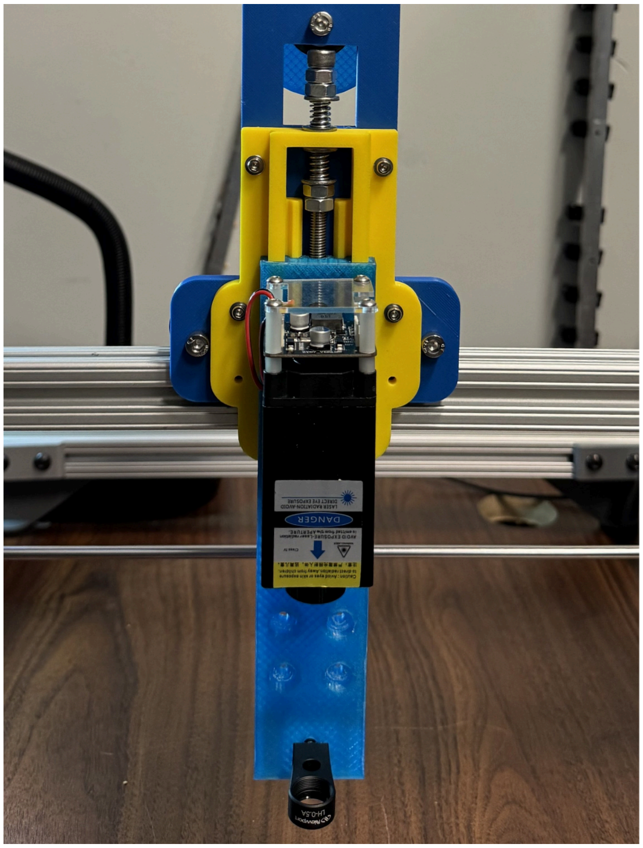


Figure 15: Laser Tool-Head Mount 3D Printed Model

This 3D design incorporates all of the necessary features discussed in the requirements. Being measured the appropriate size, it can house our desired laser directly centered with the tapped M3 screw holes shown. This allows the laser to be aligned directly in the middle of the mount, then bolted in through the back. The same idea and methodology goes for the lens mount being bolted directly below the center of the laser exactly 5 cm below it, ideal for the correct focal length of the laser. Directly below the laser lens mount is an appropriate cutout hole for the laser beam to be directed through upon the initiation of the laser engraving process. To the right of the laser tool-head model lies another mount specifically for the fiber optics cable that would be running the spectroscopic data to the spectrometer housed somewhere separate from the laser engraving area. This mount would accommodate the specific gauge size of the fiber optics cable and be angled 45 degrees towards the specific material. Opposing that mount situated to the left of the laser tool-head model will be a mount for the COB LED light we are implementing also at a 45 degree angle directed towards the given material. This can be seen in the figure below.

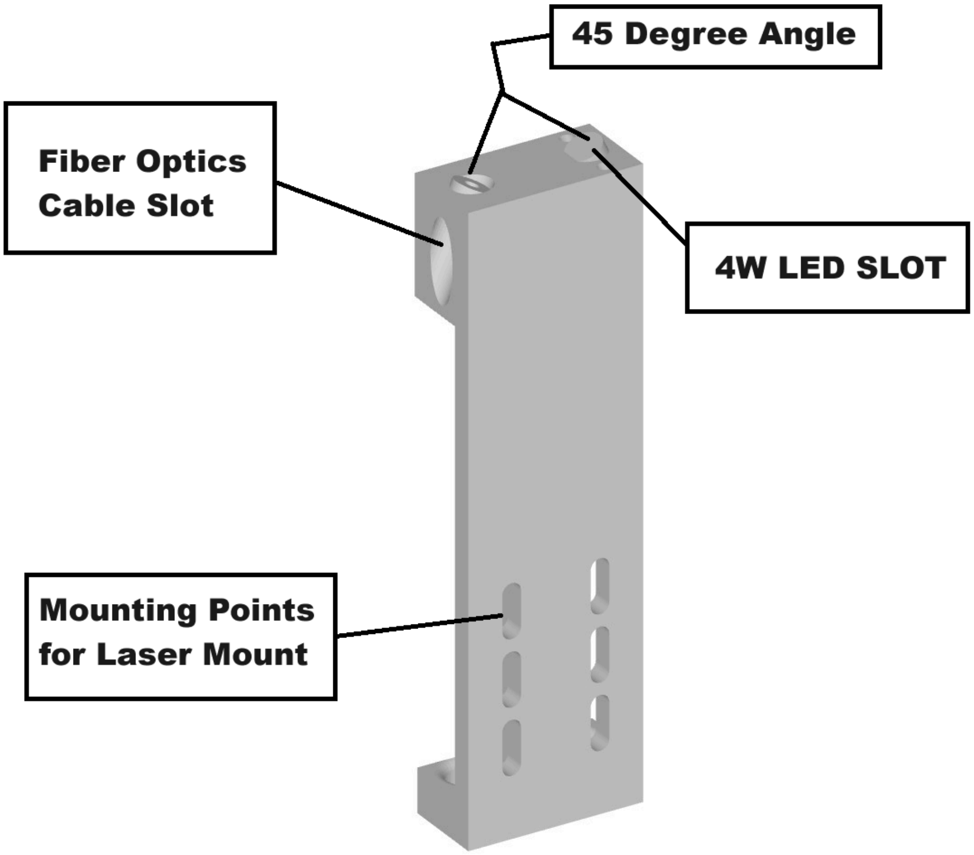


Figure 16: Fiber optics Cable Mount 3D Model Diagram

In addition to housing the LaserTree 4W 450nm laser diode secured by 4 M3 screws, our final laser mount design boasts several important features to the CNC laser engraving system. To minimize overall mount weight and ensure optimal functionality, the mount features a wall-less design. Notably, it includes an adjustable lens mounting area, strategically positioned for precise adjustment in the focal length of the diode laser. Moreover, the mount securely fastens to the manual Z-axis mechanism, ensuring stability and accuracy during operation. This modular system allows for adjustability and easy repairs of the laser, if necessary.

Gantry Tower Design

In the design for the “Gantry Towers” for our movement system, emphasis is being placed on creating a rigid support structure that is static in Z-axis movement, while being able to facilitate precise X and Y motions. Constructed from a lightweight yet durable filament material, these towers will feature strategically placed mounting holes for the desired 3 individual POM wheels that will enable smooth movement along the Y-axis rails. Cutouts and mounting brackets will accommodate the chosen Nema 17 stepper motors, responsible for driving linear actuators that overall effect the controlled horizontal motion along the X-axis of the structure.

Certain alignment mechanisms are going to be put in place, such as adjustment slots and screws, esure accurate positioning, and some reinforcements for the structure like gussets to enhance mechanical stability during the laser engraving process. Seamless integration with the CNC bed and rails, as well as appropriate dimensions for the appropriate maximum Z-height (20cm). Additionally, cable management features have been included into the design for the ‘Gantry Tower’ design for a tidy workspace and little to no interference during the engraving process. This includes housing the appropriate power and signal calves for the laser and range-finding distance sensor, as well as the fiber optics cable that is going to be fed to the stored away spectrometer unit.

Below is a display of the design for the “Gantry Tower” with some features that would benefit all the specific needs mentioned previously.

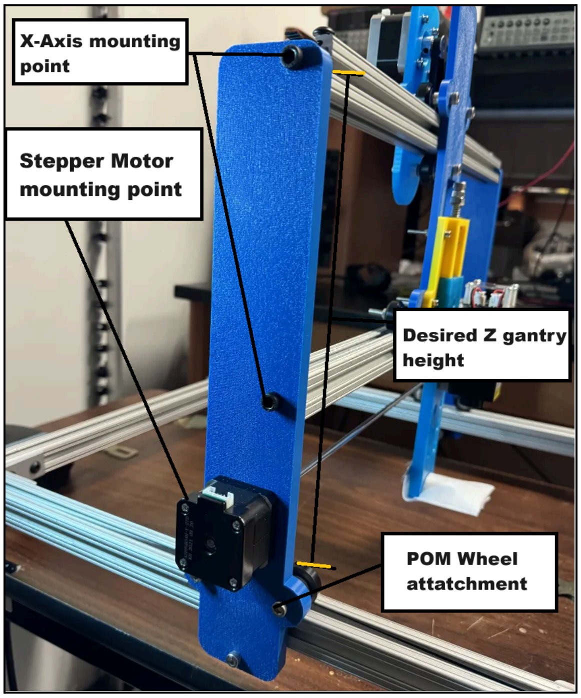


Figure 18: Above is the model outlining how the previously mentioned gantry tower was executed .

3.6.2 CNC Structure Design Considerations

Key Design Objectives

The primary focus of this proposed design is to integrate cutting-edge engineering principles and advanced material technologies to develop a gantry and support structure that excels in precision, reliability, and durability. By emphasizing the strategic utilization of robust materials, precise motion control mechanisms, and stress distribution optimization techniques, the proposed design aims to elevate the overall performance and functionality of the laser engraving CNC system.

Frame Material and Rigidity

Selecting a robust and lightweight material for the bed frame is crucial to ensure structural stability and minimize unwanted vibrations during the engraving process. Aluminum extrusions, renowned for their high strength-to-weight ratio and excellent machinability, are a preferred choice for the bed frame, offering superior rigidity and corrosion resistance. The integration of reinforced steel supports further enhances the overall structural integrity of the bed, providing additional load-bearing capacity and ensuring long-term dimensional stability.

In our laser engraving CNC system, we are incorporating European standard 80/20 anodized linear rails made from aluminum extrusions. These rails ensure precise movement for the laser head and spectrometer along the designated x and y axes. Adhering to European standards guarantees seamless integration with other components. The anodized finish provides robust protection against corrosion and wear, ensuring long-term durability even in demanding environments. Additionally, the sleek appearance of the rails enhances the overall professional aesthetic of our CNC system.

We are planning on opting for an overall frame size of approximately 400x400mm. This specific design will provide enough space around the bed for the gantry system to move freely without any blind-spots while also ensuring stability and rigidity. Vertical supports are going to be strategically placed along the overall frame to provide additional stability. This minimizes any potential flexing issues during the engraving operation.

Cross-bracing may be incorporated for optimal rigidity, reinforcing the frame's structure and preventing any unwanted flexing or distortion. This attention to structural integrity is crucial in any movement, where precision is essential.

Figure 19: 80/20 Aluminum Linear rail figure (Amazon.com)

Structural Stability and Rigidity Enhancement

Prioritizing the design of the gantry and support structure to optimize structural stability and rigidity is essential to minimize any potential deflection or vibrations during operation. Having a solid structure that can withstand all the constant jerking, and vibrations throughout the laser engraving process is essential to a quality end-product. The utilization of truss or lattice framework designs, coupled with the strategic placement of reinforced cross-sectional beams and support brackets in the gantry and support structure, embodies the foundational principle of static equilibrium, ensuring that the sum of forces and moments remains zero (ΣF = 0 and ΣM = 0) to enhance structural stability and minimize deflection and vibrations within the laser engraving CNC system.The gantry, which supports the laser and moves along the X and Y axes, should be designed to span the entire bed size. Ensure that the gantry design allows for smooth and precise movement.

3.6.3 Bed Design

The bed serves as the fundamental platform for material support and engraving within the laser engraving CNC system. In addition to the material selection for the bed surface, several other structural considerations contribute to the system's stability, precision, and overall performance.

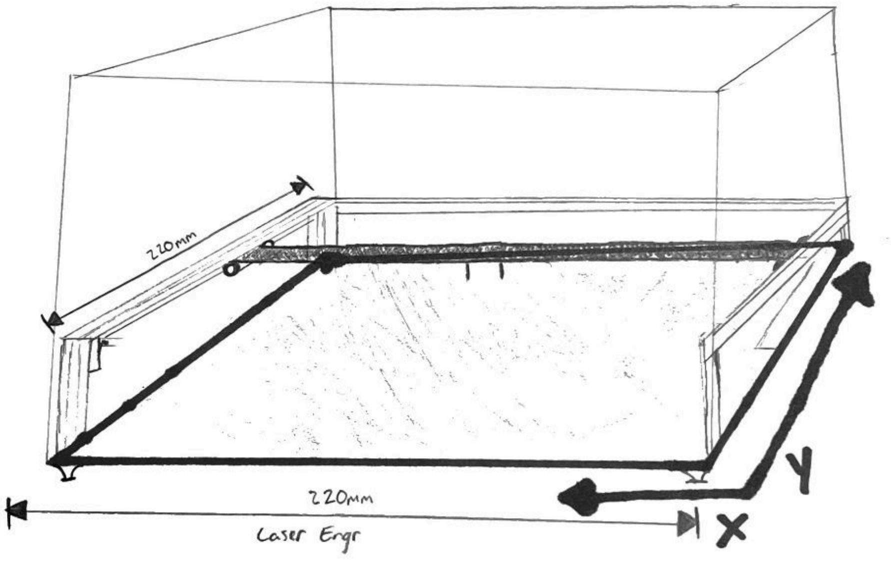


Figure 20: Above is a rough sketch outlining how the bed will be configured with respect to the gantry system.

<u>Dimensional Specifications and Material Selection</u>

The base' precise dimensions of 540 x 470 x 660mm are strategically tailored to accommodate a diverse range of material sizes and shapes, ensuring efficient and precise engraving operations within the specified work area. Utilizing high-quality dull black acrylic material for the bed surface provides a smooth and stable engraving platform, offering excellent thermal conductivity and uniform heat distribution for consistent material processing and optimal engraving quality.

The selection of materials with high thermal conductivity, coupled with the integration of efficient cooling channels and heat sinks, as per Fourier's law of heat conduction, enables effective heat dissipation (Q) and temperature regulation (ΔT) within the bed, minimizing thermal stresses and ensuring uniform material processing temperatures across the entire engraving area.

3.6.4 Integrated Enclosure Design

In the development of the enclosure for our CNC system, we prioritize seamless integration of safety components and functionality enhancements to both the operational requirements and spectroscopy material detection process of the material. Our design approach revolves around selection of durable materials, thoughtful light management, and effective ventilation to ensure a safe conductive work environment.

The enclosure design will primarily utilize a fire-retardant fabric material with insulated lining. A tint will be added at all translucent points of the enclosure itself to insure minimal light from entering the laser engraver (especially while the material detection is being initiated). By minimizing excess light from entering the system, we aim to reduce the potential interferences during the spectroscopy material detection process, contributing to precise and reliable data acquisitions without compromising the overall safety constraints.

To facilitate real-time monitoring and observation of the laser engraving/ material detection process, we plan to incorporate a monitoring webcam video camera situated on the side of the enclosure . This feature enables the user to view the whole process from start to finish.

The enclosure design will also incorporate an efficient ventilation system, equipped with specially incorporated vents and exhaust fans, to effectively dissipate excess heat and maintain optimal temperature control within the working environment.By ensuring release of hot air/ toxic fumes and promoting consistent air cooling from the enclosure system, aims to prevent overheating and prevent any thermal fluctuations thereby safeguarding the laser engraving process and material section spectroscopy process as well.

3.6.5 Z-Height Adjustment System

Material Thickness Control

This automated execution of adjusting the Z-axis distance from the laser tool head to the given material is a more sophisticated and precise solution to accommodate different material thicknesses when laser engraving. It not only allows for a more precise way to adjust the distance but also enhances automation and control for the overall system. This system incorporated the use of a separate stepper motor (Nema 17) that was carefully selected to ensure precision and control, when focusing the laser to the correct spot size. Integrated with a well known lead screw mechanism, the stepper motor facilitates the conversion of rotary motion into linear motion, therefore enabling the smooth and precise adjustments to the laser tool heads height from the material.

Z-Axis Height Adjustment Sensors Comparison

When considering various sensors for the Z-axis height adjustment relative to our laser tool-head, multiple options were on the table, each with its strengths and limitations. Primary contenders included ultrasonic sensors, infrared sensors, laser sensors, and the Adafruit VL6180X Time of Flight Distance Ranging Sensor.

In the context of our laser engraving CNC system, achieving precise Z-axis height adjustments is extremely important for ensuring the accuracy and overall quality in the laser engraving process. The resolution of the sensor plays a pivotal role in determining how finely and specifically it can detect changes in distance, which directly translates to the level of precision when adjusting the Z-axis. Engraving detail is super important. The laser engraving process demands a high level of detail, and any variance in the Z-axis height can impact the overall intricacy and clarity of the engraved design. A sensor with high resolution ensures that even minor changes in the distance can be detected and compensated for during the engraving operation.

Below are some key Capabilities of the various sensors that were considered.

Ultrasonic Sensors:

Ultrasonic sensors use soundwaves to measure distance by emitting ultrasonic pulses and calculating the time taken for the sound to travel to the target and back.

Some of its capabilities include:

- Reliable distance measurement .
- Effective in various environments (especially the enclosed laser engraver platform).

- Can be super sensitive to obstacles and reflective materials and surfaces.
- Susceptible to possible temperature variations.
- May have challenges in obtaining high precision, especially when dealing with small changes in distance.
- Moderate to high resolution, depending on the specific model.

Laser Sensors:

Laser sensors operate on the principle of reflecting laser beams off the target surface and measuring the time of flight or phase shift.

Some of its capabilities include:

- High precision in distance measurement, therefore optimal resolution.
- Suitable for applications requiring accurate readings (i.e: our Z-axis measurement mechanism).
- Can be sensitive to ambient light conditions (Designed platform enclosure eliminates this issue).
- Involved setup, alignment, and calibration.
- Higher cost comparative to other sensor types.

Infrared (IR) Sensors:

IR or infrared sensors measure the amount of infrared light reflected off of the target surface.

Some of its capabilities include:

- Commonly used in proximity sensing and detecting.
- Simple integration
- Cost effective
- Limited in precision comparative to other sensor types, therefore hindering resolution.
- Susceptible to variations due to the various material surfaces its going to target.

Capacitive Sensors:

Capacitive Sensors detect changes in capacitance caused by the proximity of an object or target.

Some of its capabilities include:

- Effective in non- contact sensing.
- May require involved calibration for accurate readings and measurements.

- Suitable for our need of detecting multiple materials.
- May be effective by various environmental conditions.

Time of Flight (ToF) Sensors:

Tof sensors measure the time taken for light to travel to the object or target and back, often using infrared light

Some of its capabilities include:

- High precision and accuracy, directly affecting the overall resolution.
- Less affected by external factors such as ambient light or environmental changes.
- Suitable for distance ranging applications (such as our Z-axis height adjustment mechanism).
- Can be more compact in dimensions and light weight. Contributing to its integration into the laser tool-head mount design.

Although initially considering the integration of a range-finding sensor, such as the 'Adafruit VL6180X Time of Flight Distance Ranging Sensor', to continuously measure the distance between the tool head and selected material, we ultimately decided against its implementation. While the VL6180X offers precise measuring capabilities and compact hardware for seamless integration into the designed mount, we concluded that a manual adjustment system better suited our needs. Unlike traditional IR sensors, the VL6180X eliminates linearity problems in measuring distance. However, after careful consideration, we determined that a manual system would offer greater flexibility and control over the Z-axis height adjustment, ensuring optimal engraving results without the need for automated adjustments.

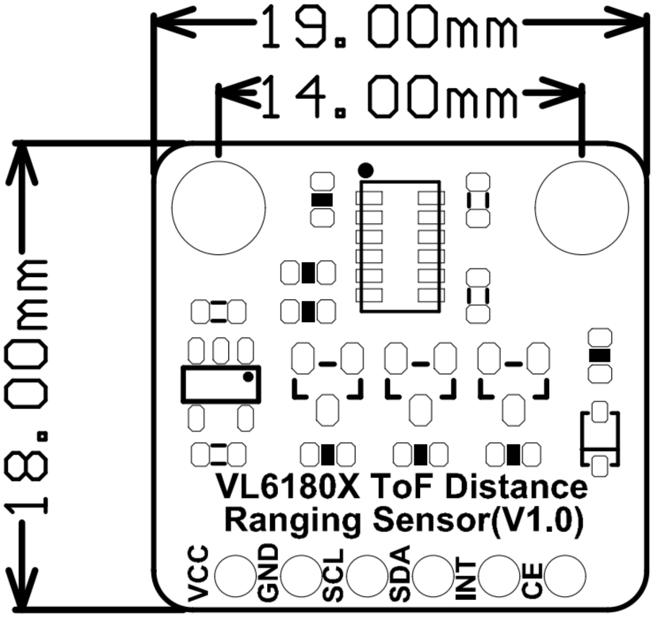


Figure 21: VL6180X ToF Sensor Schematic

https://wiki.dfrobot.com/DFRobot_VL6180X_TOF_Distance_Ranging_Sensor_Breakout_Board_SKU_SEN0427

Sensor Dimensions: 20.5mm x 18.0mm x 3.0mm / 0.8" x 0.7" x 0.1"

Sensor Weight: 1.4g / 0.0oz

Above information provided from product description on https://www.adafruit.com/product/3316

While initially planning to integrate the Arduino Uno microcontroller to process real-time data from the range-finding sensor and automatically adjust the laser tool head to the appropriate Z-axis height from the material, we ultimately decided against this approach. While the Arduino Uno offers capabilities for automation, programmability, and remote control, we concluded that a manual adjustment system better suited our needs. Manual adjustment not only ensures repeatability but also offers greater control and flexibility, particularly in CNC-based laser engraving setups. Additionally, manual adjustment simplifies maintenance requirements and reduces reliance on a consistent power supply, enhancing overall system reliability and performance over time.

Alternate Material Thickness Control with Manual Crank System:

In the context of our laser engraving CNC system, specific control of the Z-axis height from the laser module itself (more specifically the lens) plays a pivotal role in ensuring constant quality engraving when considering the various thicknesses of the material that is being selected. To address this specific requirement, we are considering a robust, user-friendly, manual crank system that is integrated in the laser mount itself.

Our proposed approach for the solution of accommodating the height of the laser system entails integrating a manual crank system that is adjustable up to 30 cm downward from the surface of the material. The design for the crank system will include a durable crank handle, precise screw mechanism, and visual height indicator contributing to the user's convenience and control.

This method of height adjustment ensures ease of operation, since manual adjustment allows for greater precision and control over the Z-axis height, ensuring optimal engraving results. Moreover, it preserves the autonomous nature of the laser engraving process, offering flexibility and adaptability to varying material types and engraving requirements. By choosing manual adjustment, we maintain the integrity of the engraving process while maximizing precision and efficiency.

3.6.6 Selected Materials Properties and Engraving Parameters

In the realm of laser engraving, having optimal results is dependent upon a nuanced understanding of the spectroscopic structure and properties inherent to the materials at hand. In this specific section, we delve into the specific characteristics of three primary materials - plywood, paper, and leather - that are poised for engraving in our laser engraving system. Each material demands unique absorption and reflection profiles, influencing the overall interaction with laser power and energy during the engraving process. As we embark on the creation of the material database, our research will not only include the spectroscopy properties of the materials but also the tailored laser parameter setting necessary for achieving precise and consistent results ranging across plywood, paper, and leather. This systematic approach assures fundamental understanding of how these materials respond to the intricacies of laser engraving, creating a solid database for our automated system to incorporate.

Determining the correct laser parameters and settings for engraving poses a challenge, mostly due to the challenge of deciding several critical factors. Some of these critical factors include the desired end product quality of the engraving, the required speed to complete the engraved product, the focal length of the lens, the wattage of the laser beam, the size of the laser spot, and most importantly the inherent properties of the material being engraved on.

Birch Plywood:

The composition of plywood is traditionally composed of layers of wood veneers glued together. The wood types and glue can vary depending on the material and grade , this all influences the materials light absorption and reflection properties. Speaking on the absorption spectrum, wood generally absorbs laser energy very well, especially in the near-infrared range. The absorption spectrum may differ depending on the specific wood species used in the plywood. In our case the specific plywood material we are opting for ‘birch plywood’ due to its general availability. Birch plywood tends to char when being engraved on with a laser due to the pyrolysis of wood components. The contrast in wood components is often high, showcasing a darkened appearance against the darker wood background..

Laser Parameters:

Plywood comparative to the other materials in our selection may require moderate to high laser power settings for effective and precise engraving. Below are the main parameters in question that will be automatically selected for plywood in our material detection process.

- Wattage Machine: 80 60 40
- Percent Wattage: 14 18 20
- Speed MM/s: 350
- Scan Gap mm: 0.085
- DPI: 300
- Passes: 1 Pass

Ideal laser parameters for plywood sourced from https://www.cs.cmu.edu/afs/cs/academic/class/99353-f16/speedsfeeds_RL.pdf

Cardboard Paper:

Paper is composed of cellulose particles and fibers. The thickness and density can vary depending on the selection. In our project's case we decided to opt for a Pen+Gear “cardboard paper” which bosses the thickness of 0.254 mm. This characteristic drastically influences the laser penetration and absorption. As far as the absorption spectrum, cardboard has high absorption in the ultraviolet and visible light ranges. Its most of the time tends to absorb the laser energy introduced efficiently, contributing to localized heating during the engraving process. Charring and contrast brings some heavy considerations when selecting specific parameters. Paper specifically can char easily during the engraving process. The contrast is usually high during the engraving process, with the darkened area against the lighter hue of the surrounding paper material.

Laser Parameters:

- Wattage Machine: 80 60 40
- Percent Wattage: 14 18 20
- Speed MM/s: 350
- Scan Gap mm: 0.085
- DPI: 300
- Passes: 1 Pass

Ideal laser parameters for Paper sourced from https://www.cs.cmu.edu/afs/cs/academic/class/99353-f16/speedsfeeds_RL.pdf

Full Grain Genuine Leather:

Leather is derived from animal hides and overall consists of collagen fibers. The finish, quality, treatment, and type of leather affects the laser engraving properties. Leather absorbs laser energy pretty well, especially with a near-infrared range. The absorption spectrum may vary based on the tanning method. As far as the charring and contrast it is important that a genuine leather is selected when engraved on. Having a faux leather, vinyl, or ‘pleather’ can contribute to flare-ups, chemical fumes, and or excessive charring on the material. This introduces a safety hazard if the material selected is not actually leather. Darker leathers usually provide higher contrast generally.

Laser Parameters:

- Wattage Machine: 80 60 40
- Percent Wattage: 45 50 60
- Speed MM/s: 325 325 325
- Scan Gap mm: 0.085
- DPI: 299
- Passes: 1

Ideal laser parameters for leather sourced from https://www.cs.cmu.edu/afs/cs/academic/class/99353-f16/speedsfeeds_RL.pdf

3.7 Additional Architectures & Diagrams

In this section, we did delve into additional architectures required for the project. This includes things like the PCB, specifically the board we did be implementing into our laser engraver, which is responsible for controlling our material detection during the process.

3.7.1 PCB Schematic

Part of this project is being able to create our own PCB. It is to be designed, assembled, and printed by us and included in the final product. Most of this is possible in part to having prior knowledge in creating schematics for custom PCBs in a class previously taken called Junior Design. Our members have had the opportunity to create custom PCBs through another class, using an MSP430 as its MCU. This will be important in the development of our own PCB, having these previous schematics as a great jumping off point as helpful jumping off point.

While having schematics for a completely separate board for another use, it is a great jumping off point for what can be done for this project. What will be implemented in the board will depend of course on the necessary pins or components that will be needed. This was designed using Eagle, an AutoDesk software that's become a popular software tool for designing PCBs, thanks in parts to its functions such as the schematic design, its extensive list of libraries, and manye design assistants that will check for errors, or even its 3D visualization of the PCB design. This software has been used for a wide range of devices, such as robotics, consumer electronics, high grade equipment used in large industries, or even for a laser engraver.

3.8 Spectroscopy System

Within this section, we did discuss the spectroscopy system that will be implemented to capture the reflected light from the engraving materials. we did incorporate a spectroscopy system into the laser engraving device to recognize materials to automate the laser power and scan speed input process. In this section, we did discuss spectroscopy techniques along with the spectrometer components we did be using within our setup.

3.8.1 Spectroscopy Fundamentals

Spectroscopy is a branch of science that is concerned with the analysis of the electromagnetic spectrum emitted from a source. The goal of spectroscopy is to take a source of light and break it into its component wavelengths and draw conclusions from the distribution of wavelengths. Typically, the spectrum of light is plotted with wavelength (or frequency) on the x-axis and intensity on the y-axis. Spectroscopy can be used in several ways from medical imaging to astronomy and is a critical tool used to gain information from materials.

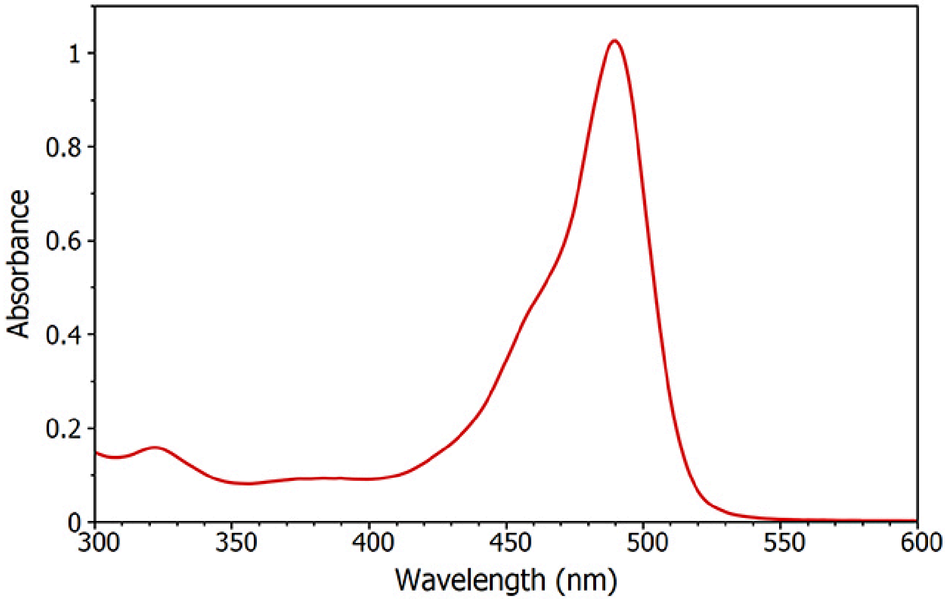


Figure 22: Absorption spectrum measured using a spectrofluorometer (Edinburgh Instruments)

Spectroscopy is useful in identifying materials as each element or material absorbs/reflects light differently. By looking at how a material absorbs light at each wavelength, it is possible to get a plot of intensity versus wavelength which is unique to each material. In chemistry, a material can be identified by cycling through the visible spectrum of light and looking at how each wavelength is absorbed/transmitted. This data helps to determine the unique absorbance pattern of an element and identify the element without running any invasive/destructive tests.

There are a number of different types of spectroscopy that can be used in our project. we did discuss three common techniques and weigh the advantages and disadvantages of each in the context of our project.

3.8.1.1 Absorption Spectroscopy

Absorption spectroscopy is a common technique that uses a broadband light source containing a wide range of frequencies, then uses a diffractive element such as a prism or diffraction grating to break down the broadband light source into its component frequencies then cycle through each frequency one by one.

Each wavelength is emitted and passes through the material being analyzed. An optoelectronic component such as a photodiode captures the intensity of light at each wavelength. After cycling through each wavelength, a plot is made comparing each wavelength to the intensity of light read by the photodiode. This plot shows the relationship between absorbance and wavelength for a given set of frequencies. The absorbance plot can be used to identify the material under investigation or to find how specific wavelengths interact with the material.

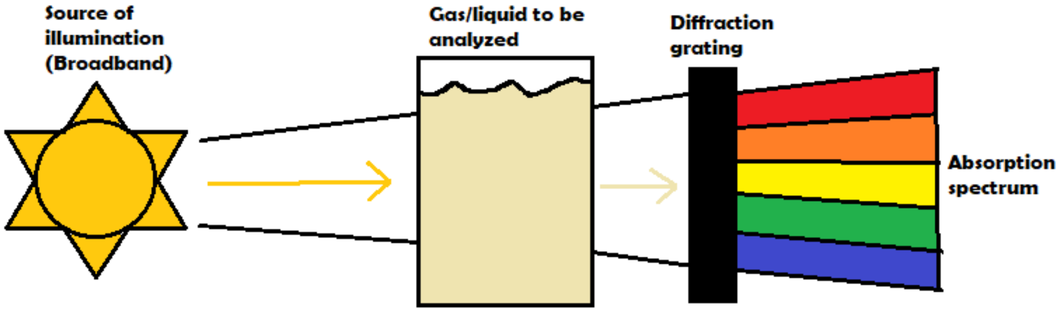


Figure 23: Schematic of absorption spectroscopy scheme

As shown above in figure XX, the material labeled “high density hot matter” emits light to illuminate a gas (“cold gas”). This gas will absorb a portion of the light from the source and pass through a diffractive element such as a prism or diffraction grating (seen as the zig-zag pattern in the figure) which will separate the light into its component wavelengths. The spectrum can then be represented as a continuous band (rainbow) with segments missing where the gas has absorbed certain wavelengths.

Typically, absorption spectroscopy is used with translucent materials such as gasses or liquids because a significant amount of light can be detected after passing through a sample. Absorption spectroscopy is not realistic for our application since wood, leather, and fabric would absorb nearly all of the light leaving little to no signal to analyze.

3.8.1.2 Reflection Spectroscopy

Reflection spectroscopy is very similar to absorption spectroscopy. However, instead of analyzing the light being absorbed, reflection spectroscopy analyzes the light that has been reflected off of a material. In a way, reflection spectroscopy just quantifies what our eyes already see. When looking at different materials, our eyes take in light that has been reflected off of a material. Based on the wavelengths of light that hit the rods and cones of our retina, our brain creates an image with color. Similarly, in reflection spectroscopy, light that has been reflected off of a material is analyzed and broken down into its component wavelengths. Reflection spectroscopy is a conjugate of absorption spectroscopy in that all of the light that is not absorbed gets reflected which can convey similar information.

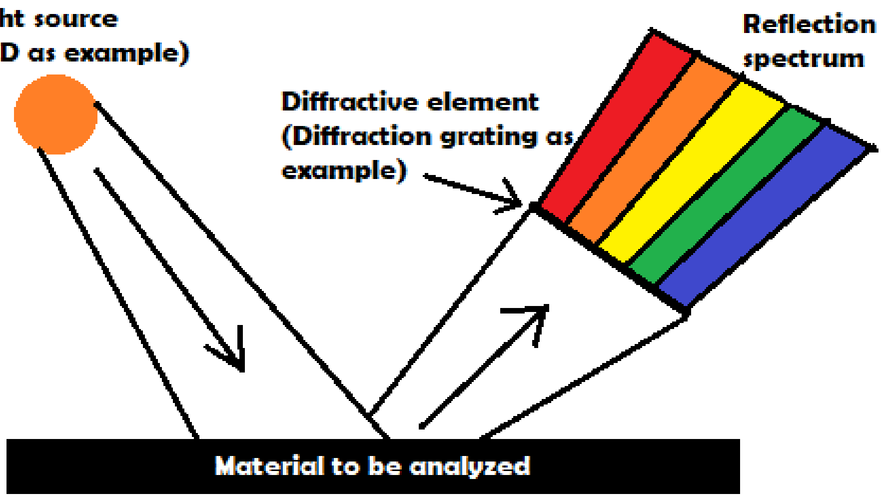


Figure 24: Schematic of reflection spectroscopy scheme

Using reflection spectroscopy is a more realistic option for our project since we are using solid, opaque materials that strongly absorb light. Additionally, reflection spectroscopy is non-invasive and does not impact the material in an irreversible way. Though not related to light-matter interaction, reflection spectroscopy is also affected by surface roughness. While the shape of the reflection spectrum would not be affected by a change in surface roughness, the rougher the surface, the less light will be captured by the spectroscopy system. This will be factored into the identification process as the overall intensity of light will be a factor when looking at the reflection spectra of materials in addition to the shape of the spectra.

3.8.1.3 Emission Spectroscopy

Emission spectroscopy examines the spectra of light emitted from a material when excited. This technique is used to examine black-bodies such as stars which emit photons due to their high temperature. The wavelengths of the photons emitted are unique to the elements emitting the photons. By analyzing the light emitted from an excited body, we can gain insight into the exact composition of the body. Since materials at room temperature do not have enough energy to emit photons without excitation, the only way to capture emitted photons is to provide energy through an external heat source. This is a possibility for our project as we can use the laser to heat the material until it begins to emit lots of photons and then capture this light and analyze its spectrum.

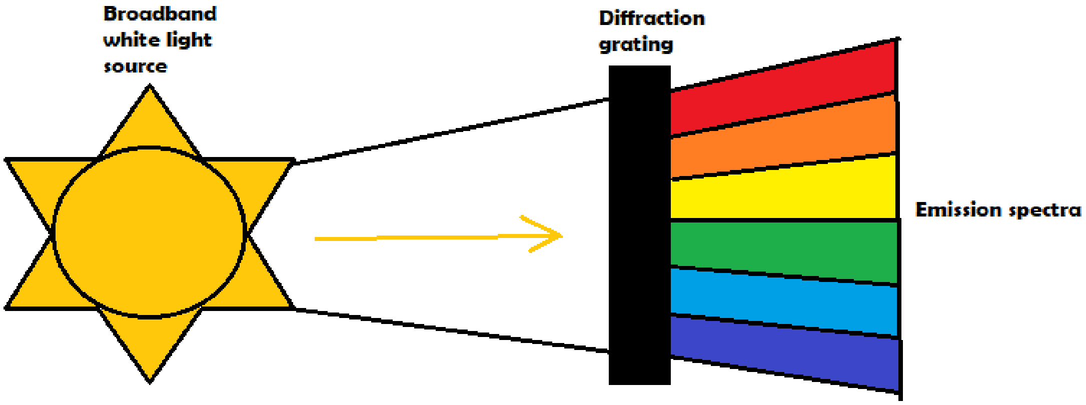


Figure 25: Schematic of emission spectroscopy scheme

There are a few downsides to using emission spectroscopy, however. Firstly, in order to proceed through the recognition process, a material would have to be burned with the laser which might negatively impact its appearance. Since engraving is used for aesthetic purposes, this is a deal-breaker if the material recognition process would ruin part of the material's exterior by burning a spot at the start of the engraving process. Secondly, in order to limit the damage done by the laser and not cut through the material, the laser should not be powered on for a long duration. This limits the window to capture light for spectroscopy and decreases the robustness of the system. Lastly, for a low-cost spectroscopy system such as the one we are building for the laser engraver, low-sensitivity methods should be avoided. When capturing the light from the laser hitting the material, the vast majority of light will be directly from the laser itself at 450 nm. This could make detecting other wavelengths harder and the whole process less accurate.

3.8.2 Spectrometer Basics

While in our project we are not building a traditional spectrometer as would be used in a lab, we did be using many of the same components and ideas to capture spectral data. Spectrometers work by first collecting light. In many spectrometers, a fiber optic cable is utilized in order to allow for freedom in capturing light at different angles and physical positions. After the light passes through the cable, the light exits the fiber through a slit which shapes the beam appropriately for the linear sensor. After passing through the slit, the light reflects off of an array of mirrors (or lenses) which direct and shape the beam onto a diffraction grating that splits the incident light into its component wavelengths. Light reflected off of the diffraction grating is then focused onto a linear CCD detector which will read the intensity value at each pixel as the intensity of light at a certain wavelength. The spectral data captured from the CCD is then sent to a computer which will be able to read and visualize this data.

Our project will seek to capture and manipulate light in a similar way but built into the setup of the laser engraver. Some challenges that come with moving the compact setup of a spectrometer into a larger system such as the laser engraver are misalignments, power loss, and interference with the CNC arms.

When incorporating a system of lenses, mirrors, diffraction gratings, and a sensor, aligning all components accurately and consistently is important. Traditional spectrometers have all of their optical components secured within a tight form factor which is highly resistant to mechanical misalignments. Building the same optical system spread apart over a much larger area leaves the system susceptible to shifting and movement. Therefore, when integrating the spectroscopy system within the laser engraving setup, it is imperative that care is taken to secure all components.

Another issue that comes with a larger form factor is power loss. Due to the nature of incoherent, broad-band light sources being highly divergent, having a long optical path length means that much of the generated light will not reach the detector. Even for high-powered light sources, power drops exponentially with distance making it tricky to collect enough light for consistent readings. A long optical path length combined with the use of materials with diffuse reflective surfaces makes gathering enough light for the spectrometer tricky.

3.8.2.1 Light Source

A key component of our reflection spectroscopy system is the source of illumination. As our engraving device will be encapsulated by a protective shield, most of the ambient light will be blocked, leaving the vast majority of the reflected light from the engraving material from the chosen light source. Picking a good light source is essential because the spectrum of light emitted from it will have a large influence on the spectrum of light collected and directed toward the spectrometer. Since our spectrometer will use a CCD which is typically sensitive to visible wavelengths, we should also use a light source that emits in the visible spectrum.

Sources of white light include LEDs, fluorescent lamps, incandescent bulbs, and gas discharge lamps. Each of these are broadband sources and has center wavelengths within the visible range (400 nm - 800 nm). Differences between them lie in the mechanism of emission, form factor, energy efficiency, and cost. Since our light source must be mounted directly on our moving laser, it must be within a small form factor. Additionally, since our engraving system will be enclosed with minimal air circulation, we would prefer a light source that emits little heat and is very energy efficient.

In terms of size, fluorescent lamps, incandescent bulbs, and gas discharge lamps take up a lot of space which would make integration difficult. LEDs are compact and come in many forms which makes mounting them to a laser simple. LEDs have two pins, the anode (positive) and the cathode (negative). Controlling illumination intensity is as simple as applying a varied voltage across the anode and cathode above the minimum level which will be straightforward with a microcontroller.

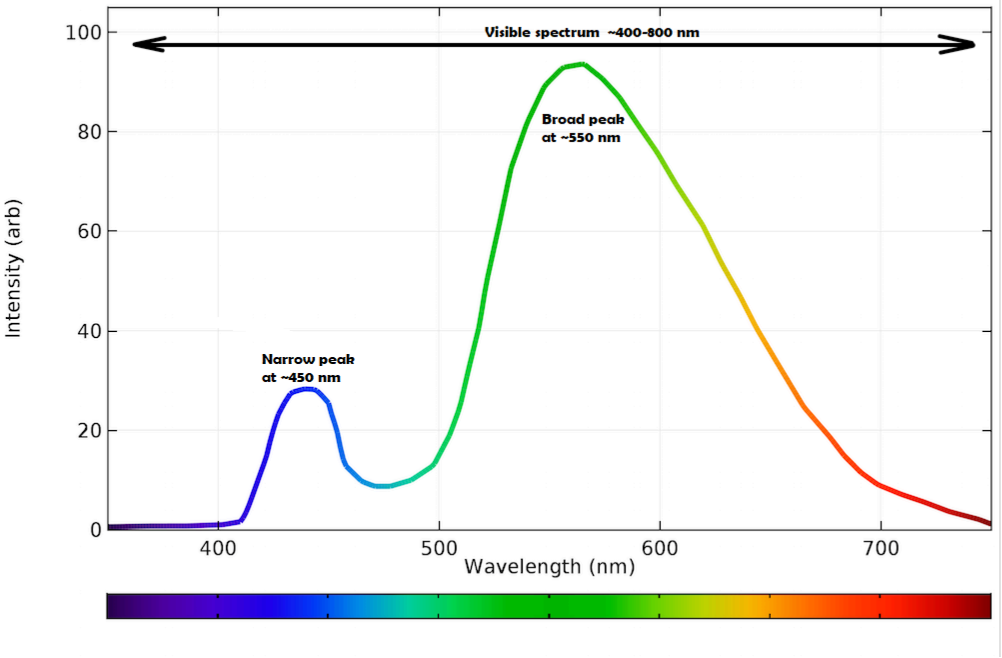


Figure 26: Emission spectrum from a white LED (Cosmol)

White LEDs vary in terms of bandwidth, central wavelength, and optical power. The selection of our LED should be dependent upon the sensitivity of our sensor with each wavelength. According to Edmund Optics, CCD and CMOS camera sensors are typically most responsive to wavelengths in the range of 400-1000 nm which falls in the visible to near IR range. While most white LEDs on the market emit within this broad range, the challenge lies in finding an affordable option that emits enough power.

3.8.2.2 Slit

A slit is an essential component within the spectroscopy system as it is used to shape the incoming light to be easier read by the spectral sensor (CMOS camera). Within typical spectrometers, a slit is placed immediately after the fiber input which turns a Gaussian-like beam into a slit-shaped beam. Most commercial spectrometers use linear CCD sensors to capture spectral data and thus need incoming light to be shaped in a similar way to the sensor. The slit shapes the incoming light into a long, narrow shape that will travel through the optical system and interact with the diffraction grating and mirrors/lenses before it is captured by the CCD and read as a spectrum.

Within our project, we are using a 2D camera sensor which gives us more flexibility and allows us to use a larger slit within our system. The narrower the slit used, the narrower the beam of light traveling through the system. Since our 2D CMOS sensor will capture light in the x and y dimensions, only a slice of the image will be taken and used to create a spectrum. A slit is still useful for aligning the optical components and reducing excess light but an ultra-narrow entrance width is not necessary. According to StellarNet, “Most spectrometers offer slit sizes of 14, 25, 50, 100, and 200 µm.” (StellarNet) Slits of these sizes need to be specially ordered and are likely not required for our application. A slit of a few millimeters should be enough to shape the incoming light and can be made using simple cutting tools like an Exacto knife.

3.8.2.3 Dispersive Element

In order to capture the reflection spectrum for our spectroscopy setup we need an element that will split the reflected light from the engraving materials into its component wavelengths. Typically, prisms and diffraction gratings are used for this purpose. we did discuss the advantages and disadvantages of each in the context of our project.

3.8.2.3.1 Prisms

Prisms are transparent objects with polished, flat surfaces that are used to refract light. Prisms utilize the principle of dispersion innate in the optical material from which it is made. Prisms are typically made from glass and plastics which have various refractive indices depending on the wavelength of light traveling through them. Due to the difference in refractive indices that light of various wavelengths sees while passing through glass and plastic, different wavelengths travel at different angles throughout the prism spreading out the incident light into its spectrum. Light exiting the prism can be seen as the sum of the components of the light entering the prism and could be coupled with a sensor to capture the spectrum more easily.

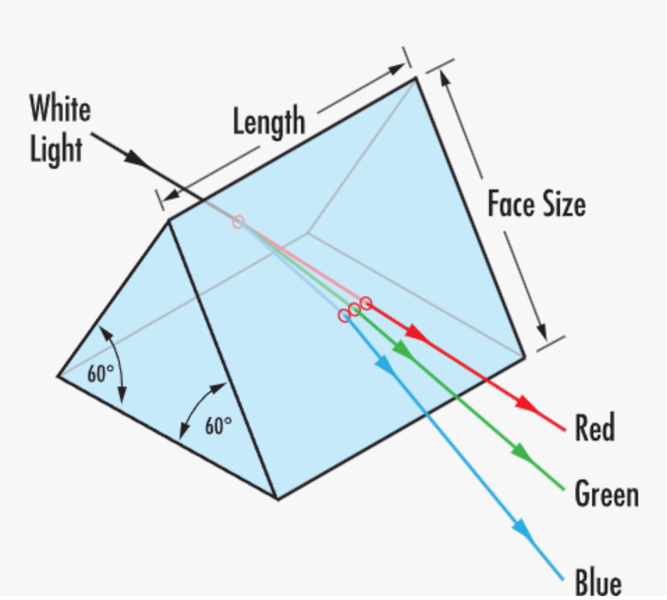


Figure 27: Mechanism of a prism separating white light into component wavelengths (Edmund Optics)

Prisms are effective at separating light into its component wavelengths and do so with high efficiency (Edmund Optics). Prisms experience loss due to fresnel reflections upon entry and exit as well as some absorption from the glass/plastic media. These losses are not severe however as the vast majority of incident light will be transmitted. The dispersion effects also depend on temperature as the refractive index of the material changes as a result of heating or cooling. This should not be a problem as temperature should be kept relatively constant throughout the material identification process. While performance may be high with prisms, they are typically very expensive which could be prohibitive for our cost-limited project. Prisms are suitable for high-end applications such as industry spectrometers but alternatives should be considered for a student-led project.

3.8.2.3.2 Diffraction Gratings

A diffraction grating is another useful tool for separating incident light into its component wavelengths. Diffraction gratings are flat surfaces with periodic structures that reflect light at different angles depending on the wavelength (Edmund Optics). Incident light will be reflected as a spectrum with shorter wavelengths reflecting at shorter angles and longer wavelengths at larger angles. Diffraction gratings reflect light in multiple “modes" in which each mode contains a full spectrum. The exact angle at which light is reflected from a diffraction grating is given by the equation $m\lambda = d(sin\alpha + sin\beta)$ where m is an integer representing the mode, d is the distance between grooves, α is the angle of the incident light, and β is the angle of the reflected light. As λ varies, so does the reflection angle β. Higher wavelengths will be reflected at higher angles.

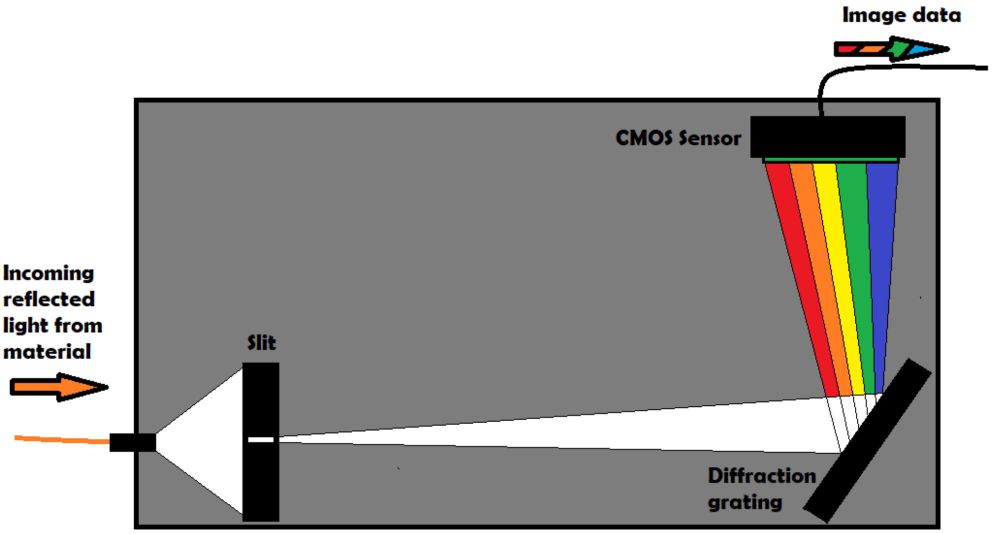


Figure 28: Schematic of spectrometer design using diffraction grating which splits incoming white light into a spectrum

Diffraction gratings have some notable differences compared to prisms. Diffraction gratings are much less efficient in terms of output-to-input power ratio. Due to the fact that gratings reflect light into multiple modes, the output power is spread into multiple different angles which limits the amount of light within a singular mode. The spectral resolution is similar to prisms which means that light will be split into component wavelengths just as accurately. Diffraction gratings also give you the freedom to choose the groove density as well as the blaze wavelength which is the wavelength with the highest efficiency. Since we did be operating within the visible spectrum, we want to choose a diffraction grating with a blaze wavelength of around 532 nm which will be in between blue and red. Importantly, diffraction gratings are typically more affordable than prisms. Since diffraction gratings are cheaper and have nearly identical spectral resolutions, diffraction gratings are the ideal choice for our project.

3.8.2.4 Spectral Sensor

In order to capture usable data for the spectrometer in our project, we need a sensor to capture visible light. In typical spectrometers, a linear CCD (charge-coupled device) is used which is a one-dimensional array of pixels that are sensitive to light intensity. Since light will be dispersed through either a prism or diffraction grating, the light that hits the CCD will be already split into wavelength and intensity. The linear CCD outputs a one-dimensional array of data that corresponds to the intensity of light read at each pixel, which in a physical sense relates to the intensity of light at each wavelength. The higher the pixel count for the CCD, the higher the spectral resolution attainable.

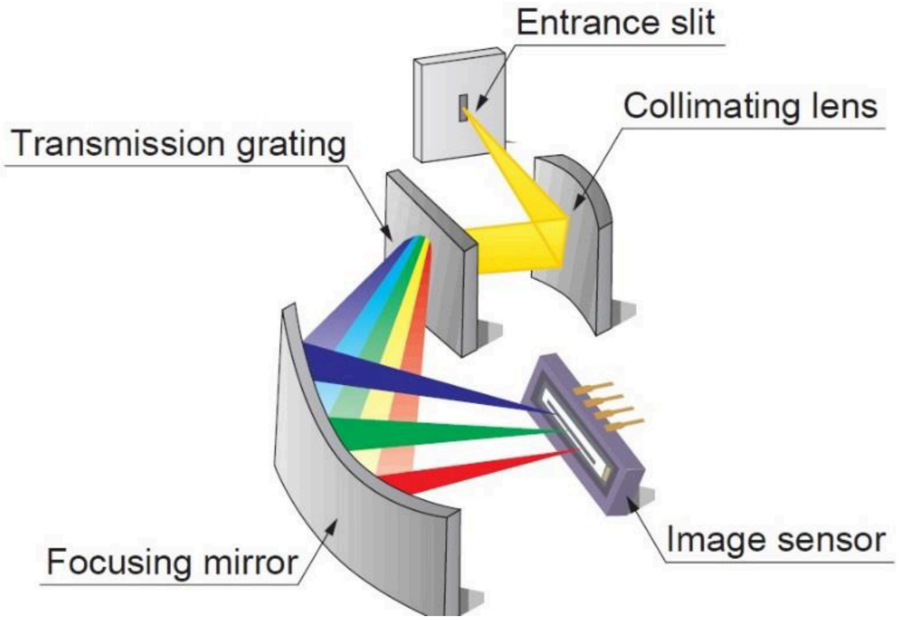


Figure 29: Use of linear CCD within a spectrometer (MDPI)

Linear CCDs are fairly affordable but are not very user-friendly. Due to the nature of the linear CCD, the physical shape of the device makes it convenient for a compact, portable spectrometer. Since the sensor we did be using in our project will be incorporated into a larger engraving system, minimizing size is not of the utmost priority but is still valuable. Linear CCDs are not widely available and are not typically used in standalone applications without paired software.

Another option for the spectral sensor is a CMOS (complementary metal-oxide semiconductor) camera. CMOS cameras work similarly to CCD cameras in that each pixel measures the intensity of light at a spatial region at a given time. CMOS sensors have an amplifier at each pixel however which reduces the light intensity requirement to obtain good images. Additionally, CMOS sensors have lower power consumption and faster signal processing. Since our spectroscopy system will have high loss due to absorption from the engraving material and a divergent light source, having a highly sensitive sensor is important in order to obtain accurate spectral data.

Out of the CMOS products on the market, 2D CMOS sensors are the most abundant and affordable option. 2D CMOS sensors are used heavily in a wide range of applications and have a large selection to choose from. Additionally, many 2D CMOS sensors come with software packages which makes it very easy to interact with and obtain data from. Many 2D CMOS sensors are made to be used with popular microcontrollers such as a Raspberry Pi or an Arduino which makes integration much simpler.

3.8.2.5 Light Collection

A vital part of the spectroscopy scheme is light collection. In order to form an accurate spectrum, there needs to be an efficient way of transporting light from the source to the spectrometer. Proper light collection is important for multiple reasons. First, the majority of the light collected needs to be from the subject of interest. If a high proportion of light collected is from sources outside of the subject of interest, then the signal-to-noise ratio can be low, reducing the quality of results. Additionally, in order to meet the needs of the sensor (CMOS, CCD, etc.), there needs to be enough light in order to stimulate the pixels to a readable level (above background noise). Our laser engraving system will be enclosed by a protective shield which not only will protect the user's eyes from UV light damage but will also block out ambient light from the spectroscopy system's sensor. Blocking out ambient light is essential as average room lighting can be too intense for an exposed sensor and can make accurate spectral readings difficult.

As mentioned previously, our light source will be a high-powered LED which will have a divergent beam. Light intensity from an LED drops off exponentially with distance which means that placement of the light source and collection mechanism is important to ensure the spectrometer receives enough reflected light.

There are two options for light collection to consider for our spectroscopy setup. The first is an open setup composed of a system of lenses to focus reflected light onto the diffraction grating and then subsequently focus light onto the sensor. The second is a fiber-based setup which utilizes a fiber to collect reflected light close to the source and transport that light to the spectrometer body.

3.8.2.5.1 Open Light Collection

One method we can use to transport light reflected from the engraving material to the spectroscopy setup is through an open lens-based scheme. The basic idea behind this open setup is to mount a collimating lens close to the surface of the material to stop the divergence of the reflected light (originally from the LED) and direct the beam onto a diffraction grating. In this setup, the diameter of the collimating lens will be roughly the same as that of the diffraction grating such that we get as much light as possible for analysis. Light will then be reflected off of the diffraction grating into multiple modes. The first-order mode will be reflected onto our sensor which will collect the spectral data.

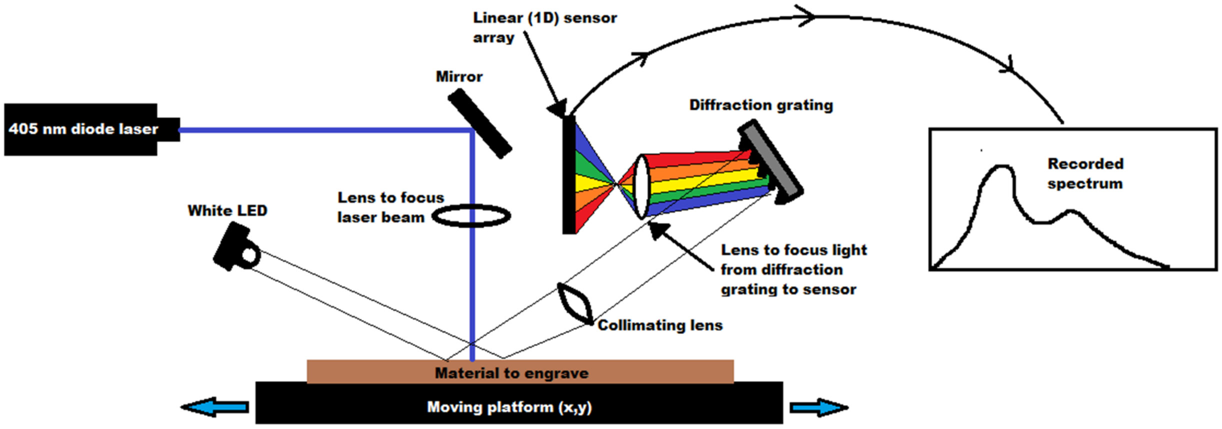


Figure 30: Schematic of open light collection design

One potential benefit of using an open design is that it gives us a high volume for light throughput. Given the large diameter of the collimating lens, a big portion of the reflected light can be collimated to the diffraction grating and through the system. If aligned well, the open design should capture lots of reflected light and make spectrum interpretation easier. However, this design does not fit well with a laser engraver. Due to the fact that the laser will travel around on dual-axis rods which will cover the space directly above the engraving platform, placing any optical equipment such as a lens will get in the way of the laser. If this system is to be implemented, the optics would have to stay stationary while the platform moves around. While this solves the problem of integrating a spectroscopy system, it makes the whole engraving device much larger and unnecessarily bulky.

3.8.2.5.2 Fiber-based Light Collection

An alternative method for light collection is to use an optical fiber to transport reflected light from the material to the spectrometer setup. Using an optical fiber is common among commercial spectrometers. Optical fibers are waveguides that transport light from one location to another using total internal reflection. Optical fibers are bendable which gives freedom to move the complex optical components involved within a spectrometer around our engraving system without the worry of interfering with the laser. An optical fiber opens up the possibility of moving the spectrometer out of the engraving area and enables us to continue with the dual-axis design instead of the moving-platform design.

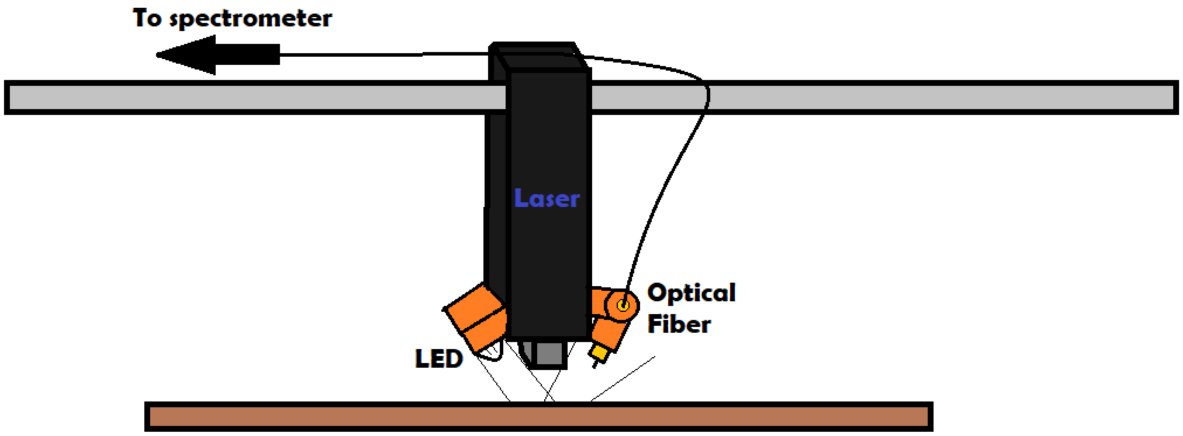


Figure 31: Fiber-based light collection system integrated into the laser engraver

While optical fibers give us freedom in terms of component placement, they certainly have downsides. Firstly, optical fibers capture much less light due to their narrow diameter which makes it more difficult to have a strong enough signal to overcome background noise. Typical single-mode fibers have a core diameter in the range of 8-10.5 micrometers. For a self-built spectrometer, low light levels can make getting good readings difficult and block out background noise of high importance.

Due to the physical freedom that optical fibers give us, they will be the best option for integrating a spectroscopy system into our engraving setup. we did mount the optical fiber to the traveling laser using a 3D printed part which will house the laser, optical fiber, and the LED light source. Mounting the fiber and LED within such close proximity enables the fiber to collect as much reflected light as possible which will be vital with such a small entrance diameter.

3.8.2.5.3 Spectrometer Integration and Housing

In the integration of the spectrometer into our laser engraving system, we decided to include a strategic approach to ensure optimal functionality and precision, during the material detection process, as well as the laser engraving process respectively. The spectrometer being a sensitive optical instrument, it definitely calls for being situated from the immediate vicinity of the laser engraver to deter from potential interferences and overall environmental influences or effects. Having this separation is designed to protect the spectrometer from any ambient light, vibrations, and any possible thermal changes associated with the laser engraving process.

This ultimately preserves the accuracy and precision of the spectral measurements during the material detection. To include seamless material detection during laser engraving, a fiber optics cable is strategically mounted on the side of the laser tool-head mount situated at a 45 degree angle towards the material surface. Measurements were taken of the fiber optics cable gauge size and implemented in the threaded mount on the side of the laser tool-head. This design allows the more flexible and lightweight fiber optics cable to be on the laser mount vs the more rigid, heavyweight, and delicate spectrometer that could possibly cause material detection errors upon several engraving trials. The fiber optics cable serves as the conduit for collecting the light being emitted or scattered after the LED light is being reflected onto the material itself. By situating the spectrometer remotely away from the laser system, and using the fiber optics cable for data transmission,the spectrometer can keep its precision and sensitivity.

In configuring the mechanical components of our spectrometer setup, we've embraced the use of our previously mentioned 3D-printing filament selections. The spectrometer frame, meticulously designed for precision and stability, is constructed using a Polycarbonate-Based filament in a 3D printing process. This innovative choice integrates the flexibility of 3D printing with the robust characteristics of polycarbonate, ensuring a lightweight yet durable structure to support our optical elements. Polycarbonate's notable optical transparency and impact resistance make it an excellent fit for the 3D-printed components, aligning seamlessly with the rigorous demands of spectroscopic measurements. The linear actuators, POM wheels, and other critical components are intricately incorporated into this 3D-printed framework, guaranteeing both adaptability and optimal performance. This approach not only represents a technological leap in manufacturing but also underscores our commitment to pushing the boundaries of precision and functionality in our spectrometer design.

3.9 Part Selection

When speaking in terms of developing a laser engraver, we did need to highlight some of the important aspects of development, including the specific hardware that will be included for this project. In this section, we did go in depth in the various parts selected for all three disciplines, including computer, mechanical, and photonics.

3.9.1 Computer Hardware Selection

In terms of part selection in relation to the computer portion of the project, many different aspects need to be taken into consideration, as it is directly attached to its usage with the electrical and photonical portion of the project. One clear thing is that we did use two individual PCB boards, one that will be used as the material detection, being able to carry essential elements needed for the project. One of them will be a custom PCB, this will be the one responsible for creating the material detection, most likely using an ATmega32 as its microcontroller. The other will be a premade board still using the ATmega32 as its MCU, this one will be responsible for creating the motions done by the CNC motors, working to maintain, control, and function properly.

Item Description	**Quantity:**	**Total Cost:**
Microcontroller Chip for the PCB (TBD)	1	$20
PCB Components + Printing Cost (Custom PCB)	1	$25
Arduino Uno: ATmega328 (GRBL)	1	$25
DRV8825 Stepper Drivers	3	$10
Limit Switches	2	$5
CNC shield: HiLetgo A4988HiLetgo 2pcs A4988	1	$8
LEDMO 12V 5A 60W LED Power Supply	1	$13
LCD Display (2.4-inch TFT LCD Display Module with touchscreen)	1	$30
Software (Windows Engraver Software + MCU Software)	1	Free

Table 05: Part Selection for Computer

The biggest thing to take into consideration will be the implementation of hardware in this project. We are planning on using two separate boards, one using an MCU of ATmega32, and another board that will be a custom made PCB, with the specific MCU to be determined. The primary reason for choosing these MCU will be to have the ability of using the in house Arduino compiler and GRBL, which has been gone into further detail later in the report. Careful consideration will also be taken in account when trying to delegate reasonings for the specifics on the PCB board, such as how many I/O pins, and its compatibility with certain software that may be used, such as the GRBL with has capabilities of using many features that are compatible with each other, streamlining the work process.

3.9.2 Photonics Part Selection

For the laser system, we need a diode laser module that does not require a vast amount of electrical input power as well as around 5W of optical power output in the blue/UV range of the spectrum. Laser diodes in this wavelength are most commonly gallium nitride (GaN) and these are relatively cheap laser diodes. For the sake of this project, we did be using a laser module that has a PWM control pin as well as attached drivers and fan for simplicity. we did also be using a plano-convex lens with an EFL of 12.7mm and a diameter of 6.25mm.

The laser autofocusing system, optically, will only have one component. This time of flight (ToF) distance sensor, the VL6180X, is compatible with Arduino Uno, the main motion controller of our system, so it will be easily implemented among the other motor configurations related to movement.

Our reflection spectroscopy system will consist of a bright white LED, a VISNIR fiber optic cable, input and output coupling lenses.

Item Description	**Quantity:**	**Total Cost:**
LaserTree 20W/4W 450nm Laser Diode	1	$60
Plano-Convex Lens Diam. 12.5mm, EFL 30mm (and mount)	1	$80
Diffraction Grating 600 lines/mm	1	$30
CMOS USB Webcam (2592X1944)	1	$20
QP400-VIS-NIR Optical Fiber	1	$300
White LED	1	$3
3D printer filament for spectrometer body	1	$10

Table 06: Part Selection for Photonics

3.9.3 Mechanical Part Selection

Rails and Linear Motion Components:

Item Description	**Quantity:**	**Total Cost:**
Aluminum extrusion rails	5	$10
Linear motion guides	N/A	$5
Linear bearings	N/A	$10
Shaft supports	N/A	$20

Table 07: Part Selection for Rails and Linear Motion

Mechanical Components:

Item Description	**Quantity:**	**Total Cost:**
Lead screws or ball screws	N/A	N/A
Threaded rods	N/A	$4
Flexible couplings	N/A	$9
Pulleys and belts	N/A	$10
Polycarbonate (For mounts and brackets)	1kg	$20

Table 08: Part Selection for Mechanical Components

Bed and Enclosure Materials:

Item Description	**Quantity:**	**Total Cost:**
Aluminum bed plate	1	N/A
Acrylic enclosure panels	5	N/A

Table 09: Part Selection for Belt and Enclosure Materials

Fasteners and Hardware:

Item Description	**Quantity:**	**Total Cost:**
Assorted screws, nuts, and bolts (M3, M4, M5,	N/A	N/A

etc.)		
T-nuts and brackets for the aluminum extrusion	N/A	N/A
Cable management accessories	N/A	$10

Table 10: Part Selection for Fasteners and Hardware

Item Description	**Quantity:**	**Total Cost:**
Cooling fans and ventilation ducts	2	N/A
Heat sinks and thermal insulation materials	N/A	N/A

Table 11: Part Selection for Cooling System

3.10 Software System

In this section, we shall discuss topics that are software based. Software is a huge part of technology and always advancing. It is important to investigate and learn about software for projects. Some of the ideas and topics discussed in this section will be software comparisons, material identification through spectroscopy, data transfer, user interface and controls, error handling, G-code implementation, backgrounds, and IDEs. we did describe these softwares and the implementations of them as well as a quick background to have previous knowledge.

3.10.1 Software Comparisons:

Software and compilers are used to write and compile code or make projects run. Plenty of software use libraries which are important to store data that will be used later. Looking at the different software to use for the laser engraver and material detection is important to know what will be best to connect everything together and communicate. Our embedded system will need software that can run code and send the data back and forth to the hardware and software to change configurations. An IDE (integrated development environment) will be used to write code that controls the hardware and data. Arduino IDE or Code Composer Studios are good options for IDEs. Arduino IDE is used for Arduino MCUs and CCS can be used for MCUs such as the MSP430. This software can be used to control data and our spectroscopy. Our choice of MCU will be the ATmega328P.

The board will be Arduino Uno and therefore that means we did be using Arduino IDE and software. The ATmega328P has more options that are better for our project due to how compatible it is with CNC machines and G-Code usage.

For data management and sorting information we did need a database to have our previous data and new data that we did always store and edit. Some laser engravers have a built-in database or have the databases around with the right values to use for each material and type of laser. Databases we can use are the MySQL database to store our information about the laser such as, material name, property, power, speed, and distance. If we do not want to use MySQL, we can use MongoDB which is a non-MySQL database software that is used in stack development and MERN (MongoDB, Express.js, React.js, Node.js) stacks.

we did have a UI (User Interface) on a screen that displays the data to the user and to confirm or deny certain information such as if the material is correct, start the engraving process, determine how long it will take to finish the engraving. We can create a GUI (Graphical User Interface that shows the user the information with software such as Tkinter (Python) or JavaFX (Java). For our communication between the hardware and software we must implement communication protocols like UART, SPI, or I2C which can do real-time control and data transfer from the MCU to the system. To create the bedding, surface, and other structures, we need to use software to create designs such as AutoCAD or SolidWorks. We did need to make sure to have error checking and cases of if something is happening that is not what is intended and make sure to end the procedure.

3.10.2 Material Identification Through Spectroscopy:

Our laser engraving project will have a unique feature which is identifying what material is being engraved. The material identification will be done through the method of spectroscopy (More information in 3.9 Spectroscopy System). Using this method, we can send the data we collect from the spectroscopy system which is in a 1D array and send that information to our software and code. The software and code will scan through our database of materials to scan for which other 1D in our database matches the one scanned. If found, then our code will upload the given configurations for our laser to be able to engrave our material. If not found, we can add a function that allows the user to add the material and the information into the database.

Using the 1D array given to us by the spectroscopy method will be our unique identifier for each material in our database. Having that as our identifier would be very important to our system or there would be no way to figure out what material is in our database. Using a camera module like the HiLetgo 2pcs OV7670 640x480 0.3Mega 300KP VGA CMOS Camera Module I2C for Arduino ARM

FPGA, built into our PCB or connected will be used to scan the material and through the spectroscopy method, we can take the 1D array and send that data via communication I2C from the microcontroller to our computer. The way we must be able to collect the 1D array and send it through is taking a 2D array and finding the average of each area until the array is complete. We can use an average calculation algorithm and then send the data over to our software and database.

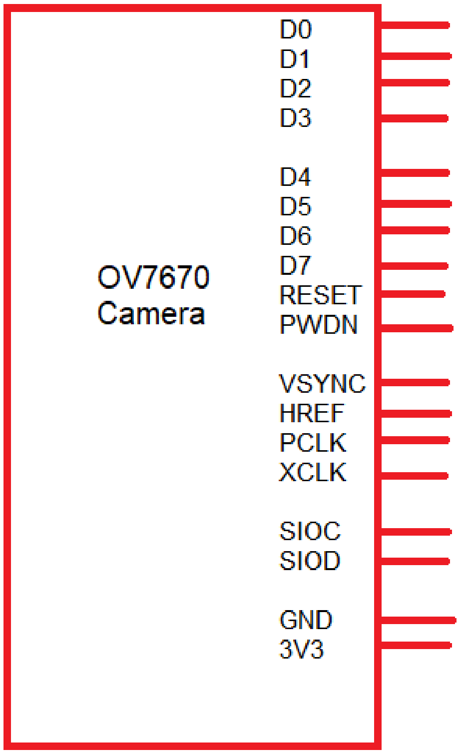


Figure 32: Schematic of HiLetgo OV7670 640x480 CMOS Camera Module (circuitdigest)

3.10.3 Data Transfer:

Computer engineering involves the use of hardware and software. Communication between both is important and there are different ways for the device and software to communicate. Some microcontrollers like the MSP430 use UART, SPI, and I2C to communicate between the hardware and software and that is useful to transfer input data to output it into the window. The communication we did use for our project will consist of I2C, UART, and PWM. I2C and UART will be used to connect the user inputs with the software and relay them back to the machine and PWM is used to change the settings for the laser. For example, if we press a button that would connect to the LED to turn on, the software will have code that says if that button's register is pressed then the register of the LED would turn on as well.

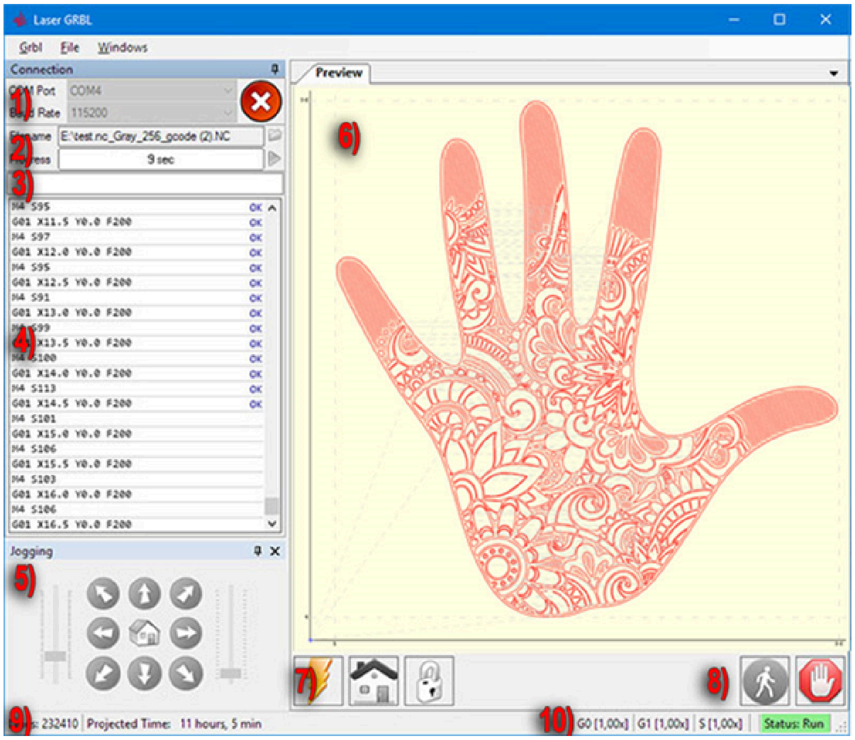
Data transfer is important since it is used in almost everything that is technologically related. To store the image we want to engrave on the material, we need to be able to transfer the image into a format of data that our software can recognize. We need to be able to store data and transfer it back and forth with the hardware and software. When a new material has different settings of power, positioning, and movement, we must be able store that information in a database of data and be able to retrieve that information to send it back out to the hardware to change to the settings we desire. Overwriting data and inputting new data into the database or library is a task as well that is needed.

Data transfer is used for the laser, platform, sensors, material, image, user input, user interface, and errors. Choosing the right way to transfer the data is important due to speed and not losing the data while sending it to each other. It must be reliable and safe. Our MCU (microcontroller unit) must be able to take input we give it and use that to connect with the software to give us our desired results. We can use UART (universal asynchronous receiver / transmitter) to send our data in bits to communicate between the device and software as well as I2C (Inter-Integrated Circuit). As stated in the MCU and I2C section, using the serial clock and serial data for transferring. For our spectrometer sensor, the sensor must detect the amount of light the material is giving off and send that data back. The data will be sent in the form of a 1D array (more information in section 3.10.2) and use that array to search the database for any material with a similar array.

3.10.4 User Interface and Controls:

A user interface (UI) is used to be the bridge between the user and the computer. In a simple way, it shows the user information that is relevant to the subject. It is an important piece to have in anything that involves user interaction. UIs are used everywhere and part of many things in our lives. Our computers, phones, video games, machines, appliances, and smart devices all have UIs. Some are more simplistic than others which means it is a friendly UI for the general audience. Some UIs are specific to people who use them at work or for other reasons.

Our UI will be a generic and simple UI consisting of things relevant to the objective. We plan to have UI show the material scanned and if the material is not in the database, then we can create it and add the information about it into the collection. If it is in the database, the UI will let us know if we would like to proceed with the engraving and we can confirm or deny. If we confirm then the UI will let us know it is starting the process and tell us how long it will take to finish the process. Our UI will be shown on a GUI with all of our other software applications that we use.



COM Port: COM4
Baud Rate: 115200
Filename: E:\test.nc_Gray_256_gcode (2).NC
Progress: 9 sec

```
M4 S95                 OK
G01 X11.5 Y0.0 F200    OK
M4 S97                 OK
G01 X12.0 Y0.0 F200    OK
M4 S95                 OK
G01 X12.5 Y0.0 F200    OK
M4 S91                 OK
G01 X13.0 Y0.0 F200    OK
   S99                 OK
    X13.5 Y0.0 F200    OK
    S100               OK
G01 X14.0 Y0.0 F200    OK
M4 S113                OK
G01 X14.5 Y0.0 F200    OK
M4 S101
G01 X15.0 Y0.0 F200
M4 S106
G01 X15.5 Y0.0 F200
M4 S103
G01 X16.0 Y0.0 F200
M4 S106
G01 X16.5 Y0.0 F200
```

s: 232410 | Projected Time: 11 hours, 5 min
G0 [1,00x] | G1 [1,00x] | S [1,00x] | Status: Run

Figure 33: GUI of LaserGRBL (lasergrbl.com)

3.10.5 Error Handling:

Everything created can cause errors or break in time. It is important to have important measures that can give feedback to the errors or be able to end a process and not continue. Base cases and fail safes are imperative when creating code or a design. For example, if there is something that cannot be recognized in code that should not be inputted, it is better to create a base case saying if an input other than what is needed is given, then send a reply to the user about the input error. When a laptop's battery is running low or needs to be replaced, the system will let the user know the issue to resolve it. Giving a "heads up" is one of the important things in engineering. We create fail safes and check for errors all the time. If the device is created and sent to the public and there wasn't enough error checking, it can cause major issues. Something wrong could happen such as injuring a person or even death. If that occurs, users can sue the company and the government can take action as well.

Our system will need error checking for the hardware and software. If the hardware does not work properly our software will detect this with an error checking method and let the user know on the LCD. If there is an error in the code or a bug, the software or IDE will let us know the error to be able to fix the issue. If for some reason a sudden issue occurs where something does not work correctly a shutdown function can be enabled just in case. The more safety measures, the better to not cause injuries or harm to users.

When the material is in the closed area sealed shut, we can create a measure to indicate if the area is enclosed and nothing is preventing the system from closing or starting. Before the spectroscopy system starts, we can have the software of the system check if the whole area is closed to not let any light cause issues with the scan and if there are any issues the system will notify the user to fix the issue. When the laser is engraving onto the material, there will be some particles when engraving and we must make sure that the particles are blown away and not getting in the way of the laser which can cause a fire. Making sure the system consistently blows air for the laser to have a clean engraving is crucial.

3.10.6 G-Code Implementation:

As mentioned in the introduction of G-Code (Section 3.3.1), G-Code can be used for our project. We can use G-Code to assist our system where to go when we start the procedure which is useful. Using the G-Code for CNC machines as stated, we can use it for our project as well. We can program the machine to tell the motors and machinery what position to move or our origin point when starting our design. We can configure the speed of our system and where to follow, which is beneficial. Using G-Code can be used to tell the laser where to start and stop and help us figure out the estimated time to finish the design as well.

When implementing G-Code for our laser engraver, we must use the IDE for the G-Code and create a project. When that is ready, we can import a design/image into the project or draw it there if we want to do that as well. Now we must edit the object and create a toolpath that will allow us to know what will be engraved. Once that is done, we can check and make sure the file is what we want it to be and generate the G-Code file. Then we export the file which sends it to our laser engraver to start its process. There are plenty of supported file formats such as: .svg, .png. jpeg, .bmp, .dxf, and more which is good for people who only have certain file formats. G-Code, simple and straightforward to use, makes sense to why most people use G-Code for their projects rather than from starting a whole design, uploading and implementing it to the system from scratch.

3.10.7 Database Background:

A database is a collection of data that stores information, and we can use it to update, add, delete, search, and send the data. Databases have been around for years and in the past when computers were not invented yet too. The concept of database systems is useful for managing data in a wide variety of ways. Some companies have workers or people who registered an account, and a database can store that information of every single person's data. In the 1960's computers were astounding and after that started the database systems in computers. The first database was created by Charles Bachman and was called the Integrated Data Store.

Later, IBM created a database called Information Management System as well. In the 1970's, a paper by E. F. Codd wrote "A Relational Model of Data for Large Shared Data Banks" which in turn showed differences in databases such as records, space, and cost for data. This led to new models and languages. Then, IBM released a relational database called System R and was the first to use Structured Query Language (SQL). SQL was a huge advancement in database systems as most databases use the SQL language. In the 1990's the World Wide Web was booming and needed client-server databases which led to the creation of MySQL in 1995. Large companies used MySQL and Object-oriented database systems became popular as well. In the year 1998, NoSQL databases were made and used more as the years went on.

3.10.8 Material Database

For the material database, we are going to need information for the laser regarding each material and the settings for each material. The database will store the name of the material, type of material, the power the laser should use for each material, spectral signature of the wavelengths, thermal conductivity, reflectivity, laser speed, distance, and depth. we did have a CCD camera that will convert to a 1D array representing the spectrum. The database will store a unique 1D array for each material to identify what material it is from the spectroscopy scan. For any new material, we did get that data initially and use it as a reference point. We may need to average the spectra (3 – 5 initial scans to produce the average). These spectra will be stored in a database or locally as separate entries. For every new scan, we did run some comparison algorithm. The spectra between our materials will be distinct enough that we cannot misclassify them.

For the database, we can use a database management system (DBMS) such as MySQL or a non-MySQL database like MongoDB. With a DBMS we can add and manage our system however we would like and change the settings for the engraving by searching for the material. Laser printers and engravers have applications that have built in settings in their database for each material, its properties, and its laser configurations. We can create a database without using a DBMS by creating an array for each material and its configurations with lines of code on an IDE. It is suitable for smaller projects and not for large ones and more difficult applications. The best option is to go with a DBMS and MongoDB due to experience and how user-friendly MongoDB is compared to MySQL. MongoDB can create databases and libraries called collections to store each unique record. Each collection has a JSON file that is used with all the data. The data can store information such as name, age, status, groups. With that in mind we can have a collection called materials and each one has its power, speed, and every configuration for the laser. It is easier to search through the MongoDB database than to create the array in an IDE and parse through each 1D array which takes up more time. Sometimes softwares has built in databases for materials. These can be handy as they are already pre-added into the software for later use in projects. LaserGRBL as described in section 3.5.2, is a software that has a built in database for materials and the specifications of those materials for cutting or engraving. This is very useful and they are just testing data which means it can be modified for users to change the data of each material specification and data if needed.

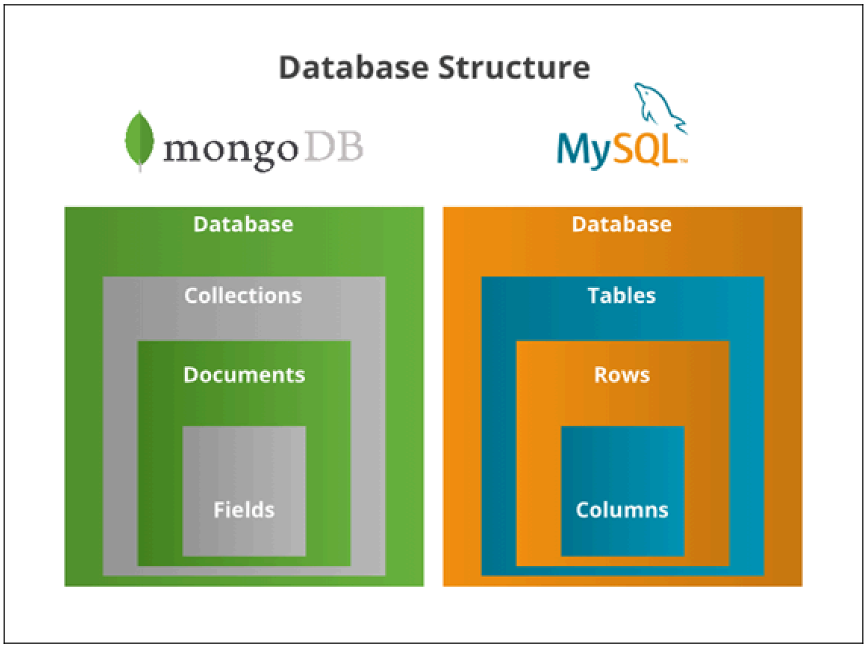


Figure 34: Database structure for MongoDB and MySQL (phoenixnap.com)

3.10.9 Database Comparisons

Going more in depth with the type of database systems or structures we can use for our project and what seems the best fit is important to compare. If we choose not to use a database system, we can go with the old straightforward method. In our IDE and code, we can create a database in-memory using an array. This can be achieved in a few languages such as Python. This is a simple and easy way to create a database that has everything in front of the user. This choice is also faster to retrieve the data stored in the array if an actual database system is using a remote database server to retrieve the data from a network request.

Sometimes we need extra software and libraries for databases and for a database in the program or code we do not need to worry about that. There are issues with using an array-like database though. Since we are using a programming language and IDE there is no built-in security like database systems. Another issue is memory size. We cannot be able to store large amounts of data, or we did get full. Database systems store and keep data that is run and still there unlike an array-like database which loses its data when the program is done. In coding, arrays sometimes store only a single data type like int, double, string, and more. Databases that are not array-like can use multiple.

We can create a database in our MySQL that can perform well due to high performance and scalability like Arduino IDE. People use MySQL in their LAMP Stack projects. Since users will have to store plenty of information about people, MySQL is used often due to being able to store huge amounts of data to be optimized for applications. For developers, companies, and everyone, MySQL is an open-source database for all which is great for people who want to use a reliable database system that can be freely modified too. MySQL is usable for many Operating Systems such as Windows, Mac, and Linux which is good for people who have different OS’. The community that uses MySQL has a wide range of users with plenty of answers, forums, tutorials, and documentation for people who would need assistance using the software. An important feature of MySQL is how it handles security. The security features on MySQL are convenient as it has authentication, control accessing, and data encryption. This is great for people who use MySQL for storing huge amounts of data of users and private information about them. MySQL is a great database system to use for newcomers and other users due to its reliability and usefulness.

Another database system we can use is called MongoDB. MongoDB is used in a MERN stack for projects and is another reliable database system. MongoDB is open source for developers which allows them to modify the system if it complies with the terms. If you need more servers due to work and high-traffic applications, then MongoDB is useful for those reasons and MongoDB shares data across those multiple servers too. MongoDB uses JSON file format to store data as documents which makes it simple for developers by creating a JSON file of data and just importing it to the database. MongoDB has software that can assist developers by making it easier to work with the database. There is MongoDB Compass and MongoDB Atlas which are other compatible software that can be used for user friendly purposes and a simpler time working on the database for importing, creating, uploading, and deleting. Same as MySQL, MongoDB has a community that can provide support for users in need and there are third party tools that can assist users as well.

As mentioned previously, the choice of our database system we are going with is MongoDB. MongoDB has many uses and the ability to use other software for simpler database development helps the user organize the data better. We can have it in our local server instead of an online one for simpler database development and just on a local computer to host everything.

Features:	**MySQL:**	**MongoDB:**
Rich Data Model	No	Yes
Dynamic Schema	No	Yes
Typed Data	Yes	Yes
Data Locality	No	Yes
Field Updates	Yes	Yes
Easy for Programmers	No	Yes
Complex Transactions	Yes	No
Auditing	Yes	Yes
Auto-Sharding	No	Yes

Table 12: Table showing differences of each database (geeksforgeeks.org)

3.10.10 IDE History

Integrated Development Environment's (IDE) is one of the bases for software development. IDEs are used to write code and create programs like the ones we use in our daily life. Our applications were created by IDEs and without them we cannot let our creative software ideas come to life. Before IDEs, programmers used text editors to write their programs just like we can do sometimes with HTML. They would have to save the document and check for revisions and then do it in the document again if needed due to errors.

In the year 1983, was when the first compiler and editor was created. It was called TurboPascal and had the Pascal compiler by Borland Ltd. TurboPascal paved the way to creating IDEs for life and Microsoft is one of the first. In 1991, Microsoft launched the first IDE which was called Visual Basic (VB). At the time Basic (The programming language) was popular and one of the most used languages which was good for the IDE. As time went on, more IDEs have been made available and used for different purposes. Some for companies and their tech, others for teaching and learning. Microsoft made more IDEs (Visual Studio Code, Visual Studios), Oracle has made some (Eclipse (Java)), and other ones as well.

3.10.11 IDE Comparisons

Choosing the right MCU and IDE is important to creating a project that uses hardware and software. For our project, we did be looking at the Arduino IDE and MSP IDE (Code Composer Studio (CCS)). First the choice is what MCU will be used, and which is in relation to the IDE. Arduino IDE is simple and has a user-friendly system. There are useful features in the Arduino IDE which include syntax error checking, auto-filling, code formatting, and debugger. Arduino can be used on multiple OS devices such as Windows, Mac, Linux, and even an online Arduino IDE and compiler.

Arduino IDE is simple and compatible to use which is why many users use the Arduino MCUs and IDE. There are many Arduino boards to choose from and they can be programmed from the IDE. Many users use Arduino for small projects, or their own solo projects like with Raspberry Pi. A small issue is that the Arduino MCU and IDEs are not really used in commercial companies like MISRA C for embedded development. Some neat reasons people use Arduino IDE is due to how flexible the IDE is for users.

Arduino IDE can be used to write programs in C, C++, and assembly. This gives the users some free will on what language to write their code in for their projects if they know one better than another. Arduino IDE allows users to create their own libraries, functions, and existing libraries which can be useful for writing code and quicker. Interesting details like in embedded systems, the Arduino IDE can let the users change the registers, timers, and interrupts of the devices in turn can be useful for certain projects. Other issues with the Arduino IDE are that it cannot multitask and has tools to have reliability, security, quality insurance for code. The software and IDE are open source which is good for people who want to dig deep into the software and tinker.

Our other choice of IDE is Code Composer Studio which is used for MSP MCUs and Texas Instrument devices. Code Composer Studio uses the C and C++ language and Texas Instrument processors. The way it communicates is by using Real-Time Data Exchange. The neat tools that Code Composer Studio has is a C and C++ compiler that is optimized, project build environment, debugger, editor for source code, and more. It comes with many uses for the user to program processors and for specific projects a person might want to create. The interesting thing that Code Composer Studios has is that it is based on the Eclipse IDE software framework which allows an expansion of embedded programming.

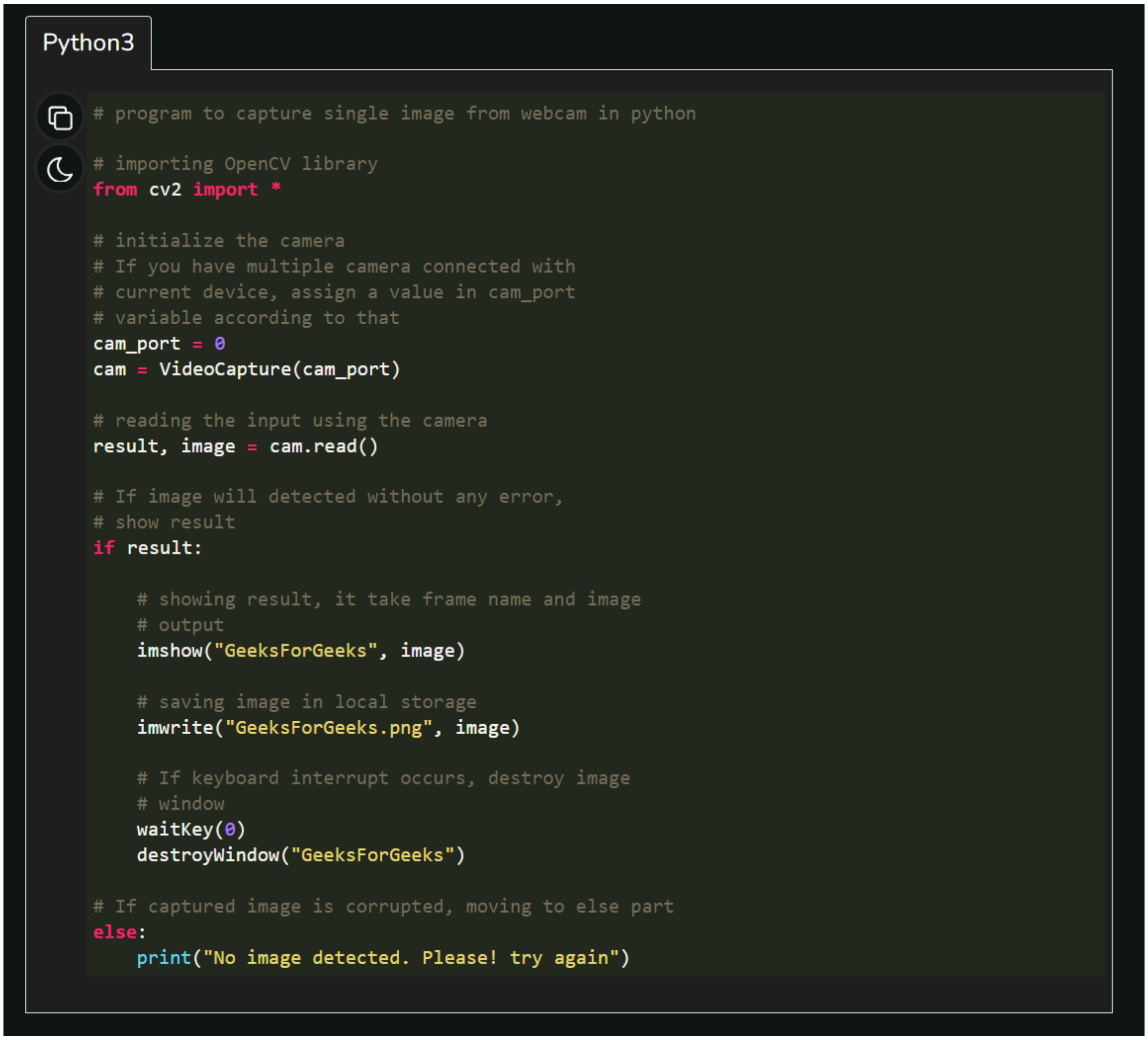
3.10.12 OpenCV Background

OpenCV stands for Open Source Computer Vision Library. It’s an open-source library that includes numerous computer vision algorithms. The project initially started at Intel, developed by Gary Bradsky in 1999. The first release of OpenCV came out the following year. Bradsky was then joined by Vadim Pisarevsky to manage Intel’s Russian software OpenCV team. The development of OpenCV then came under the support of Willow Garage, a robotics research lab. One of the major projects that used OpenCV was the Stanley vehicle in 2005. Stanley was an autonomous driving vehicle that won the 2005 Darpa Grand Challenge, a driverless car competition.

OpenCV supports several programming languages like C++, Java and Python. It even supports interfaces for optimized GPU operations based on CUDA and OpenCL. There are several versions of the OpenCV API. The original OpenCV 1.x API is based on C and is now deprecated, no longer tested by the developers. OpenCV 2.x API is based on C++ and is being actively supported. OpenCV-Python, a fork of the OpenCV 2 API for the Python language now also exists. This library will be the most relevant for our application since Python supports numerous additional packages that can work in conjunction with OpenCV.

OpenCV-Python actually functions as a wrapper for the C++ implementation. This is one of the primary advantages of coding in Python. It allows for code to be extended with C or C++, which are used to write the underlying computationally intensive algorithms. The programmer retains the efficient speed of the C++ code as well as the ease of programming in Python. Another advantage of OpenCV-Python is how it works with Numpy. The OpenCV array data structures can be converted into numpy arrays. This means that images can be read as highly-optimized n-dimensional array structures including RGB data.

OpenCV-Python supports the ability to interface with webcam devices directly. This will be very useful for our project, allowing us to pull image data in real time on the PC. The objective is to read the image data of the diffracted spectrum in our spectroscopy system. Since the image data can be converted into an array structure, we can write code to extract the slice of the image we want, pull the necessary pixel data and perform some data analysis. This analysis will be used to classify the material which the reflected light is coming from. It will be useful to look at the existing computer vision algorithms available in the OpenCV library. We may find that some algorithms can be used for our specific application.



```
# program to capture single image from webcam in python

# importing OpenCV library
from cv2 import *

# initialize the camera
# If you have multiple camera connected with
# current device, assign a value in cam_port
# variable according to that
cam_port = 0
cam = VideoCapture(cam_port)

# reading the input using the camera
result, image = cam.read()

# If image will detected without any error,
# show result
if result:

    # showing result, it take frame name and image
    # output
    imshow("GeeksForGeeks", image)

    # saving image in local storage
    imwrite("GeeksForGeeks.png", image)

    # If keyboard interrupt occurs, destroy image
    # window
    waitKey(0)
    destroyWindow("GeeksForGeeks")

# If captured image is corrupted, moving to else part
else:
    print("No image detected. Please! try again")
```

Figure 35 : Simple Python OpenCV example to get Webcam image (geeksforgeeks.org)

3.10.13 Use Case Diagram

Within this section, we go in depth into the requirements included into our project with the relationship between the user and its various hardware components. The diagram above is known as the use case diagram, a great visual representation of the system from the perspective of an end-user. It is an important tool to use in relation to software engineering, required sometimes to create an analysis on how various parts will interact with each other. We included thorough and concise graphical elements, including things such as actors, use cases, the various relationships in between all aspects of the diagram. Using a use case diagram will provide a high level overview of the overall functionality the system will provide and its various ways a user will interact with the system. Use cases are used specifically as an overview to show to those who are not as well versed on the technicality of the product. It is used as a bridge connecting those who worked as developers with others in the company who serve a different purpose, allowing any individual the possibility of understanding the concepts.

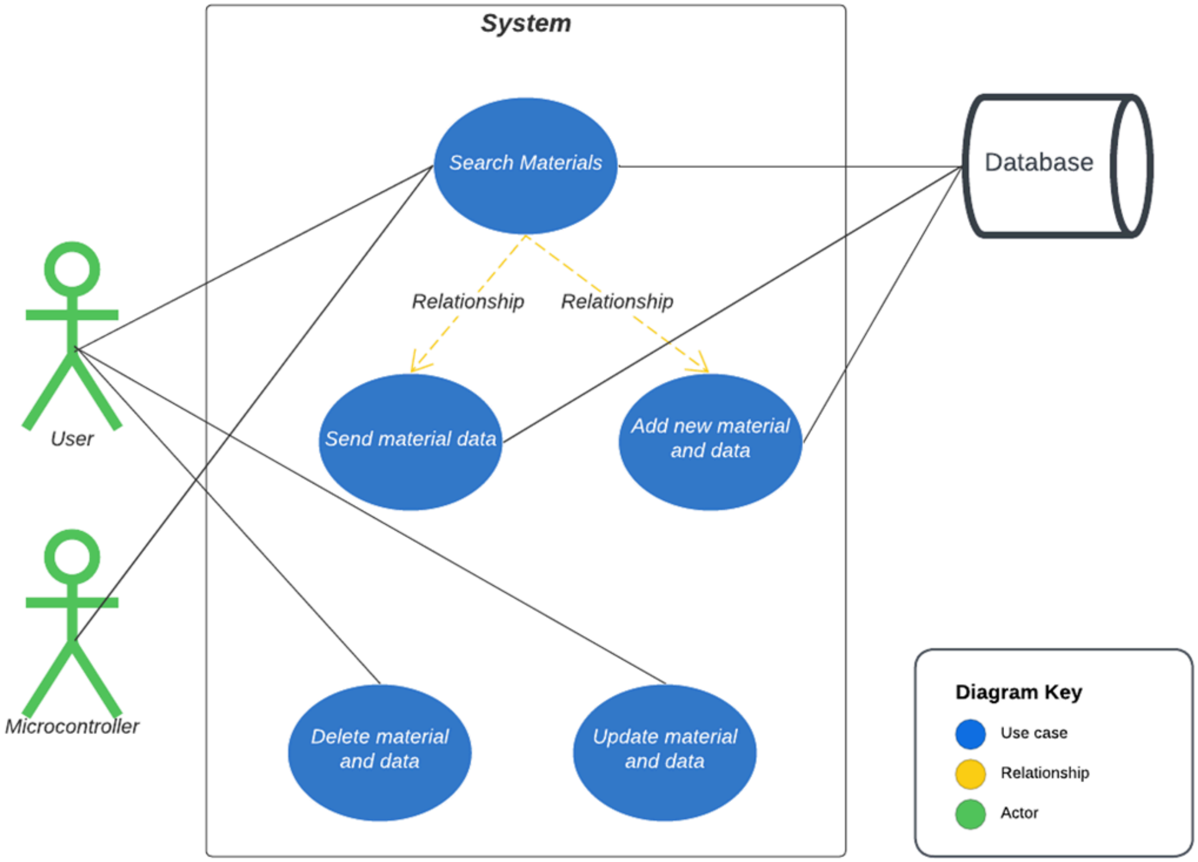


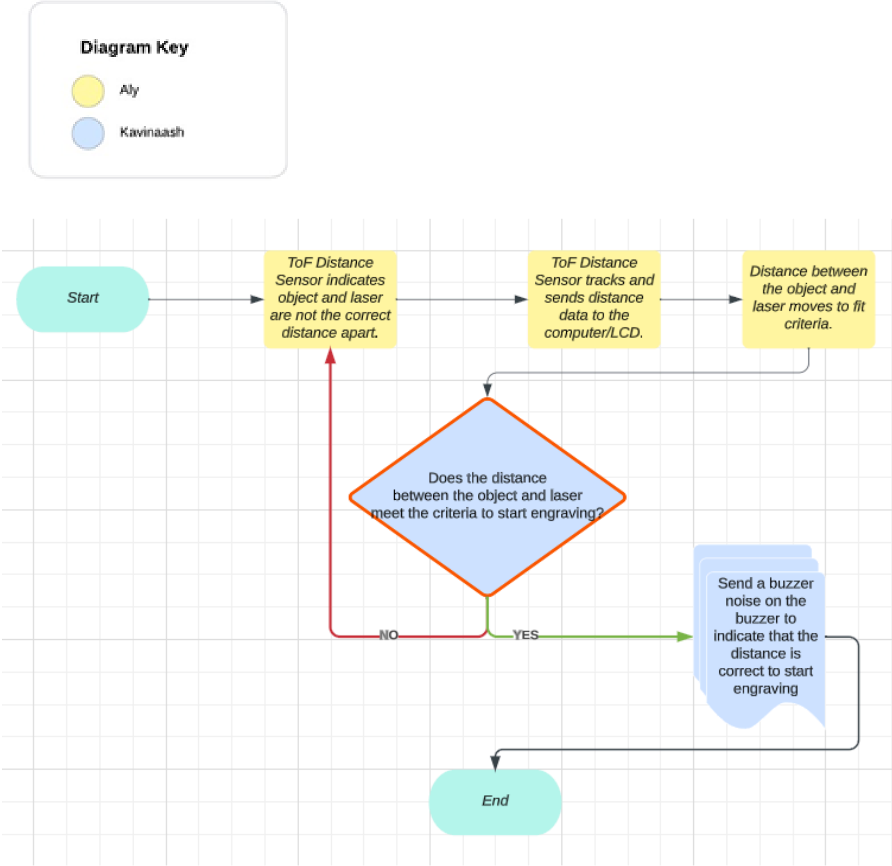
Figure 36: Use Case Diagram of Database

In our specific diagram, we included two main components that are to communicate with each other externally, those being the user and the microcontroller. While they do not directly intertwine, they are essential in running as they coincide in many portions of the system. Our user will have a direct connection to “Search Materials” which in turn communicates to the microcontroller. The user also will communicate with two different use cases, those being “Delete Material and Data” as well as “Update Material and Data”. Besides these use cases, they each also have other connections such as “Search Material Data” and “Add new Material and Data” having a direct relationship with “Search Material”. The following two use cases also have a direct connection with the database, that being the main library holding all of our information on the specific materials.

3.10.14 Software Flowchart

Software flowcharts are used for many businesses and companies for keeping track of their system. This helps shareholders, managers, software designers, and everyone in the project to understand what is happening and give a description of the system. When the designers meet with the business group for a discussion about what the project and system is about, the software flowchart is a good way to describe the design to them. This informs them about the project and how it works.

The designers can communicate with others involved in the project talking about algorithms, programs, and systems. There are start and end points, steps, decisions, connectors, and inputs and outputs. Before the engraving process, there is a separate system that works with a ToF distance sensor to make sure our laser and object to engrave is the right distance. Once that is correct, we can start the engraving process.



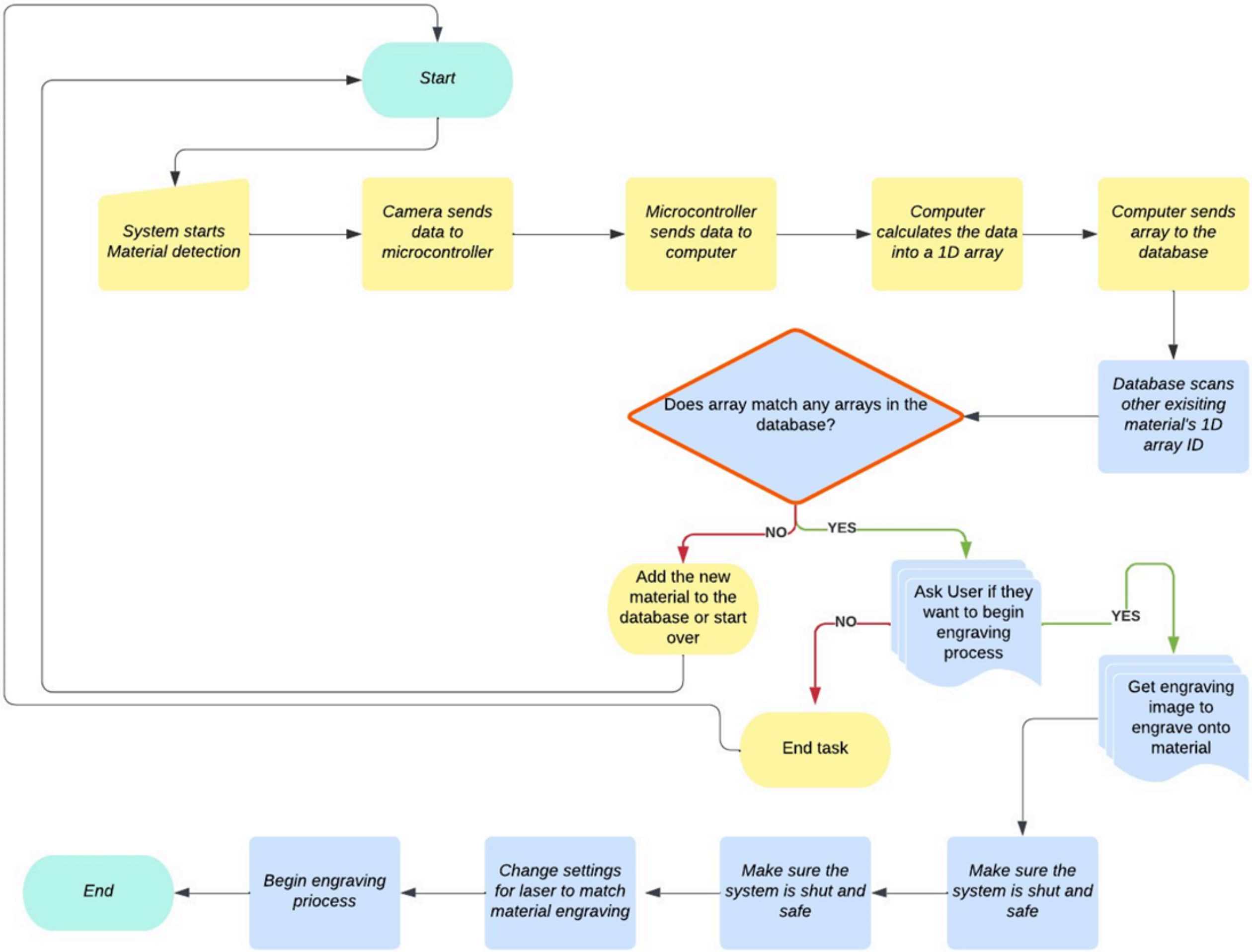


Figure 37: Software Flowchart for Software System of Laser engraver.

4 Related Standards & Real-World Design Constraints

Regardless of whether or not this product will reach the point of becoming a consumer product as a 6-person university level project, we should still treat it to the same standards of any other product. we did strive to make our designs reach the standards of safety that all companies that created products for consumers. When researching for this project, we had come to the conclusion that finding ICP standards online were very difficult to get our hands on, so the standards included are portions of what can be found online, as a way to get the point across on what kind of standards must be included when creating a commercial project.

4.1 Related Standards

In this section we did prioritize giving a broad look into the various standards that are used in the development of any product onto the market, using IPC. This will go into detail on some of the background history on its inception, as well as a general idea on the different distinctions being put into various types of electronics and hardware.

4.1.1 IPC Standards Background

The name IPC stands for “Institute for Interconnecting and Packaging Electronic Circuits”. It has been a long standing organization used as a global trade association with its main attention being put in the creation of standards in relation to the electronics and manufacturing of consumer goods in the engineering industry. These standards are used globally, which if done correctly, will allow the communication between designer and manufacturer to be greatly reduced. IPC saw its origins beginning in 1957 being founded, with its focus being more so on the electronic interconnections. By the time we hit the 960s, they began developing further by pushing standards to the next level by also including the use of PCB design in its standards, which is what we did focus on in our next section. Beyond this, they began to include other aspects of circuitry including the standards for soldering and assembly.

4.1.2 General IPC Standards

IPC sorts its electronic circuit standards into three main classes for its products. Class one is the first class, which is usually referred to as the most general form of electronics with the simplest, and lowest quality requirements in their products.

These are generally perceived to have small life spans, due in part to the quality being cheap. Examples of these would be cheap toys, flashlights, or even smart phones. As their quality diminishes and is held to the lowest standard, they get mass produced at incredibly high volumes. The typical consumer is definitely privy to this fact, as most people replace these common items every year or two. The next subsection is Class Two, which is basically a continued evolution from class one. This means that the devices in this section have better performance and an extended life cycle. Generally speaking, the consumer will want a product that will last several years, with service going uninterrupted for an extended amount of time. Some products that would be classified as a class two include televisions, air conditioners, laptops, and refrigerators. If problems begin to occur within the first two years it is a cause to raise suspicion but never critical. Because these products have a higher standard in relation to its sustainability, they typically begin to include downtime, while not necessary, as a way to maintain a longer lifespan.

The third and final section is class three, the highest level of guidelines in relation to standards. These are incredibly strict and often subject to going back to the drawing board, due to its delicate nature in the field. As the sections progressed, we began with class one with cheap and replaceable items, class two using electronics that last longer, with finally class three having electronics that need to be fully functional at any vital moment. Items such as a pacemaker, or military products are under this umbrella, which are electronic components that are highly reliable and must have uninterrupted services. These products must go through rigorous testing, inspection, and experimentation before being fully on sale for consumers on the market. As the classes progress and their functionalities become precise and reliable, there is a relation in price as well, as cost of manufacturing rises.

	IPC Class 1	**IPC Class 2**	**IPC Class 3**
Category	Basic Electronics	Long Service Electronics	Reliable Electronics
Life Span	Short (1-2 Years)	Medium (5+ Years)	Long (10+ Years)
Quality	Cheap to Decent	Durable	Made to last as long as possible
Cost	Generally available to be purchased by all consumers	More of a once in a while purchase for several years	One time purchase to last you a lifetime

Examples	Toys, Phones	Microwaves, Heaters	Military-grade systems, hospital machinery, etc

Table 13: IPC Classifications

In relation to our own project of a laser engraver, after careful consideration, determined our project will fall under the Class two standard. Although the product will not be manufactured at a commercial level for everyday use, we did strive to reach this quality of standards. On the market, many printers that either print with ink or engraved are generally classified as two as well. We want this product to be able to withstand wear and tear of everyday use for at least a couple of years.

4.1.3 Laser Safety Standards

Creating and operating a laser engraver is inherently dangerous due to the implementation of a laser system into this device. Lasers are potentially very dangerous and must be used with the utmost caution and care to prevent accidents, which have a wide range of severity. Depending on the power of the laser system, they can range from being virtually harmless to being deadly because of the vast array of different laser powers and wavelengths. Laser safety also varies widely. Very low power lasers do not require any external components to block the beam because the natural reflex to look away from the beam is sufficient to prevent any substantial damage. While high power lasers need to be completely enclosed in a black box which the light cannot escape.

Lasers can be harmful in many different settings, but the chief hazards to worry about for our project are hazards for the eyes, skin, and flammable materials. While in use in APALES, the laser can harm the eyes from reflection off the material being engraved. It is very important to understand the difference between specular reflection and diffuse reflection. Specular reflection occurs when light is reflected off of a nearly flat and highly reflecting material, this can reflect a majority of the beam's power and must be taken into extreme consideration when working with certain engraving materials with high reflectance. Diffuse reflection is much less dangerous and occurs when the light beam is reflected and scattered in many different directions due to the surface of the material being rough and having low reflectance.

Different wavelengths of light can have different hazards. Ultraviolet rays can cause eye sunburn, photokeratitis, and photochemical cataract. Visible light can cause photochemical burns and retinal burns. Infrared can cause cataracts, retinal burns, aqueous flare, and corneal burns. Since we did be using a 450nm laser diode system, the most important hazards are in the near-ultraviolet and visible regions of the electromagnetic spectrum. we did act to prevent eye sunburn, photochemical burns, and retinal burns.

One of the most important aspects when working with a laser system is the maximum permissible exposure limit (MPE-limit), which dictates how much laser radiation the eye can be exposed to without requiring eye protection. The MPE-limit depends on the laser wavelength, power, and pulse duration.

Lasers are split into different classes, ranging from Class 1 to Class 4, as outlined in Table 14. Class 1 lasers are the least hazardous and totally safe when operating without any protective eyewear. Other higher class lasers can also be demoted to Class 1 provided they have a sufficient enclosure to prevent light escaping; a great example of this would be a laser enclosed in a laser printer.

Class	Maximum power	Hazards
1	<0.4mW	● Harmful to eye with prolonged exposure
1M	>0.4mW	● Higher power than Class 1 lasers, but due to larger beam diameter and divergence, they fall below the MPE-limit
1C	>0.4mW	● Primarily used in cosmetics ● Not harmful due to safety mechanisms in place
2	0.4-1mW (only visible light)	● Eye hazard, natural blinking reflex is sufficient to prevent damage
2M	0.4-5mW (only visible light)	● Higher power than CLass 2 lasers, but due to larger beam diameter and divergence, they fall below the MPE-limit are safe when paired with the natural blinking reflex
3R	<5mW	● Direct viewing and specular reflection may cause damage
3B	<500mW	● Hazardous lasers from direct and specular reflection ● Requires key-switch and safety

		interlocks
4	>500mW	- Very dangerous to eyes, skin, and may cause material combustion - Requires key-switch and safety interlocks - Direct view, specular, and diffuse reflections are dangerous

Table 14: Laser classifications

For the purposes of this project, which are purely educational, we reference the American National Standards Institute (ANSI) Z136.5 standard of Safe Use of Lasers in Educational Institutions. The laser used in APALES will be a Class 4 laser with a wavelength of 450nm at a maximum output power of 5W. This is a potentially very dangerous laser and must be handled with extreme caution to prevent any injuries to the eyes and skin, and to prevent any combustion accidents.

4.2 PCB Standards

Although our design will not be implemented into the market, we wanted to still give enough time and investigation to what the classifications would be for our product if it were to be released to the market. To do so, we did go a little in depth into the general history of the creation of PCBs, as well as the various IPC standards used for PCBs, to ultimately decide on which distinction we did approach in creating our own custom board in the engraver.

4.2.1 General PCB History

PCB standards are a subsection of guidelines that manage and govern the quality assurance for PCB (Printed Circuit Board). PCBs are incredibly fundamental in the usage of modern electronic technology, as these standards were created to ensure and maintain the quality of products. PCB begins to have its history starting with its development in the mid-20th century, where PCB were rudimentary, really only including a single side. The PCB standards and their development go hand in hand, as standards started being produced at the same time. For IPC standards, there are a variety of PCB standards laid out, such as IPC-A-600, which is the standard used for very simple and basic PCBs.

4.2.2 IPC-2221

In general terms, we did discuss the IPC-221 specifically, as this is the standard board requirements that includes most of the basics of the board including the design, how things are laid out, as well as all of its electrical components. IPC-221 is the largest of a broad family tree of standards known as the IPC-2220. This generic design encompasses every basic feature required, including how the PCB is laid out, electrical components, and the design.

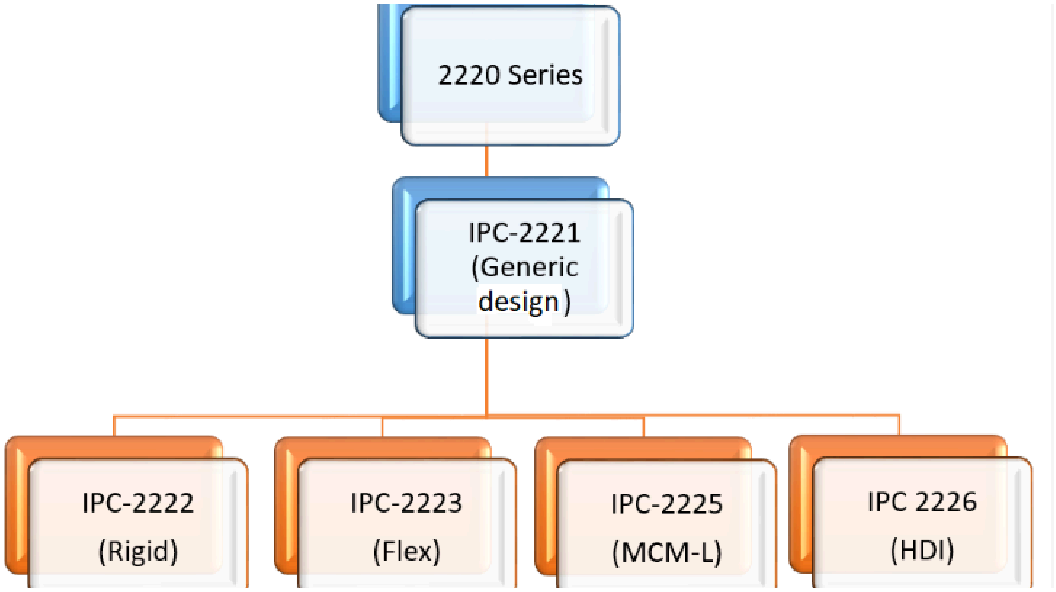


Figure 38: IPC 2220 Family Tree

Most of the time, you will need to use the general design of 2221 in relation with another more specific to your project. Flex is generally used to have more selective plating, with minimum bending radius. When speaking directly towards our project, the PCB standard we did most likely include in our own would be the rigid, as it aligns the most with the specific requirements that we need. Rigid includes things such as the specifics on holes, the thickness of the board itself, and the parameters of all the spacing and mechanics included on the board. Typically speaking, many of the PCB boards get higher in cost the further up the 222 family we go, and rigid includes many of the features needed, provided enough efficiency while sticking within our budget,

4.3 Economic and Time Constraints

When it comes to a 4 year undergraduate project, our budget and its related constraints are definitely one of the priorities that need to be accounted for, as they can greatly shift the scope of the project, what materials can be used, the time spent, and how plausible it is in general. One of the largest hurdles we as a group have to overcome is the fact that we are in the process of developing this project without the third party assistance of a sponsor. This is due to the fact that we voluntarily chose this project, so everything will be done out of pocket.we did continue practicing low cost effective methods, such as trying to use 3D printing equipment that is readily available. The selection will ensure that it will balance both material and labor costs, while simultaneously keeping in consideration certain safety features done further down the line. The choice of laser module was greatly dependent on not just our needs for this project but the monetary value in which it holds. This was greatly taken into consideration, as we wanted to all be able to accommodate the needs of each individual member as to not go over the limit that one specific member would be able to afford.

Given the fact that our project reaches through two semesters, it is important to keep the necessary tabs on the dates moving forward. While this timeline allows for extensive research time and developing comprehensive designs that can be used, troubleshoot any issues that can potentially arise, and refine our project to its highest potential, it can also introduce a new set of hurdles in the coming semester. While the end goal is still out of reach, it is still something essential to keep note of. Effective time management can make or break this project, as having a top or bottom heavy project (time-wise) could lead to an unsuccessful project, so doing so will allow us to avoid any last minute moments of lapsed judgment. Another thing to keep in mind is being able to finalize the materials as ordering them as soon as possible will help us avoid further delays in the future, as we did need time to further tinker and refine the design and having everything on hand will help expedite this process. Overall while this time limit will offer us an incredibly valuable opportunity to provide a well crafted project, it will still demand in relation to time management and our ability to adapt on the fly with any potential problems that can be created with the time constraint.

4.4 Equipment Constraints

The development of a laser engraving system will require a variety of different hardware and software applications that can bring in a new potential to the market. While this is an important aspect to consider, we still need to take into consideration the specific equipment constraints that can either withhold or push us forward towards the goal. One certain constraint to keep in mind about our equipment would be the dimensions of the workspace that we are using. If we were to create a system that was too large, it would be deemed inefficient, as it would be hard to transport, maintain, and operate. For our specific project, we did be developing a project that can be easily transportable, since we are aiming to have the dimensions be able to fit on top of a desk. Understanding the constraints will allow us to deliver a high quality engraver that can operate as efficiently as possible, in any wide range of applications and environments.

4.5 Safety Constraints

Regardless of the possibilities of the project being reached, our number one factor to keep in mind during the entire progress of this product is safety of the members, and any user as well. In broad terms, whenever a laser is being handled, there has to be constraints in the power limit as a way to avoid any skin or eye damage to the user. Doing so will ensure that we minimize the potential risk to users or observers. Rather than using laser safety goggles as our primary form of protection during operation, we did use a different form of protection. For this project we instead enclose the laser, the base, and everything encompassed under a hood. This will help us streamline the process, rather than each user having to exchange goggles, we can maximize the number of people to observe by having the laser itself be enclosed. The last major safety constraint to keep account of is the use of an emergency stop. If all else fails, and a potential accident happens, we did include an emergency stop button that is easily accessible to immediately cease the activity being used on the laser, and cut off power. Another emergency stop that we can implement is done on the software side. Inside the software using GRBL there is a way to stop sending the code from whichever G-Code sender we use, whether it is Universal G-Code Sender or LaserGRBL. This is another factor to keep in mind in relation to the safety constraints, having multiple forms of stopping the machine will allow for less risk and higher chances of no accidents.

4.6 Manufacturability Constraints

To build this product we must consider the feasibility of the design currently being made. Once we’re able to prototype our design, we’ll get a better idea of what manufacturing looks like at a larger scale. We’ll know what the cost and skill requirement looks like to manufacture our product. As part of the manufacturing process we must consider factors such as component availability, supply chains, production capacity and quality control.

If our product were to be released to the market, we would have to ensure that there are enough units available to meet the demand of users. This is where supply chain and production capacity must be considered. Issues with the supply chain such as disruptions, shipping delays and shortages can lead to very limited production. Production capacity puts a limit on how many units are shippable to the market.

The complexity of preparing the parts and assembling our laser engraver play a large role in its manufacturability. Factors such as lens alignment, positioning of the CMOS camera and wiring of the stepper motors must be considered. How much of the manufacturing process can be automated with robots vs how much needs a human to work on it. A mixed assembly line must be considered.

Quality control is needed to maintain a consistent product quality across each unit. In manufacturing the product, we must minimize defects in the components. There is a tradeoff in the time and resources spent on quality control. Too much quality control may be unaffordable and it can significantly limit production capacity

4.7 Ethical and Sustainability Constraints

There are various ethical considerations associated with the development of this project. Sourcing of the parts is a primary one. As a group, we must ensure that the parts are sustainably sourced while also making sure they're affordable. The energy requirements are also a consideration. The end product must use power efficiently from the mains electricity source. Ideally, we should also aim to minimize the power lost through DC-DC conversions (ie. 12 V to 3.3 V for microcontroller) if possible.

The procurement of raw materials: aluminum, plastics must also be sustainable. While cutting and shaping the parts we must try to avoid wasting material. Creating a robust structure for our CNC machine increases the lifespan of the product. This ensures that it'll be used for years to come, limiting the need for replacement.

Since the laser being used is highly precise and since the stepper motors have a high resolution, the engraving will be sharp. This actually limits waste of the materials being engraved. Having a diode laser with a more limited precision or lower resolution stepper motors would lead to potentially worse engravings. Poor quality engravings can mean that the material/board is wasted.

Another ethical consideration is the use case for engraving. The user could engrave offensive or malicious content onto the material. As the designers, we would like to avoid this. If our product were to be released to market, we would need to add user guidelines to dissuade this behavior. We would also need to market the product accordingly; promote the product as being for artwork engraving.

5 Use of Large Language Models

Large language models (LLMs) such as ChatGPT have taken the world by storm in the past year, impressing the population with their ability to create and answer questions previously impossible by search engines. LLMs are a type of artificial intelligence (AI) that has been trained on massive data sets to understand and predict text. LLMs read data from books, websites, social media, scientific journals, and more to understand the context behind words and sentences to be able to understand language and generate predictive responses. ChatGPT and other LLMs are incredibly useful tools that can be used for a wide variety of applications such as writing papers, generating code, and learning new material.

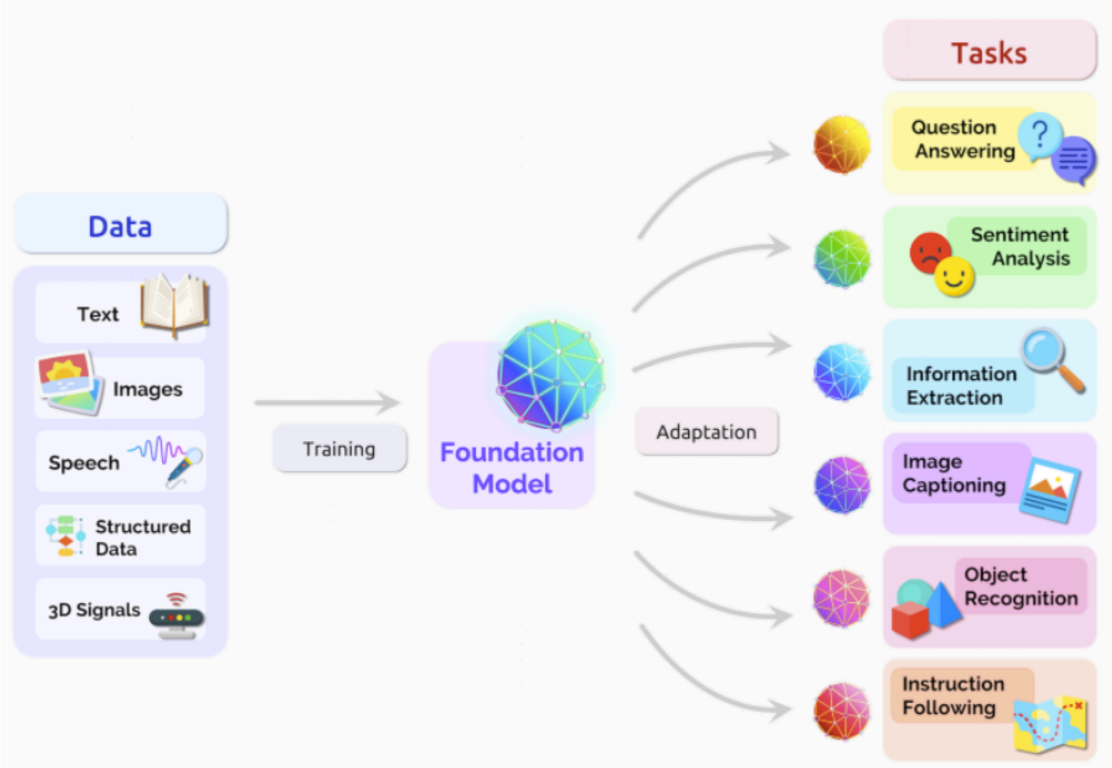


Figure 39: Function of the training and adaptation of large language models (Elastico.com)

LLMs differ from search engines like Google in that LLMs generate a response tailored to the prompt it is given. Search engines (as the name suggests) search the internet for the websites that are most relevant to the words put into the search box. Google, Bing, and other engines do not generate new content, they merely search through a nearly infinite pile of data to find the best fits and lay them out to the user. But while search engines may lack in generative ability, search engines are not necessarily inferior to LLMs. LLMs operate for completely different purposes than search engines and are fantastic tools to be used in conjunction with each other.

While LLMs may be useful for content generation, there are some notable downsides to the content LLMs output. As mentioned earlier, LLMs *predict* words and sentences based on their training from massive datasets. LLMs are good at understanding the context behind words and can understand meaning quite well, but they lack an understanding of *truth*. LLMs have a strong understanding of the association between words but cannot know whether what it is generating has any basis in reality. Users of LLMs should be cautious of trusting content generated from ChatGPT and other models if using them for applications requiring factual information.

Where LLMs shine is in their ability to *create*. While content from an LLM shouldn't be trusted as fact, some applications such as generating outlines or writing emails don't require fact-checking and can help save time and energy. In the context of senior design, there is a large amount of research and writing that must be done to form a quality paper. LLMs can be helpful but in the right context.

5.1 LLMs in Senior Design

As discussed earlier, LLMs shine in applications where creativity is involved and falter in applications where truth is a necessity. For senior design, writing with accuracy is essential as explaining research or the functionality of our project loses value when falsehoods make readers question the validity of the writing. Thus, using purely LLMs for research should be avoided and any content generated where accuracy is essential should be taken with a grain of salt. Where LLMs can be useful however is in generating ideas for writing such as in outlines or corrections to fix grammar, spelling, or word choices.

5.1.1 Research

The research portion of senior design lays the foundation for the rest of our project moving forward, influencing our choice in design, part selection, and project function. Research is traditionally done through search engines like Google where users type in a question and a list of websites relevant to the question appears which can then be read and screened for useful information. LLMs can also be useful in research but for a different purpose. LLMs generate content that *seems* true but might not always be true. As an example, let us examine a response from ChatGPT where we ask "What are some examples of laser engravers available on the market that have the capability to detect the material it is engraving?" This question might be relevant to examining similar technologies to our project such that we aren't repeating what has already been done and so we can draw knowledge from the methods that other existing technologies use to achieve the goal of our project. The answer from ChatGPT is as follows:

As of my last knowledge update in January 2022, there were laser engravers available on the market with the capability to detect the material they are engraving, typically through a process called "material recognition" or "automatic surface detection." Keep in mind that the availability of specific models and their features may have evolved since then. Some examples of laser engravers with material detection capabilities include:

Trotec Speedy series: Trotec offers a range of laser engraving machines, such as the Trotec Speedy 400, that can automatically recognize the material to be engraved using a camera-based system called JobControl Vision. This feature helps optimize settings for various materials, ensuring precise and efficient engraving.

Epilog Fusion Pro with IRIS™: Epilog's Fusion Pro series, equipped with the IRIS™ Camera System, allows for real-time material recognition. The camera captures the material's texture and grain and adjusts the laser settings accordingly to achieve the best results.

Universal Laser Systems VLS Series: Some models in Universal Laser Systems' VLS series come with the Material Database Package, which includes a barcode scanner for material recognition. It scans a barcode on the material and automatically loads the corresponding settings from a database.

Gravograph Laser Solutions: Gravograph offers laser engraving systems like the Gravograph LS900XP, which has a Vision camera system for material detection. It can identify the shape and size of objects and adapt engraving settings accordingly.

BOSS Laser LS-900 XP: BOSS Laser's LS-900 XP series includes a camera system for material detection and alignment, allowing the laser to adjust settings based on the material's characteristics.

Full Spectrum Muse Core: The Muse Core laser engraver by Full Spectrum Laser includes a camera that can capture the design on the material and automatically align the laser for precise engraving.

Please note that the capabilities of material recognition may vary from one model to another, and it's essential to check the most recent product specifications and features when considering a laser engraver. Additionally, newer models with improved material detection and other advanced features may have been introduced after my last update. Always consult with the manufacturer or a trusted distributor for the latest information on available laser engravers with material recognition technology. [ChatGPT, GPT-3.5]

At first glance, ChatGPT seems to generate a quality answer, pulling six separate devices that have the capability to detect the material it is engraving. After doing some basic research, all six devices do exist but none of them have the functionality that ChatGPT says they do. All devices are laser engravers or cutters and some have camera-vision systems, but none are listed as having material detection capabilities. This is a good example of the good and bad of ChatGPT and other LLMs. It is typical for the majority of an answer to be truthful, but the small part of the answer that is incorrect can often be overlooked since the answers seem legitimate. Using LLMs for research can still be useful however for generating ideas, as long as the output is double-checked using reliable resources.

5.1.2 Planning

While LLMs have notable downsides in terms of producing factual responses, they are quite useful for creative endeavors such as creating outlines and planning timelines for group work. Since creative applications do not require fact-checking, output from LLMs is completely valid. At the start of a group project, it is imperative to set guidelines for members to follow in order to stay on track and to divide work equally. While these tasks can of course be done manually, LLMs like Google Bard can do them quickly and effortlessly. Let us take a look at an example. I gave ChatGPT the prompt: “Create a timeline for my senior design project for my group and I. We are tasked with writing a 120-page paper that follows the guidelines outlined in… [pasted the guidelines from EEL4914.Project Documentation Guidelines(2).pdf]. This is from August 21st, 2023 till December 5th, 2023.” The response is shown below.

Creating a timeline for your project, given that you have from August 21st to December 5th to complete a 120-page paper, is essential for staying on track and ensuring you meet all the required milestones. Here's a suggested timeline with key tasks and deadlines:

August 21 - September 10: Project Initiation
- Form your project group (if not already formed).
- Choose a project topic and define the scope.
- Begin preliminary research on the project.

September 11 - September 24: Project Planning
- Develop a detailed project plan.
- Create an outline for the paper, based on the provided guidelines.
- Assign responsibilities for different sections of the paper.

……[section removed due to extensive length of answer].......

December 4 - December 5: Finalization and Submission
- Proofread and format the paper according to the specified guidelines.
- Compile all necessary appendices, including copyright permissions.
- Print, bind, and submit the final document, source file, and a PDF file before the deadline (by 12:00 PM on December 5th).

Throughout the entire timeline, it's crucial to regularly meet with your group to ensure everyone is on track and to address any issues or concerns. Be prepared to revise the timeline as needed to accommodate unforeseen challenges or changes in project scope.

This timeline provides a general structure for your project, but you should adapt it to your specific project's needs and your group's working style. [ChatGPT, GPT-3.5]

ChatGPT generates a good rough draft of an outline from the given prompt. It breaks down the work in two-week periods with a description of the work for each period with references to the guidelines given in the pdf. While there are some slight errors, this outline is a good start to a legitimate outline for group work that should only require slight modifications and tweaking. What is often the case with LLMs is that the quality of the output is directly related to the quality of the prompt given. LLMs answer what is asked, which may or may not be what the user of the LLM wants. Thus, care must be given to crafting a quality prompt before using an LLM.

Overall, for outlines and planning purposes, ChatGPT is a suitable tool if given the proper information. As planning does not require fact-checking as research does, the output does not need to be scrutinized as heavily. Regardless, output from LLMs should be proofread and double-checked but can provide useful outlines for group work.

5.2 Comparison of LLMs

There exists a number of different LLM-based chatbots available for use free of charge on the internet. While most LLM-based chatbots operate using similar principles, they differ in style, accuracy, and functionality. The most popular LLM-based chatbots are currently ChatGPT, Google Bard, and Microsoft Bing. These three AI-powered chatbots will be compared and discussed with relevance for use in our project.

For each LLM, we did ask the same prompt (“Explain how solid-state lasers work”) and compare the results for accuracy, creativity, and conciseness.

5.2.1 ChatGPT

Chat Generative Pre-trained Transformer, or ChatGPT is an AI-powered chatbot created by OpenAI. ChatGPT runs on the GPT-3.5 and GPT-4 LLMs which are created and trained by OpenAI on websites, books, and Wikipedia data. ChatGPT operates on a freemium model where users can access the chatbot using GPT-3.5 without needing to pay but can access the more-trained model using GPT-4 if they are willing to spend $20 per month. GPT-4 has been trained on a much larger dataset (100 trillion vs. 175 billion parameters) and is more up-to-date (2023 vs. 2021) than GPT-3.5.

ChatGPT Prompt: “Explain how solid-state lasers work”

ChatGPT Output:

Solid-state lasers are a type of laser that use a solid medium, typically a crystal or a glass, to generate coherent and intense light. The operation of solid-state lasers involves a process of stimulated emission within the solid-state medium. Here's a simplified explanation of how they work:

1. Energy Input: Solid-state lasers require an external energy source to pump energy into the laser medium. This energy source is often a high-intensity flashlamp or a diode laser. The energy source excites the atoms or ions in the solid-state medium, raising them to higher energy levels.

…[section removed due to length of response]...

6. Laser Emission: The photons that emerge from the partially reflective mirror form the laser beam, which is monochromatic (composed of a single wavelength), coherent (all waves in phase), and highly directional.

Solid-state lasers can use various gain media, such as neodymium-doped yttrium aluminum garnet (Nd:YAG) crystals or erbium-doped glass. The choice of gain medium determines the wavelength of the laser output. Solid-state lasers have applications in fields like medicine, material processing, communications, and scientific research due to their ability to produce high-power, high-quality laser beams. [ChatGPT, GPT-3.5]

Based on this example, ChatGPT provides a solid answer to the function of a solid-state laser, breaking down the explanation into an introduction, the steps to generate photons from the laser, and some additional commentary. The response was accurate, but not very concise and did not provide any citations.

Where ChatGPT is beneficial compared to other LLM chatbots is in its thoroughness. Out of the three chatbots, ChatGPT tends to produce the longest answers with paragraphs at the start and end of its responses adding some additional clarification such as warning the user that its knowledge is limited to 2021 or that extra research by the user needs to be done before taking its advice. Out of the three chatbots, ChatGPT seems to be the best at generating quality creative works such as poems and novel names.

While ChatGPT may be good at creating serviceable bodies of text that appear well-written, it is not the best research assistant. ChatGPT often has the flaw of fabricating information that appears truthful. As shown previously, ChatGPT said there were six laser engraving machines equipped with the capability to detect the material being engraved. After doing research, none of those systems were actually capable of doing so. Additionally, ChatGPT is incapable of producing sources or generating links to where it is grabbing its information from. For example, if I were to ask how solid-state lasers work, I would receive an answer but would have no way of determining where ChatGPT gathered its answer from. The inability to gather sources is a big problem for a research-driven project and is close to a deal-breaker compared to other platforms.

For use in our project, ChatGPT will likely be used infrequently. ChatGPT is good at generating new ideas for guiding research and creating timelines to guide our workflow but does not provide enough sourcing to be relied upon.

5.2.2 Google Bard

Bard is Google's AI-based chatbot that runs on the LaMDA family of LLMs and was created as a response to OpenAI's ChatGPT. Bard was released in March of 2023 and is integrated into the Google ecosystem well. The Google ecosystem includes Drive, Docs, Sheets, Slides, and more, and works seamlessly with the Bard interface. One big advantage that OpenAI has over Bing and ChatGPT lies in its ability to analyze files. If the user is running Bard through a Google account linked with Google Drive or any other Google platform, Bard is able to access PDFs, Word documents, and PowerPoint slides for analysis. This is especially useful for our project as research papers and our own writing can easily be read by Bard for helpful suggestions or clarification without needing to copy and paste section by section. As Bard is integrated within the Google ecosystem, every answer given by Bard has a Google icon that when clicked on, allows the user to double-check responses using a Google search.

Google Bard Prompt: "Explain how solid-state lasers work"
Google Bard Output:

A solid-state laser is a type of laser that uses a solid material as its gain medium. The gain medium is the material in which the laser light is amplified. Common solid-state laser materials include crystals such as ruby, neodymium-doped yttrium aluminum garnet (Nd:YAG), and titanium:sapphire (Ti:sapphire), and glasses doped with neodymium or erbium.

…[section removed due to length of response]...

Here is a more detailed explanation of the physics behind solid-state lasers:

- *Energy levels of atoms: Atoms can have different energy levels. The lowest energy level is called the ground state. Higher energy levels are called excited states.*
- *Optical pumping: Optical pumping is the process of exciting atoms to a higher energy level using an external energy source.*
- *Stimulated emission: Stimulated emission is the process by which an excited atom emits a photon of light when it is stimulated by another photon of the same wavelength.*
- *Population inversion: Population inversion is the condition in which more atoms are in an excited state than in the ground state. This is necessary for laser operation.*
- *Optical cavity: The optical cavity is the region between the two mirrors that reflects the light back and forth through the gain medium.*

When a solid-state laser is operated, the atoms in the gain medium are optically pumped to an excited state. This creates a population inversion. The excited atoms then undergo stimulated emission, emitting photons of light in the same direction. These photons are reflected back and forth through the gain medium by the mirrors, causing them to amplify. When the photons reach a certain intensity, they can escape from the optical cavity as the laser beam.

Solid-state lasers are very efficient and can produce high-power laser beams. They are also relatively compact and lightweight, making them suitable for a wide range of applications. [Google Bard]

Bard explains solid-state lasers well, with an accurate, thorough answer. Similar to ChatGPT, Bard provides a step-by-step breakdown of the process behind laser-light generation within solid-state lasers. Interestingly, Bard produces a longer answer than ChatGPT and also does not provide any sourcing.

Though our group has limited experience with Bard, users online have reported that Bard is the least accurate out of the group of three. Since Bard is still an LLM, it is prone to generate false information so the same care should be taken when using Bard as with other models. Similar to ChatGPT, Bard does not cite its sources when generating responses which poses the same problem when doing research.

Bard will likely be used in our project for the analysis of files and papers for review, but will likely not be used for research purposes. From limited usage, ChatGPT seems more competent at generating new ideas for research, so Bard will serve a limited role in our group.

5.2.3 Microsoft Bing (AI-powered copilot)

Microsoft Bing has an LLM-based chatbot that is integrated into the Bing search engine. Bing's AI chatbot is completely free and runs on GPT-4. Bing differs from Bard and ChatGTP in that it creates hyperlinks for the text that it draws from outside sources. This is a huge advantage for use with our project as it allows us to double-check the exact source that Bing draws its answers from removing the guessing element and adding validity to the answers it outputs. As Bing runs on GPT-4, it has been trained by a much larger dataset than the free version of ChatGPT (running on GPT-3.5) which should generate better, more accurate responses. Additionally, Bing gives users the option to set their answers to "More creative", "More balanced", or "More precise". The "More precise" option tells Bing to prioritize truth in its answers, with more citations and less creative answers. This option is best suited for research purposes, giving tailored answers while backing them up with evidence from direct links.

Bing Prompt: "Explain how solid-state lasers work"

Bing Output (output set to “More precise”):

A solid-state laser is a type of laser that uses a solid gain medium, rather than a liquid or a gas[1]. The gain medium is typically a glass or crystalline “host” material, to which is added a “dopant” such as neodymium, chromium, erbium, thulium or ytterbium[1].

The process of how a solid-state laser works can be explained in the following steps:

1. ***Pumping**: The atoms in the crystal are excited to a higher energy state when they absorb photons from a pump source, often a flashlamp or another laser[2]. This state of higher energy is known as an excited state[2].*
2. ***Stimulated Emission**: The excited atoms then emit photons, and this process is called stimulated emission[3].*
3. ***Amplification**: The emitted photons travel through the crystal and stimulate other excited atoms to emit more photons of the same energy, in the same direction and phase. This leads to amplification of the light beam[3].*
4. ***Output**: The mirrors at each end of the laser cavity cause the light to bounce back and forth through the crystal, increasing its intensity and producing a very bright light[4].*

Solid-state lasers have many applications, including in optical disc drives, laser printers, barcode scanners, DNA sequencing instruments, fiber-optic and free-space optical communication, semiconducting chip manufacturing (photolithography), laser surgery and skin treatments, cutting and welding materials, military and law enforcement devices for marking targets and measuring range and speed, and in laser lighting displays for entertainment[3]. [Bing AI]

Bing provides a concise, accurate, and well-sourced response which is also visually appealing, broken down into four quick steps. For use in our project, this type of answer is desirable since the output can be fact-checked and sources are automatically provided if we wish to explore further. Overall, Bing provided the best answer in terms of scientific accuracy and reliability. Bing can also be used for creative purposes similar to ChatGPT, however, Bing runs on the superior GPT-4 model and is free.

Bing is the best overall LLM-based chatbot for our project given its reliability, capability to source, low cost, and the fact that it runs on GPT-4. Bing is a valuable research tool and will be used frequently within our project.

6 Project Hardware and Software Design Details

Throughout this section we did discuss the hardware components and software packages we did be using for our project prototype. we did discuss the options for each major component within APALES detailing the important information related to part and software selection.

6.1 Overall Design Options

This section will brush over broad strokes on what will be included for the design of the project, including some of its electrical components, as well as computers and ways we did prevent fires and include safety into our project.

6.1.1 Electrical Design Options

Originally we had plans to design a PCB that would be responsible for the capturing of the data for the material detection. This would include a CMOS camera, specifically the OV7670. This captured output data from the camera would then be used as input into the next step of the process. The output of the picture would use pixel data of the diffracted spectrum, which would in turn be used for classifying the materials. While this idea seemed feasible on paper, we decided to differ from this and start the development of the PCB to in turn be used for the Z-axis coordination.

As far as other major electrical components go, we did focus on having them all be connected to our PCB or other boards as well. Right now our current plan is to implement a custom PCB for the Z-axis, and another for the X/Y axis, and have the material detection being completed while connected directly to the source, which in this case would be to a computer. This would allow for more easy transferring of data from one form to another. Components such as the motor system, including the stepper motors, will be connected directly to our microcontroller. This will allow for our motors to run with greater precision, being controlled using the data inputs from the microcontroller.

When it comes to the distribution of power in our system, there are various options that could be considered for the system. Some of these include using a power adapter, one that can be commonly found, as it is what we did most likely end up using. Most of our components in the project will run in a DC connection, so because of this, having an adapter that can easily be connected to most if not all standard wall outlets will be essential in powering our system. Some of these components include the PCB, the additional board(s), the sensors, laser diode, and other smaller, less significant additional components as well. Most of the work will be implemented into the boards, as it will be our communicator between the power sources and the components being used.

The primary component that we must have finalized and highlighted in this section is the PCB for the project. We want to have a large PCB that will work in tandem with the other board, as these will work hand in hand in powering and distributing the source of energy to all of our components that are necessary. While having an additional board will use more of our limited spacing on the project, it will further streamline the process of engraving, as having an individual z-axis component will alleviate the need for further complication worrying in three different directions. This MCU will take the input from the sensor and use this to move the height of the bed to the specific requirements for each material being used.

6.1.2 Computer Design Options

we did no longer be performing any image processing on an MCU. As mentioned in section 6.1.1, we found that it wasn't feasible to depend on the OV7670 for our material detection. After consulting Dr Zheng, one of our ECE reviewers, we found that it may be a better idea to use a webcam connected to a PC. Part of the reason for this design change is that images have a higher data volume and it would be more difficult for a microcontroller with limited memory to handle that data. A PC has more processing power and will be able to handle the image data much more effectively. From the programming side of things, it would also be simpler to write code for a PC to extract the necessary data from the images. There are Python packages to interface with the webcam, extract the necessary pixel data, and perform the classification of materials accordingly.

The computer design for our system will revolve around one central PC. The idea is to have one PC function as the main hub for our electronic modules. We'll have a laptop that connects to the CNC module (Arduino Uno with Shield) as well as the webcam for the spectroscopy system. We can write Python code to pull the webcam footage, take a horizontal slice of the diffracted spectrum and run the necessary classification algorithm. The classified material can then be sent to our G-code sending application running on the same PC. According to the material, the application will adjust the g-code parameters in preparation for the CNC module.

After doing some investigation online, we found that a Python script can actually be used as the g-code sender. Python supports serial input and output through the ‘serial’ package. We found some projects online that used a Python script to access a g-code file and send the contents to the microcontroller sporting GRBL. This may be a more valid approach than using the pre-existing GUI applications for g-code sending (LaserGRBL, UGS, Lightburn etc.). This is because we’ll need a Python script to interface with the materials detection module and accordingly parameterise the g-code file. We can save the data of the diffracted spectra and their associated g-code parameterisations locally in some files. Through simple file I/O this data can be accessed by the Python script to then generate or alter the appropriate g-code files. This is the main approach we’re currently considering for automatic parameterisation of the laser job.

6.1.2 Fire Prevention Safety

The first rule of fire prevention in this project is awareness. Everything in relation to safety begins with documenting what materials can be used for our project. For example, sticking to the ones that we know are feasible is the best way in preventing an accident from occurring. Becoming aware of these accidents, we can prevent them from happening before they can even start. we did stick to a small list of legal materials that can be used to prevent fires or smoking from occurring. Besides just having awareness, we did include a final safety mechanism which is later referred to in the design of the PCB, in a further section.

6.2 Laser Optical Design

The laser system in our project aims to be able to produce fine details. This requires us to dive deep into the realm of laser focusing and the optics and methods needed for creating a small spot size at which the laser focuses. Among the many different lasers which could be useful in creating a laser engraver, our design implements a semiconductor laser diode, which has special properties to take into consideration which are not necessary for other lasers.

As discussed in 3.4.2.5 Diode lasers, the output beam from the laser diode is a rectangle. This requires some optical and lens design to get to the smallest spot size possible, which is one of our main goals. In order to get the smallest details possible for engraving, a lens with a relatively short focal length is required for our system.

When laser engraving or cutting, the focal length of the lens determines many factors in the quality of the edges. If the focal length of the lens is very long, that means the convergence angle of the beam is quite small. When the divergence of the beam is a small angle, then there is an approximate column of light which has high intensity, which is very similar to what an optical axicon does when it creates a Bessel-like beam, as referenced in 3.4.5.3.4 Axicons, Figure 11. This column of light has a high intensity, which allows it to make deeper engravings or cuts in the material, but the quality of the cut and the spot size suffer from this. This would be ideal if our project was to create a laser cutter, but engraving is our main focus, so we look for a better option.

Using a shorter focal length lens allows us to generate much finer details on the surface of the material. The short focal length causes the light to converge at a much sharper angle, which creates a very small point, and does not create a pseudo-column of light like the long focal length lens does. The large convergence angle translates to a large angle of divergence after the focal point of the lens, which makes the light intensity dissipate very quickly. This enables us to create ultra-fine details on the material, as such is the goal of this project. This relationship is visibly defined in Figure 40 below, although the relationship becomes more drastic as the focal lengths become longer and shorter, respectively.

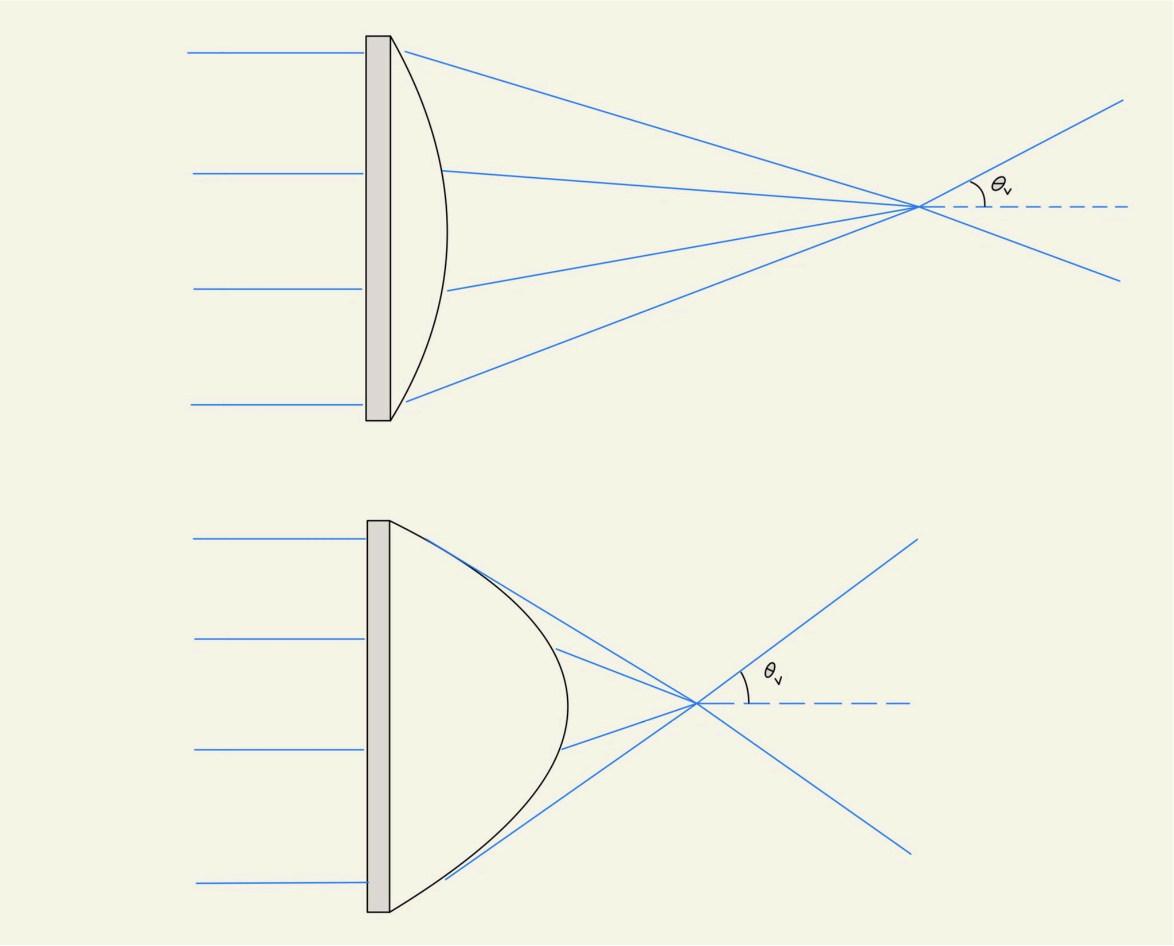


Figure 40: Comparison of short vs. long focal length and divergence angle

We aim to engrave relatively thin materials as well, therefore we must not have too long of a column of intensity from the beam so we do not cut through our materials when we only desire to engrave them. Our desired focusing lens has a focal length of 12.7mm. This is a very short focal length and therefore has a large convergence and divergence angle for the beam during focusing and divergence. This lens will enable us to generate the desired very small details that have been our project goal since day one.

Our lens design for focusing the laser diode consists of two lenses: an adjustable focal length lens which is built into the laser diode. This lens changes its distance from the laser diode by a screw mechanism. Our ideal setup has this lens 4mm away from the laser diode’s emitter, which has a very high divergence angle so the lens must be very close to capture all of the emitted light. The lens focusing at this distance makes the beam focus 20mm after the lens. After this lens, we are using a single plano-convex lens, the Edmund Optics #38-291 lens with a diameter of 12.5mm and an effective focal length of 30mm. The lens is positioned 2 focal lengths away from the first focusing point. This creates a 2f Focusing System. This system means that the image will focus at the same distance as the object distance, both at 2 focal lengths. This also creates the same spot size as the original focus, maintaining the tight focus we desire.

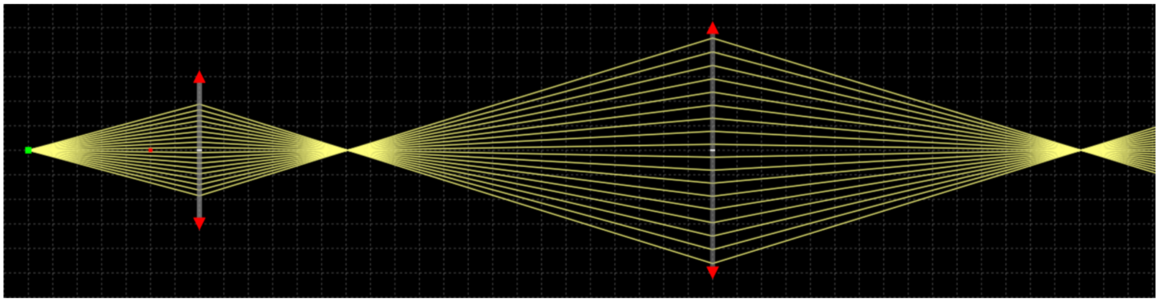


Figure 41: Simulation of beam focusing, performed in PhyDemo Ray Optics Simulator [55]

6.3 Spectroscopy System Design

The spectroscopy system incorporated in our project aims to utilize broadband white light to illuminate the material during engraving and subsequently capture the reflected light for analysis. This process involves directing the captured light into the spectrometer, where it is shaped, separated into its constituent components, and its spectrum recorded. This section goes over the various components comprising this system.

Traditionally, spectroscopy systems function as standalone entities solely dedicated to analyzing a material's spectrum. This standalone nature simplifies the analysis process, as spectroscopic techniques are not required to integrate within a larger system. However, in our project, the spectrometer must seamlessly integrate into a functioning laser engraver without compromising or diminishing the engraving quality.

To ensure the spectrometer does not interfere with the engraving process, it must possess a compact form factor to fit within the overall footprint of the engraver. Moreover, its design should allow for movable light collection to synchronize with the movement of the laser during engraving. Additionally, the quality of the spectrometer is contingent upon the signal-to-noise ratio obtained through the light collection method. Inadequate light available for analysis may lead to the intrusion of stray light and background noise, potentially compromising the quality of our results and rendering material identification challenging.

Shown below is a schematic of the proposed design of the body of the spectrometer.

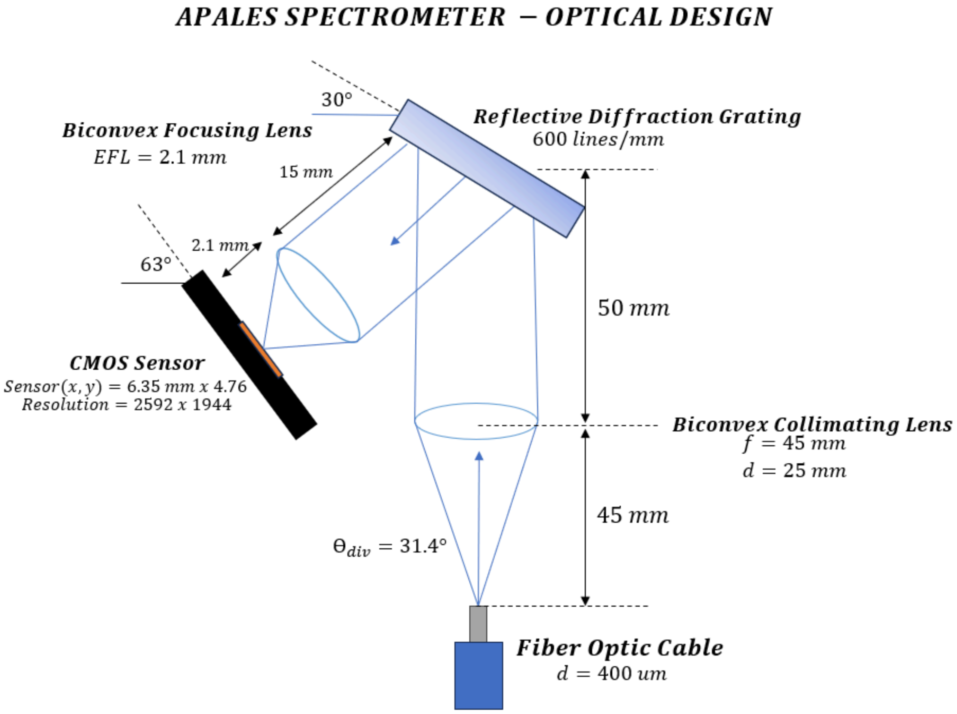


Figure 42: Schematic of spectrometer body

The spectrometer body will be composed of an optical fiber, a slit, a transmissive diffraction grating, and a USB webcam. The optical fiber will be the method for transporting light from the source to the body of the spectrometer. A slit will be used to shape the beam to get a good spectrum on the camera. Lastly the camera will be used to capture one mode of the spectrum from the diffraction grating.

In terms of placement, the optical fiber, diffraction grating, and slit will be aligned along the same axis in order to ensure accurate measurements. The optical fiber will be connected to the body of the spectrometer using ST fiber couplers which aids in the ease of connectivity and maintenance. The slit and diffraction grating will be oriented perpendicular to the optical axis. For the slit, perpendicular orientation ensures that the slit opening maintains shape and does not diffract light in an unpredictable way. For the diffraction grating, perpendicular alignment allows the angle of the first mode to be easily calculated using the equation $a sin(\theta_m) = m\lambda$ where a is the slit separation, θ_m is the angle of the mode, m is the mode, and λ is the wavelength of interest. This equation relies upon the fact that the angle of incidence is zero. Within our project we want to capture the spectrum of the first mode and thus we did place the camera in line with the angle calculated. The separation of each component is a rough estimate and will be tweaked with further hands-on testing.

Shown below is a schematic of how the light will be collected using an LED and fiber optic cable.

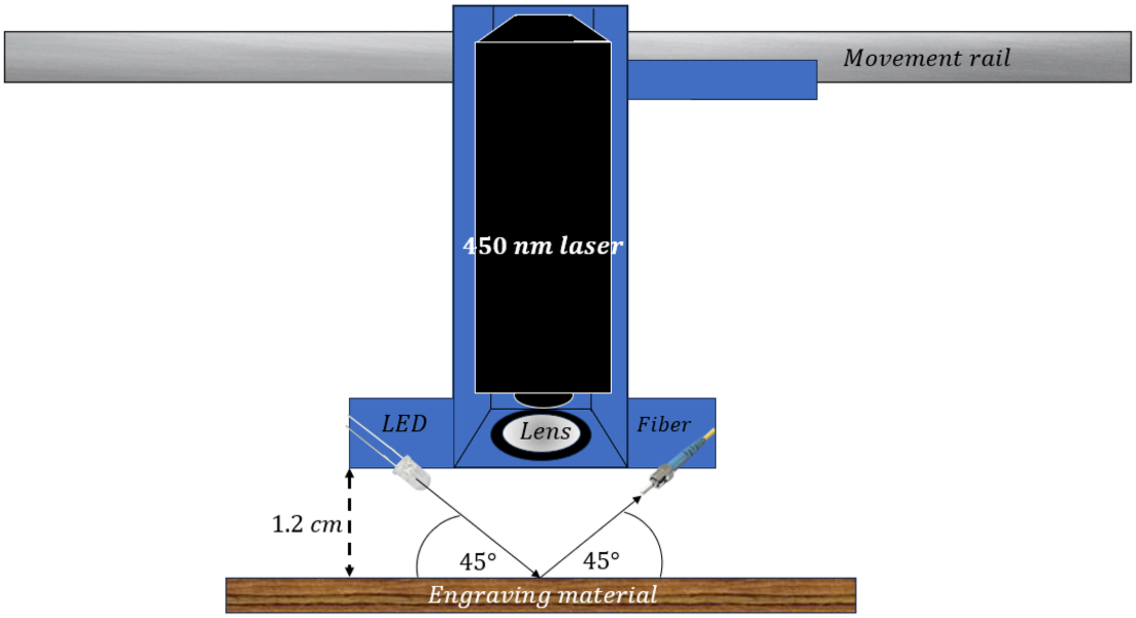


Figure 43: Schematic of reflection spectroscopy integrated within laser setup

As can be seen, the design of our light collection mechanism is integrated within the laser module. For the final product, we did 3D print an enclosure for the laser, lens, LED, fiber, and distance sensor. Moving all of these parts together is essential for proper functionality of our device. Upon beginning the engraving process, a z-axis measurement needs to be done to determine the laser-to-material distance. Positioning the laser/lens at a consistent distance from the material is essential not only for keeping the laser spot size equal across different objects, but also to obtain consistent results for the spectrometer. If the LED/fiber are not kept at a constant distance from the surface of each material, there will be varying amounts of light captured by the optical fiber, resulting in inconsistent measured spectra. Additionally, the LED and fiber will be oriented 45 degrees from the surface of the material. If the material is not kept within a constant distance from the lens, the light collection will be negatively affected due to the orientation of the LED and fiber meeting at a point 1.2 cm away from the end of the lens.

6.3.1 LED

In regard to the spectroscopy system, an LED will be used as the source of illumination. The purpose of the LED is to provide high levels of broadband white light (within the visible spectrum) such that the spectrometer captures enough power and a wide enough range of wavelengths to make analysis possible. Selection of the LED will be dependent upon the central wavelength, bandwidth, optical power, and angle of divergence. Shown below are a comparison of available LEDs that could be used within our system.

Index	**Name**	**Central wavelength (nm)**	**Bandwidth (nm)**	**Optical power (Lumen)**	**Angle of divergence (degrees)**
1	Chanzon 5W Warm	625	158	500-600	120
2	C503C-WAS-CBBDB231	640	125	10	30
3	Chanzon 1W Cool	580	145	100-110	120

Table 15: LED Comparison

Comparing the options above, each emits with a central wavelength within the visible spectrum and produces a broad enough spectrum to cover the majority of the visible spectrum. Where each LED differs is in the optical power. LED number 2 is the classic low-powered LED that you would find in a DIY kit which takes little power and emits fairly dimly. LEDs 1 and 3 are made by the company Chanzon which produces high powered COB LEDs. COB LEDs are made up of many smaller LEDs with a phosphor coating over the top which allows the lights to be much more luminous. LED 1 produces 500-600 lumens of power whereas LED 3 produces 100-110. While we want more power than LED 2, LED 1 may produce too much light to where reflections from surfaces other than the engraving material may interfere. LED 3 should be a nice inbetween option.

The LED can be controlled simply by varying the voltage across the anode and cathode. The LED from Chanzon operates at max at 3.5 V but can be dimmed as necessary by lowering this value. This LED is not focussed very much however and we did experiment with adding in an additional lens to focus the power more and garner a higher intensity.

Mentioned previously, the LED will be attached via a 3D printed mount tied to the laser module. The Chanzon 1W LED requires 3V DC and uses 300 mA of current. The LED will gather its power from the PCB and the power supply and will turn on upon beginning the material detection process and turn off once a spectrum is captured. The LED will not be on for very long as the camera used within the spectrometer just needs to take an image of the spectrum created with the diffraction grating.

6.3.2 Fiber Optic Cable

The fiber optic cable used within our project will serve as our light collection mechanism as well as the medium for propagation to transport light from the material to the spectrometer. Considerations for the selection of the fiber are the ease of connectivity, the core diameter, and price.

To aid in construction, testing, and maintenance, the ease of installation and uninstallation will be pivotal with such a sensitive piece of hardware. For our project, we chose to use a fiber with an ST connector which has ready-to-buy components that we can integrate within the laser system. Shown below is a figure of how the ST connectors will fit within the overall engraving body.

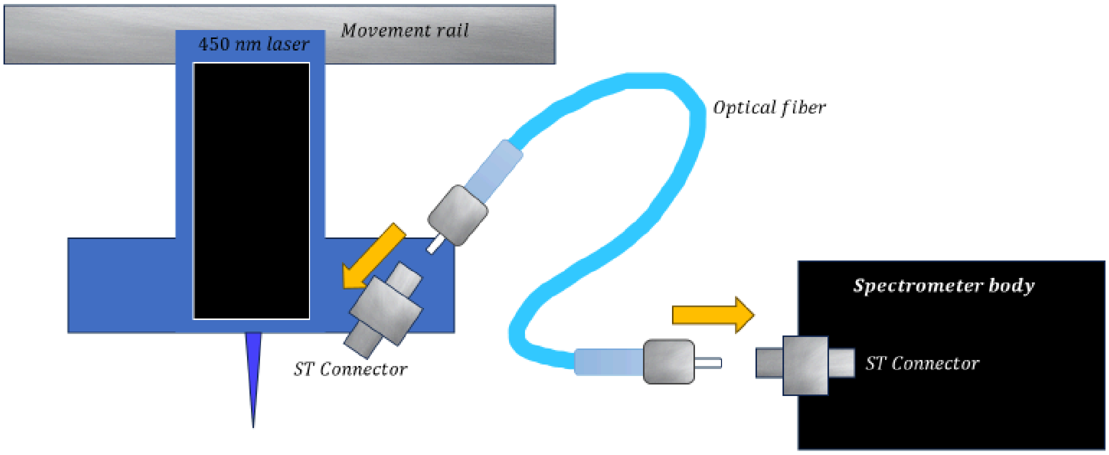


Figure 44: Schematic of ST connectors and fiber within laser and spectrometer

As can be seen above, there will be an ST connector attached on the laser mount as well as on the spectrometer body. The ST connectors are the female end of the port and the fiber has the male end of the port allowing for seamless connectivity. Using these universal connectors allows for smooth installation and removal for cleaning or replacement.

The fiber chosen for our project is the “ST/ST 62.5/125 Multimode Simplex Fiber Patch Cable - OM1 - 2 Meter” from Show Me Cables. This fiber has the ST connector end and has a core radius of 62.5 micrometers. The fiber chosen is multimode and should allow lots of light to enter for a large signal to analyze.

6.3.2 Slit

The slit within the spectroscopy system plays the role of shaping the incoming beam from Gaussian to vertically oriented. When light exits the fiber, it diverges at an angle determined through its numerical aperture. This diverging beam has a Gaussian energy profile and is radially symmetric. A circular beam is not ideal for a diffraction grating as diffraction gratings produce copies of the image side-to-side of each wavelength. For images (such as the Gaussian beam) that are wide, each wavelength will produce a circle that will overlap with each other causing interference. In order to prevent as much overlap as possible, a slit is necessary to narrow the beam.

Shown below is a diagram of how a slit will be used to shape the light exiting the fiber and moving toward the diffraction grating.

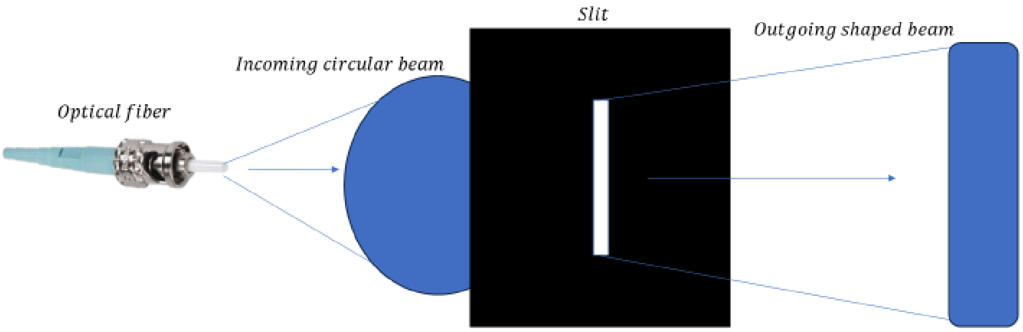


Figure 45: Beam shaping using optical fiber, going from circular to vertical

6.3.3 Diffraction Grating

The diffraction grating used within our spectrometer is an essential component to observing and measuring a good spectrum. Of the options available there are two types of diffraction gratings: transmissive and reflective. Transmissive diffract light as it passes through the grating and reflective gratings diffract light as it reflects off of its surface. Both options reflect the spectrum in modes meaning the incident light will be reflected in multiple directions. Light will be transmitted/reflected according to the equations shown below.

Transmissive diffraction grating: $a(sin\theta_m - sin\theta_i) = m\lambda$
Reflective diffraction grating: $a(sin\theta_m + sin\theta_i) = m\lambda$

While both equations are very similar, the difference lies in how the angle of each mode changes with the angle of incidence. For transmissive gratings and the angle of incidence increases, so does the angle of each mode. For reflective gratings, the opposite occurs.

Performance-wise, reflective gratings tend to be better. Transmissive gratings can be lower quality but are more widely available from consumer retailers. Reflective gratings are used in high quality hardware for market spectrometers but are very expensive and not widely available. For our project, we did be using a transmissive grating as the performance is still high enough to get a quality spectrum. As we are not aiming for sub-nanometer accuracy, transmissive gratings should prove to be more than adequate for our purposes. With further upgrades, a transmissive grating can be used instead to increase the performance of our system.

The diffraction grating will be placed within our spectrometer as shown in Figure 44. The distances are chosen because of the NA of the optical fiber. The majority of light from the fiber should hit the diffraction grating and the webcam will be placed to capture the spectrum of the first mode. The angle will be calculated given the spacing of 500 lines/mm for the grating, the angle of incidence of 0, the mode of 1, and the central wavelength of 600 nm.

6.3.4 Camera

Central to the spectroscopy system's functionality is the camera, tasked with capturing the initial mode of the diffraction grating, thereby containing the spectrum of the investigated material. The selection of an appropriate camera hinges upon considerations such as sensor resolution, connectivity options, and cost-effectiveness. Initially, our intention was to utilize a camera integrated with the Arduino; however, following preliminary testing, we determined that employing an external computer-connected camera would offer more computational power and a more user-friendly interface.

The chosen webcam for integration within our system is the BUBCOS OV5640 five-megapixel webcam, procured from Amazon. This webcam presents an impressive resolution of 2592x1944 pixels and stands out due to its compact form factor, attributed to its lack of housing. Priced at $17, the OV5640 offers remarkable resolution for its cost and is expected to seamlessly fit into the compact spectrometer design. Its driverless functionality ensures plug-and-play compatibility with Windows computers, simplifying integration. However, due to its exposed nature, a dedicated casing within the 3D printed spectrometer enclosure is necessary to protect the sensor.

Employing a USB webcam serves the purpose of simplifying image capture and processing. While advantageous in certain aspects, the use of a webcam does lead to initial setup complexities, necessitating multiple USB cables for operation. As part of future upgrades, our objective is to streamline this process to operate through a single cable for enhanced convenience.

As mentioned earlier, the camera's orientation will be directed towards the diffraction grating at a specific angle to capture the first mode of the spectrum. Upon initiation of the material detection process, once the LED activates and light traverses through the fiber, passing through the diffraction grating, the camera will capture an image for analysis. This captured image will be processed in Python, converted into matrix form as an RGB image. Focusing solely on pixel intensity for spectrum analysis, the RGB image will be converted to grayscale. Subsequently, a horizontal slice of the image will be extracted, representing the spectrum, and stored for comparison with the database of saved spectra to make predictions.

6.3.5 Lenses

Lenses play a pivotal role within the spectrometer, facilitating the collimation of light both into and out of the fiber optic cable, as well as directing the light towards the diffraction grating. When light emerges from the fiber, its divergence is determined by the numerical aperture of the fiber. Considering the limited light collection capability of the fiber itself, employing lenses becomes essential to minimize power loss due to divergence. Our approach to utilizing lenses involves exploring different options. One option involves employing a lens for collimation both into and out of the fiber, while another option involves using a lens solely for collimation out of the fiber. For our project, we opted to utilize a single lens within the spectrometer body to collimate the light as it exits the fiber.

The positioning of the lens is planned to be situated at a distance of one focal length away from the edge of the fiber itself. To ensure its stable placement, we intend to secure the lens using a 3D printed mount, maintaining its fixed position at the specified distance from the fiber, as illustrated in Figure XX: Use of collimating lens with optical fiber.

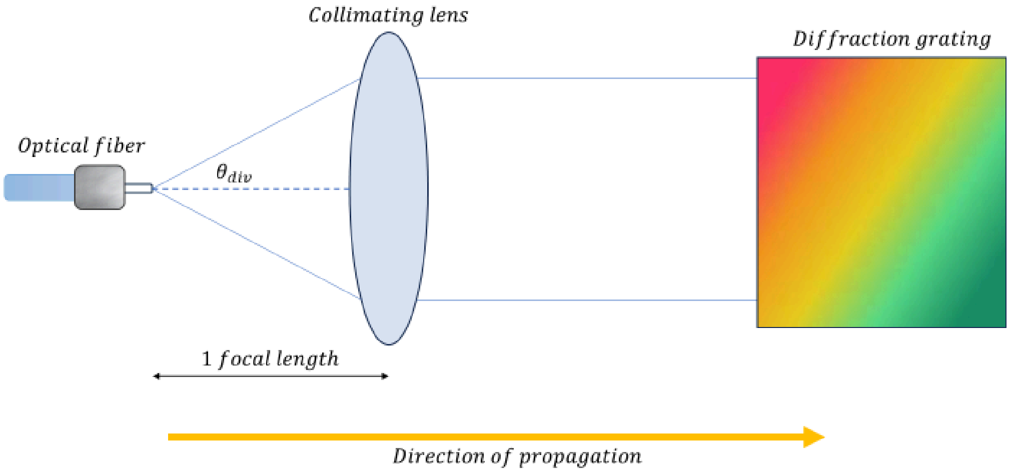


Figure 46: Use of collimating lens with optical fiber

While the specific lens to be employed is yet to be finalized at this stage, the selection will be based on factors such as availability and cost-effectiveness. Although there are fiber collimators available in the market that seamlessly fit onto fiber outputs, their cost can be prohibitive, often exceeding $100 per unit. Given the budget constraints of our project, we are inclined towards utilizing an N-BK7 lens from Thorlabs, a cost-effective alternative that can be easily mounted onto a universal lens mount, ensuring compatibility and functionality within our spectrometer design.

6.4 PCB Design

The purpose of this section is to highlight some of the various PCB designs that have been taken as a possibility, and its varying chances of possibility in being used. we did go over two that have the highest chances, as well as some of the components that will be needed to be connected to our boards.

6.4.1 PCB Design Flowchart

The PCB will be one of the most essential aspects of the project, having it power our X and Y components is imperative in creating the material detection for the system. At this stage of the project, our final PCB design has not been finalized as we are still testing numerous devices, and haven't been able to make a final call on what will, and what won't be included. In the meantime, we did include a draft on the PCB design, including all of its major components and its wiring. All of our devices will include unique connections, as well as pins and power needed, making it difficult to have a final schematic of the circuit without having last minute changes done to any device which would make us start over again. This flowchart will be a high level design of what we believe the PCB will generally look like, but also will leave us some wiggle room on what devices can be moved around depending on our needs for the final board.

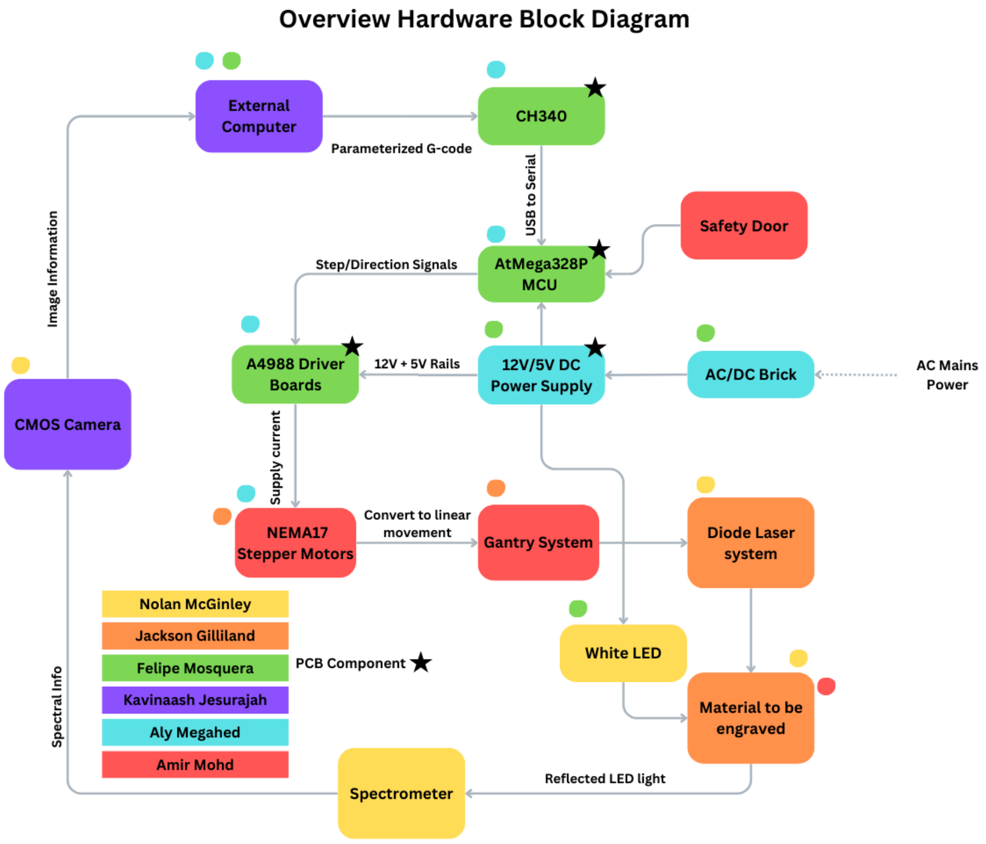


Figure 47: In-Depth Flowchart on PCB and its Components

In this chart, we go in depth into the various components that are used within the system, including the PCB having components for the X and Y axis for movements, as well as its various stepper motors and power source. While this flowchart does not have the entire specifics on which hardware will be used, it does give a very full explanation on what will be included. One of these, for instance, is the Voltage Regulators , as we did not specify what specific values will be used, as we did go into detail which ones should be used in a further section.

To give a more in depth look into the specifics on how the process works, we did take a glance at the legend provided at the bottom left. Basically, describing who is responsible for which section of the flowchart. Meanwhile, the lines show where the data connections are going, as signals with descriptions included showing what it is attached with. It is important to keep in mind that this is still relatively broad, having several connections in pins represented as one simple blue connection. Our MCU, the ATmega32, will be included onto the PCB, and will be used to be connected to the motor driver, allowing for motor control. The board will be used to connect to two motor drives, for the X and Y connections. The laser diode will be powered by our AC/DC adapter, which in turn will be our custom PCB. The laser diode will in turn be powered and controlled through the use of PWM signals, so the connection can control the intensity of the power needed depending on the material. As previously stated, some of the values for the specific components will be changed to a finalized component at a later date when everything has been confirmed and purchased.

An additional component that was not originally included but was recently added into our flowchart, is the LEDs that are attached to several of the voltage regulators. The reasoning for having these included not only in our flowchart but in our final design would be for troubleshooting. Having these LEDs included would help in any issue that would arise, so if any of them would turn off, it would be able to indicate that a certain indicator isn't working, trouble with wiring, or any other issue. Only specific portions of the flowchart will include an LED, as some components already have built in LEDs to indicate any trouble with its functionality, such as the microcontrollers development board.

6.4.2 Voltage Regulator Options

In this section, we did delve into various types of voltage regulators that can be included into the project, to be able to finalize and choose which would be best for our design. As our PCB will be fairly simple with most of its hardware including voltage regulation devices, we did need to briefly go over some of the options for our design and see which fits best.

6.4.2.1 Voltage Divider

Given a basic circuit, the most generally used voltage regulation device is typically a voltage divider circuit. These types of circuits typically include the least amount of components and are the cheapest to build. Given that we did most likely use a 24V output, in our simulation we did continue this practice and include this for our circuit as seen below:

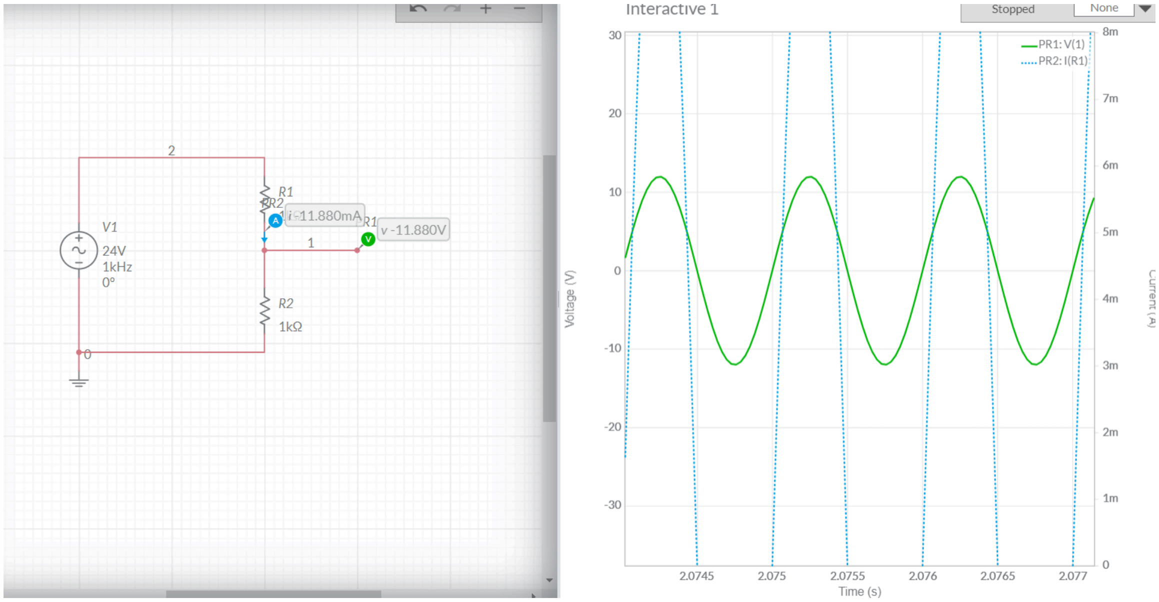


Figure 48: Voltage Divider Regulator Schematic with Simulation

In this figure above, there is a circuit that includes a voltage divider working as a regulator, with the load being shown on the resistor so we can see the output current on it. Since most likely we did include a 24V AC/DC adapter, it was included in our simulation, in addition to some 1K Ohm resistors to divide the voltage. Thanks to this, we did then test to see if the output will change its behavior as our current continues to increase. We want to have a 12V output, as many components on our system will run at a 12V power level. As shown in the simulation, the biggest current that our load can carry having 12V is 12mA, which could cause power sufficiency problems later down the line.

Our biggest concern with this regulator is that by itself, it may not provide sufficient power to draw from for our system. If only one is in use, it may not be feasible, but, if used in tandem with several other voltage regulators such as the ones shown in a further section, it is possible to have enough current to draw from. This is something to keep in mind in making the final decision on what regulator to include into our project.

6.4.2.2 Zener Diode

Another helpful voltage regulator is the zener diode regulator, as it's one of the most common voltage regulation circuits. When taking a look at it in its most simplest form, the only additional component that needs to be added to the circuit from the voltage divider regulation is a zener diode. The zener diode is responsible for maintaining a steady voltage for the current, while it is concurrently holding a steady voltage. As the zener has the capabilities of controlling voltage, this already puts it one step above the voltage divider and allows for more capabilities. The following circuit below simulates a zener diode and the way output would be presented, along with certain calculations on possibilities as seen:

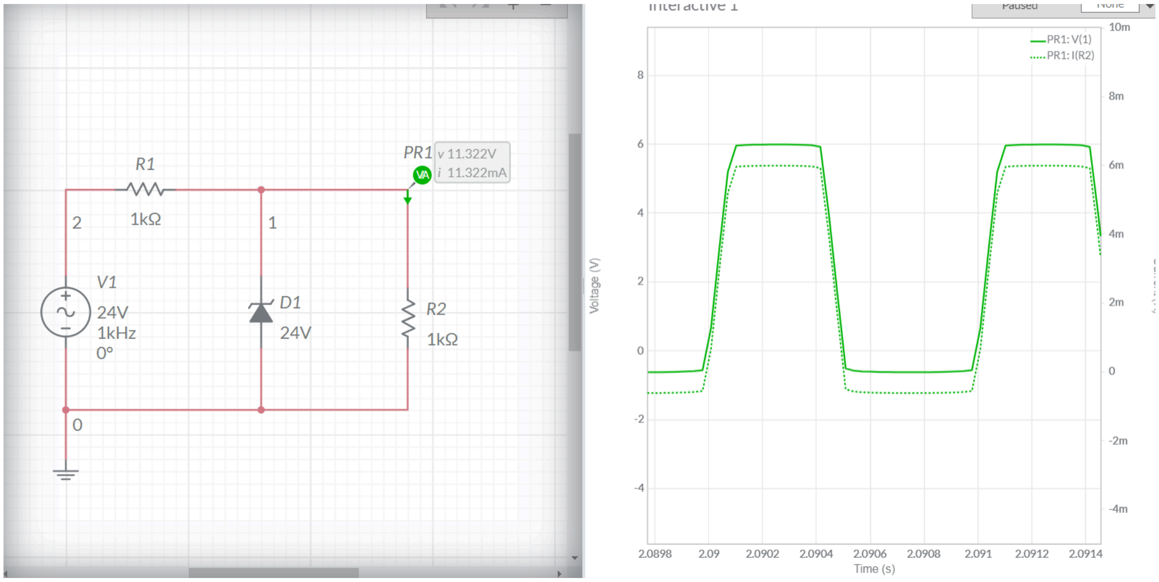


Figure 49: Zener Diode Regulator Schematic with Simulation

As seen above, the diode given was able to keep a steady voltage of around 12V, which is definitely promising to read. When beginning to draw a larger current the output begins to become more inconsistent. This causes the usage of a zener diode to become not as reliable as other forms of regulation. Nonetheless, the fact that our simulation will be able to maintain a steady 12V output during low current usage is extremely useful for our project, as we do not specifically require high levels of current. While this zener diode is very cost effective, thanks to its practically simple voltage regulation. There are some large downsides to consider, as it has a hard time operating at higher current levels. For certain components that require a lower current draw, this regulator is definitely seen as fit, but for larger more intense components, another regulator should definitely be considered.

6.4.2.3 Additional Adjustable Voltage Regulator

In addition to the various voltage regulators already described in sections above, there are numerous other options that should be taken into consideration before purchasing and finalizing our design. Two of the ones we want to highlight are the LM317 and the LM2576, both of which are common voltage regulators that are used to construct circuits, each with their own varying levels of design and functionality. The first of these, the LM317, has the capability of creating a regulated output that allows us to have an adjustable voltage range. It is seen as a versatile option, and is widely used for a myriad of applications where we need to adjust the voltage. On the other hand, we potentially may include the LM2576, which is designed specifically to step-down the voltage, making it a very viable option when we need to focus on making our project more energy efficient.

Besides these distinctions, other key differences is the fact that the LM317 uses a linear regulation approach in its design, meaning it is able to provide a stable output for its voltage, but to counteract this, it releases any excess energy as heat. The LM2576 contrastes this by using switching in its design, meaning it helps minimize the amount of heat dissipation created, allowing for an improved efficiency in power.

When trying to make a final decision on which should be implemented into our design, the biggest thing to take into consideration is its ease to implement as well as its cost efficiency. The choice between both the LM317 and LM2576 ultimately depends on what we prioritize for this application, as the former is able to be suited for a more broad range of uses, while the latter is more energy efficient, with a focus of step down voltage regulation. Ordering these regulators and testing them in the lab will help make a final decision, as whichever is chosen will help decide the form of cooling we did implement into the design as well.

6.4.3 DC Fans Design Options

The use of any of the stated regulators above, including the LM317, LM2576, zener or voltage divider, will all introduce a certain amount of excess thermal heat which will then cause the potential need for cooling fans. While we do not have fans as our design included at this moment, it is important to keep in mind that it is a possibility, given the fact we are using several components on the board that could have excess heat. There are several options for fans, including some that are 3V or 5V. With each additional component included into the project, the need for another regulator must be included into the design. So if by possibility fans will be added, there will be an additional regulator included for it.

As stated previously, the addition of fans is something to keep in mind for a failsafe, but not a concrete inclusion into the design at this time. There are several options for fans to be included into the PCB design, such as ones that are 90 mm in size or those that are 60 mm. Depending on our specific needs and size options, we can decide later in line, as these will also need to run on a 12V regulator as well.

6.4.4 ATmega32 Design Options

The microcontroller that we did be implementing into our design has been finalized to be the ATmega32, and will be programmed using a development board, which is commonly used by most microcontrollers. As a point of reference we did refer to the development board, which can come with various pincounts, such as 6, 8, 10, etc pins. Boards that are based on arduino, such as the ATmega32, come with standard sized spaced pins of 0.1 inch or 2.54 mm size. While this may be standard on certain boards, we also have a wide variety of components that will be implemented, each with its own various sizes of pins. This is important to keep in mind when developing our own board. To avoid further confusion later down the line, we did try to have most connections be done directly from the microcontroller to the PCB, so that all logic that will be done from the ATmega32 will be sent accordingly from the PCB to its various components, including the drivers, the laser diode, etc.

Our microcontroller will be powered through a PC, which in turn will be able to communicate with the other board, as well as its main interface to print any output data that will be completed. To avoid any potential accident, we did deter from giving the board multiple sources of power, including from the USB port to the adapter as well. Each will have its own connection to the interface. Our ATmega32 will have a standard board with pins of 0.1 inch in size, so we did use the appropriate cables on the board. The PCB will also have the same size male and female pins, with the appropriate labeling system to allow for a streamlined and simple to set up connection.

6.4.5 Distance Sensor Design Options

One component that we did include in our project is a sensor to measure the distance between the laser diode, and the base itself. This was included as a means to keep the distance for the Z-axis in line with what was necessary depending on the material, as keeping the length in the z axis will allow for a margin of error, with different lengths needed depending on the material. The way we did resolve this will be by including it into our final system, and as is common with most of the other components, this will have a regulator attached to it as a means of keeping the medium of printing from failing. Keeping the cables connected to our PCB and its adjacent boards with the necessary components will help keep our data signals running continuously. In addition to the sensor itself, it will be measured using millimeters, and include a buzzing system to alert the user that the laser is at its appropriate distance required for a successful laser engraving.

6.4.6 Master Switch

While sometimes going under the radar in its importance, it is essential to keep a reminder that having a master switch is key in providing a safe product no matter the intentions of its usage. we did include a feature that will control the entire power that is coming into the PCB, a kill switch. For whenever there is a possibility of an emergency and there is a need to immediately or manually disconnect all components from the power, then there will be a switch that is placed conveniently for the user to turn off all the hardware being used on the PCB, as well as its adjacent boards.

Several options are seen as viable for this design, including the Omron B3F, E-Switch, and the ALPS series. All of these run using a tactical push button, and are seen as completely justifiable options for the board, as they all include several options including surface mounting or through hole options. Depending on the final design of the board, we did see which version we value more, for compact size or longer life expectancy.

6.4.7 Additional Connections Design Options

This section will go over some additional components that will be included with the board, including its source of power with the adapter, any USB connection for transmitting data, and any additional hardware since it is important to speak in detail about all components in our PCB.

6.4.7.1 AC/DC Adapter Design Options

To try and streamline our project, we did have the source of all power begin, plugged in and powered by any wall outlet, given that we are using a standard adapter commonly used in any household. Besides the fact that the adapter will be a much safer option thanks to its longstanding reliability being produced by numerous companies that are up to safety certifications, using an adapter will help reduce heat that would otherwise have been created by using an AC power attached directly to the PCB. While continuously quantifying our power values as 24V, this is always subject to change as the project develops, in case there isn't actually a need for 24V. But for the time being, this will continue to be the input to run our entire project.

6.4.7.2 USB Connection

A USB connection is going to be implemented to allow the transmission of data to and from the microcontroller. we did use UART as our communication protocol to program and power the board throughout the process. There will not be the need for an inclusion of any voltage regulator into our project for the USB, as it is not directly connected to the PCB but rather just a means to transmit data. Since it is not attached to the board like other components, we do not worry about its connection as opposed to the adapter.

6.5 Software Design

The overall software design needs to integrate the spectroscopy system with the webcam and Python classification algorithm. This needs to interface with the G-code sending program on the PC. As discussed in the technology investigation section 3.2, we did be using either LaserGRBL or Universal G-code sender for sending the g-code job to the CNC Arduino. After installing LaserGRBL, we could see that it included a material database. Each entry in the database includes a certain laser model, material and associated parameters for engraving or cutting. This material db can also be modified to include new entries based on our testing. We can test the parameters with our laser setup based on similar entries in the database. For example, if we're testing on plywood, we can find an entry with plywood as the material and a similar laser model. Based on the job results, how sharp the engraving looks, we can adjust the speed and PWM parameters accordingly. Once we're satisfied with the parameters for a given material in our setup, we can update or create the database entry.

Once an entry is created for each of the materials, we can begin classifying the materials based on their diffraction spectrum. We'll be using a Python script with OpenCV as our computer-vision/machine-learning package. We'll have a list of spectrums associated with each of the materials. These can be saved as images or converted into arrays and saved as text. Once we got this labeled data, we can begin training our classification model. It'll be easier to test once we include spectroscopy system setup and with the proper lighting conditions. The idea is to take a slice of the image, convert into an nd array to extract the pixel data and accordingly classify the material. From our testing of the material spectra, we can see that they are distinct enough to easily classify among each other.

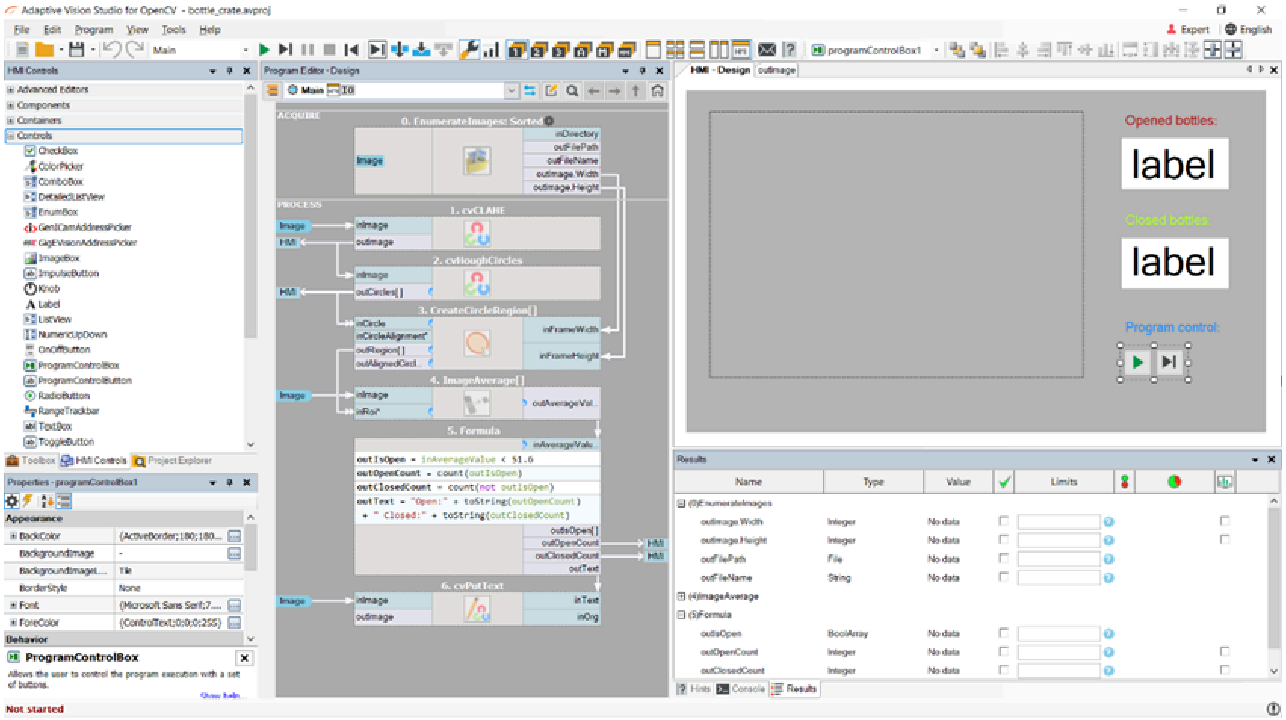
Since we only care about a certain slice of the image, we can use OpenCV algorithms or simply take a slice of the diffracted spectrum using pixel coordinates. The classification only depends on the light intensity along the X-axis of the spectrum, so the image data can be reduced to grayscale from RGB (or BGR). The data can be reduced further by averaging the Y-axis range of the diffracted spectrum. That way, the classification can be done via a 1-D array data structure rather than a 3-D one. Depending on testing with the existing OpenCV library of algorithms, we'll see what works with the object detection (spectrum) and classification.

A challenging aspect of the software design will be interfacing our Python program with the G-code sending application. LaserGRBL is open-source and supports the use of plugins, as does Universal G-code sender. The objective is to automate the process of parameterising the laser job. Once the material detection job is complete, it sends the detected material to the g-code sender. The g-code sender will have the parameterized engraving job and the user is able to start it. Whether this process will be completely automated depends on the difficulty in interfacing the script with the g-code sender.

6.5.1 Scripts

For our system we need to have a way to automate some tasks or do certain specific instructions. Scripts, in computer engineering, is a term for that job and used in many systems and projects. As time moves on, more and more systems are automated and use scripts to run tasks for users. Our system will run some automated features such as the material detection feature and the ability to laser with the image we upload. Others will be done manually, such as having a crank for the Z-axis adjustment if not automated. We can create scripts for tasks we did use repetitively which allows less manual labor.

Machine learning algorithms and libraries will be useful for our systems. We can use machine learning libraries like OpenCV for automatic material detection through the sensors and cameras we own. OpenCV can be used to take in the spectroscopy data and get the spectrum for each material.



```
outIsOpen = inAverageValue < 51.6
outOpenCount = count(outIsOpen)
outClosedCount = count(not outIsOpen)
outText = "Open:" + toString(outOpenCount)
 + " Closed:" + toString(outClosedCount)
```

Allows the user to control the program execution with a set of buttons.

Figure 50: IDE and menu of OpenCV Software.

We can write scripts for error handling as described before. If an error occurs, we can write a script for what the error is, and it will give us the issue that occurred, and we can log in that data for future purposes. Using scripts for errors can help us troubleshoot as well to know what went wrong and where to fix the issues.

Scripts can be used to control and communicate with the laser engraver such as updating the laser engraver's status and error handling. Sending data to the laser engraver for changing settings will be useful and those scripts can be from LaserGRBL and libraries of material database configurations. Some libraries we can use for material detection scripts. Using the material database with scripts, we can use that to calibrate and configure, power, focus, speed, and more laser settings for the material we detect. We can write scripts to integrate into CAD software which can import images or designs to the software where we did engrave like LaserGRBL.

Scripts can be used for many things to make the job easier by automation with the laser engraver. Some other options are remote controlling, energy consumption optimization, analysis of data, scheduling, queueing, and more. Creating scripts for our system can be beneficial for generating outputs and for control and use that as an input for our next step and so on.

6.5.2 Heuristics

For computer engineering we need to think about our problem and solve it in the most efficient way possible while trying to save money, time, and energy. Heuristics is important for solving problems in designing the computer systems and communication for our project and implementing it can have many benefits. We must take the complex constraints and break them down to solve them in a better way.

Some problems are too massive to tackle at once and breaking them down will help us as said before. This method of heuristics is called Divide and Conquer, and it means taking the huge problem and splitting it into smaller problems to be solved easier and making it simpler to solve the bigger problem.

One example is communication between all the devices. In this case it seems almost impossible to think how all the systems will interact with one another altogether. Using heuristics, we can break this problem down into subsections and see a clearer picture. We can question each part of the system and what will be used to control and communicate with each other. The laser will be configured using LaserGRBL, before that, the ToF sensor will be used to adjust the material's distance from the laser and that will be programmed with a custom PCB and other sensors. Those in turn will allow the laser to continue when the measurement is correct. LaserGRBL's built in database for material engraving configurations for a laser can be used and modified for our material's descriptions and testing as well.

There are multiple heuristics used and we can implement them in our systems which help relieve the stress of thinking problems from a bigger picture. Other examples of heuristics are when we include ideas to solve a solution and there are multiple solutions we choose the simplest one (Occam's Razor). Another is optimizing systems and code earlier when needed which can cause issues when complete. Sometimes it is not needed as well and can be a waste of resources and time. One we can implement is modularity which means creating systems from independent components which is what some of our materials are. Together they create a system altogether from separate modules such as the sensors, cameras, PCBs, and more.

We can look at relationships in our systems to create decisions. While our systems work in a way for users as turning on, engraving, scanning materials, sending data, and more, we break this down into smaller reasons of why it is this way to solve most situations for our project. Computer systems work in binary as we know and 0's and 1's for yes and no, true, and false, and others. Using this logic, we can set our systems to work in this way. An example is setting our system to scan for an item using spectroscopy and if there is no material then it will let us know. Using simple machine learning algorithms can help figure out issues that may be in the system.

6.5.2.1 Occam's Razor Implementation

As described earlier we can implement Occam's Razor for many of our decisions. Occam's Razor being the easiest solution, we can implement this into many of our ideas and systems such as the spectroscopy system. Our system was going to have a custom PCB for our camera module (OV7670) during testing and prototyping the camera was having issues working and when trying different methods. If we decide to take a step back and think about other solutions, we can make a simpler choice. Which is what we decided, a webcam instead or a different camera that is less convoluted to set up.

6.5.2.2 Modularity

As described before, modularity can be applied in our designs by creating systems from independent components. Since our system involves multiple disciplines which involve mechanical, photonics, and computer components to be used, we must be able to connect all these components together. We included the motors, base, and frame for the mechanical side and that will hold the system up and move the laser with motors and have our spectroscopy system set up for the photonics side. The spectroscopy system will send data to the computer side to our hardware and software as outputs and use that data as inputs for other procedures such as what material is being engraved and the image we did engrave on the material. Combined we did create our material detection laser engraver.

6.5.2.3 You Aren't Gonna Need It (YAGNI)

We want to make sure we stick to our objectives and goals as closely as possible without drifting away from the main idea. With this in mind, we must make sure to not go wild with our designs and make sure they are simple and straightforward which is what YAGNI represents. We want to make sure we do not add plenty of functions into our system unless necessary. Before we add any neat features, we must stick with the base which is a laser engraver that can detect what material is being engraved and use that to change the settings of the laser for each material's configuration. As we went through testing, we discussed that we might use a z-axis configuration due to how some materials' height can differ and affect the distance between the laser and material. If we do not need a z-axis configuration, we can make sure all the materials are the same thickness or height. This is fine due to us needing this idea since it can affect the laser when it is engraving if it is too close to the material which is an important function.

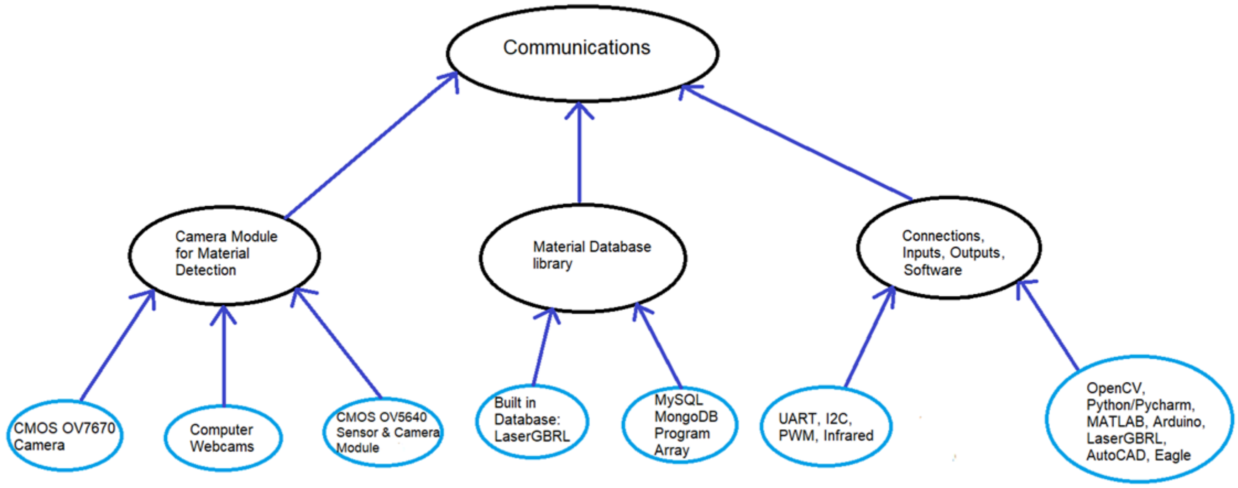


Figure 51: Heuristics example for our system.

6.5.3 Control Loops

Including control loops into our system will be beneficial for connections of all the systems and making things run. For our system we would use control loops to automate certain processes. We can use multiple things to create control loops, and this can help our system from doing plenty of manual things when the automation is complete. We can use sensors as a component of one of our control loops which can be camera sensors like the OV5640. We also included a sensor for our spectroscopy system to detect light and send the image and data to the computer for us to collect and analyze. The VL6180 ToF Distance Sensor will send us data of lux and range to the serial monitor and we can use that information to make sure the distance between the laser and object is fine or to adjust the distance of the Z-axis. We can automate these features to make it easier for users.

Another way of using control loops is a controller algorithm. We can create an algorithm that is used in our software and send it to our sensors. These algorithms can be used to improve our system and adjust it as needed. We can set an algorithm to our VL6180 ToF Distance Sensor and use it to adjust light sensor settings for better lux or range readings.

An output device can be used as a component of a control loop and that can be used to change software parameters such as our information for each laser configuration for each material. Using the spectroscopy system, the scanned material information will send us that information and we adjust it in our database of information. Using digital systems information, we can create control loops and that can help us for adjustments and automation.

7 Integration and Testing Plan

The subsequent sections aim to illustrate the present apparatus and components necessary for conducting tests. This encompasses, though is not restricted to, evaluations in spectroscopy, laser testing, material analysis for engraving, hardware testing, software testing, as well as the facilities employed in testing and prototyping for this project. This segment will be further elaborated upon during senior design to showcase our advancements in operationalizing the engraving apparatus and delineate the hurdles encountered in this process.

7.1 Integration

Our project aims to integrate a spectroscopy system within a working laser engraver in a seamless fashion to add functionality to a pre-existing technology. The design of our project is modified to include the necessary components to make a spectrometer and the code to include a diagnostic process to identify the material being engraved. Integrating these parts within one independently operating device is tricky and should be given care to ensure each part serves its purpose correctly. In this section we did go over the steps to integrate the spectroscopy system, laser system, PCB, and gantry and carriage within the device.

7.1.1 Spectroscopy System Integration

The spectroscopy system's key components have been previously outlined in sections 6.3 and 3.9. Comprising an LED, fiber optic cable, slit, diffraction grating, and webcam, this system will incorporate a discreet standalone body positioned beneath the engraver's floor for concealed operation. This body will house the slit, diffraction grating, and webcam, while the LED and entrance segment of the fiber optic cable will be affixed to the laser module, oriented at a 90-degree angle to each other. The integration of the spectroscopy system will be executed in two distinct phases: firstly, the incorporation of the spectrometer body, followed by the integration of the LED and fiber optic cable components.

For the spectrometer body, 3D printing will be employed to create an enclosure tailored to securely position each component at designated distances and angles. Upon finalizing component specifications and dimensions, a CAD model will be generated to perfectly house each element within the printed structure. These components will then be firmly affixed within the plastic shell using a series of screws, ensuring a secure and stable arrangement.

Given the sensitivity of spectroscopy to extraneous light, precautions will be taken to prevent stray light from compromising the system's performance. Stray light, originating from sources beyond the fiber optic cable such as cracks in the casing or unintended reflections, will be minimized by meticulously sealing the casing using black tape along the seams. This proactive measure aims to prevent any additional light from infiltrating the system, safeguarding the accuracy of the spectrometer's readings.

The spectrometer body functions by dissecting incoming light into its constituent parts, capturing the resulting spectrum as an image. This image will then be transmitted to an external computer for subsequent processing and spectrum extraction. Facilitating this procedure is a USB webcam, which will receive instructions via Python code. Detailed discussion of the software aspects will be provided in subsequent sections of this paper. The webcam will be directly connected to an external computer and seamlessly operated through code specifically designed for the engraving process.

Accurate alignment is crucial in material identification processes to ensure precise measurements and predictions. Calculations for optimal spectrometer distances and angles will be determined once the line spacing is known and diffraction gratings are tested. The LED and fiber optic cable input will be positioned at a 90-degree angle within a 3D printed module alongside the laser system. Integrating the fiber optic cable involves securing ST connector mounts to both the laser and spectrometer body, securing the cable by twisting it onto the connector. Additionally, the LED will fit into a slot with designated wire openings for supplying the necessary voltage.

7.1.2 Laser System Integration

The laser diode module as well as its collimating and focusing optics are very sensitive components. This means we must design the system to be as gentle on these fragile components as possible. Any misalignment of the lenses could result in anything from a reduction in engraving resolution to a catastrophic accident from specular reflections of the high powered laser beam.

Mounting the laser diode will be done with a 3D printed mount designed in Solidworks. The design of this part is outlined in 3.6.1 3D Modeled Mounts. This will enable us to keep the laser module secure using the M3 screws, and the lens mounts are compatible with M4 screws. The rigidity of the PLA used in 3D printing the mound will be sufficient for maintaining the lens alignment, provided the screws are checked regularly with regular maintenance. The alignment of the optical system also relies on the z-axis focusing system, which is outlined in 3.6.5 Z-Height Adjustment.

7.1.3 PCB Integration

Within this project, the inclusion of a PCB plays an incredibly important role in the controlling of the central unit that is being attached to the frame. It will be used to facilitate the communication between the two systems, one that is for the controlling of the z axis, and the other is for the material detection that will communicate to and from. The PCB will be used as a main component, connected to several aspects of the system through the use of pins on the PCB to the regulators. As part of this project, we need to have a custom PCB included into our system, which requires us to have a module that will be responsible for the z axis control. Due to this, our board will need to be a certain distance away from the material during the engraving process, and adjust accordingly with respect to the material that is being used.

The main reason for having the z axis be adjustable is for having the possibility of adjusting to have the exact same spot size across all the materials that are being engraved on. we did have our control module connected to the stepper motors, with its respective regulator as well. Our PCB will not be connected to the CNC shield, unlike the ones being used for the other 2 dimensions, as they do not have to work synchronously. This is due to only being used for the initialization of the engraving process, rather than working throughout.

To further streamline the process, the placement of our boards is essential in creating convenience not just ourselves as creators but the user as well. Ultimately, the placement of our boards will not be directly attached to the laser diode itself. Doing so would unfortunately cause a dilemma in the movement control of our system. One of the largest issues would be the wiring issues, as there are so many moving parts, there is a large likelihood that things will fall out of place. Having our boards placed on the frame rather than on the laser itself will help prevent any incidents with wires being moved by accident. This will help provide a sturdier project overall.

7.1.4 Gantry and Carriage Integration

At the actual core of our project, our inclusion of a gantry system provides the framework necessary for providing a safe and reliable product that will withstand multiple uses. This system will allow us to include stability to provide the utmost precision in our laser engraving. The material we select for the gantry has many deciding factors to it including its weight and durability. we did include all the basic necessities of a gantry such as rails and bearings to provide an accurate, steady motion. Our system will facilitate the ability of moving in two separate directions, the X and Y axis. In addition to this, it will be able to coincide the motion of the Z axis with our PCB being its microcontroller.

The integration process includes the designing and model on software to create our gantry system. Having our 3D representations laid out allow for easier and more direction understanding for the building process. There will be additional testing and calibration stages included into our integration, as this will ensure the possibility of a flawless operation.

7.2 Laser System Testing

This section will describe the extensive testing done with the laser diode module, as well as the testing done on our selected engraving materials. This was done in order to understand all the characteristics of our laser system that will have an impact on the engraving performance of APALES. An important note: during the laser testing, we used two laser diodes: a 450nm 5W and a 405nm 0.5W. We currently plan to implement the 450nm 5W laser diode in the project in order to increase the laser power and get a very dark char to increase contrast between the material and the engraving. We characterized the beam divergence of the more powerful laser, then opted to use the 405nm 0.5W for the material testing phase as a safety precaution. We acted to minimize the risk of exposure to high power laser radiation, and therefore minimize the risk of a devastating accident. We elected to use a 405nm 0.5W because 405nm is very close to 450nm and it is only a one magnitude reduction of the laser. The use of this laser is a proof of concept and is only for safety purposes in the lab.

7.2.1 Laser Diode Testing

In order to get a true understanding of the laser diode we are implementing in our design, we must perform some characterization tests. These tests will enable us to design a two lens collimating and focusing system for the beam in order to achieve the finest resolution in our engraving system.

The first test done was completed in order to understand the beam divergence of the laser diode. As discussed in section 3.4.2.5 Diode Lasers, the beam that is created from the active layer in the double heterostructure diverges much more in the vertical direction than in the horizontal direction because the active layer's height is magnitudes less than its width. Therefore the horizontal beam divergence is minimal, and the vertical beam divergence is marginal.

This test was performed by removing the adjustable lens from the front of the module to expose the laser diode itself. Then we placed the laser diode module in a mount and placed a screen a fixed distance away from the laser, this distance was 45mm from the end of the module to the screen. It is very important to note that this distance does not account for the depth of the laser diode, this depth is ~11mm from the emitting end of the laser diode to the opening; this makes the total distance from the laser diode to the screen ~56mm. Before turning on the laser, we ensured we were equipped with laser safety goggles with OD6 blocking at 450nm. We then turned on the laser diode, and the beam was still slightly visible through our OD6 goggles, a photo of this beam is in Figure 51. A ruler was used on the screen to measure the vertical and horizontal beam width in millimeters. Using simple trigonometry, we found that the beam diverges with a half angle of 30.13° in the vertical direction and 2.05° in the horizontal direction. This is critical information when designing the lens system, and the beam divergence at the extreme angles act as the chief rays to be used in geometric optics formulas. This will enable us to design a 2 lens collimating and focusing system to achieve the maximum resolution in our laser engraving system.

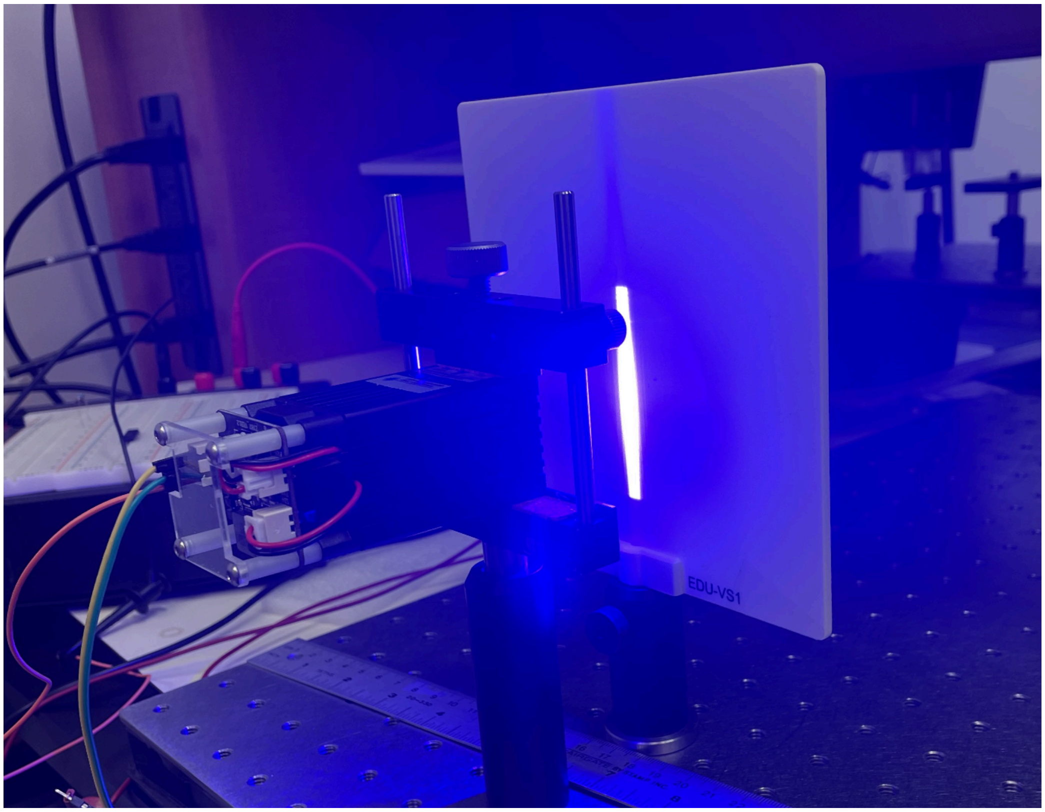


Figure 52: Testing beam divergence of 450nm 5W laser diode

7.2.2 Engraving Material Testing

In efforts of precision and efficiency in our laser engraver project, extensive laser testing unfolded in the selected space of the CREOL Senior Design Lab, a space designed for specific and intricate optical testing and experimentation. Prioritizing safety, our team adhered to the strict safety protocols, all wearing protective gear that included safety goggles to protect our eyes from any possible laser light, as well as the appropriate attire to shield ourselves from potential hazards during the laser testing phase.

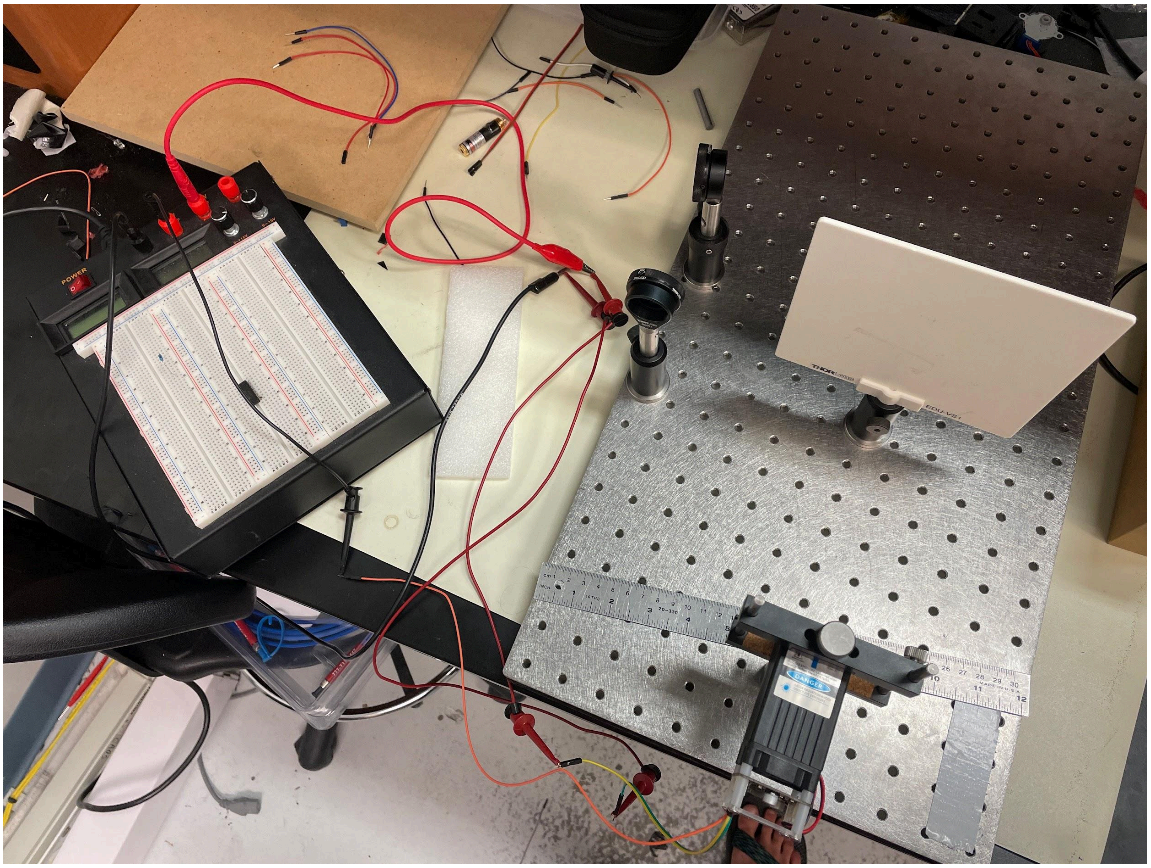


Figure 53: Laser Testing Lab Setup

In our rigorous testing phase, we strived to select and fine-tune the laser engraving parameters and settings by comparing the performance of various lasers, more specifically; the 405nm 0.5W laser, as well as the 450nm 5W laser. The differences amongst these two lasers became very apparent upon our testing and exploration on the various materials mentioned above. The two lasers, specifically the 405nm 0.5W laser, as well as the 450nm 5W laser, were temporarily mounted on a stable rig within the lab. The setup allowed us to precisely and carefully focus the laser beam and direct it onto the various testing materials, ensuring consistent and controlled engraving. The temporary mount setup also ensured swift adjustments, enabling us to experiment with the two lasers at different angles and lengths. This helped us optimize the laser's interaction with the various materials.

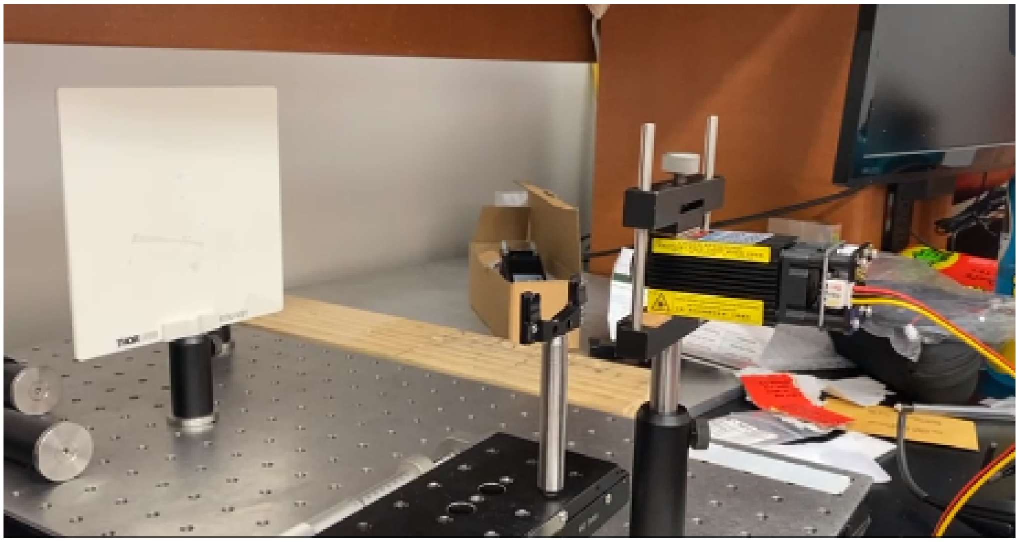


Figure 54: 405nm 0.5W Laser Mount

The 405nm 0.5W laser showed a significantly higher laser engraver power, highlighting the specific ability to burn through the materials more effortlessly than its 450nm 5W laser.

Through the process of testing and experimentation with cardstock paper, cardboard, plywood, as well as genuine leather we all observed distinctive reactions and properties from each material under the influence of different laser selections. The smaller 405nm 0.5W laser proved extremely effective for more precise and delicate laser engraving on materials on the side of cardstock paper and cardboard, preserving all the intricate details in the image with minimal charring and contrast surrounding the engraved area. Similarly it provided swift and precise details on the other materials such as the ply-wood and genuine leather providing crisp engravings.

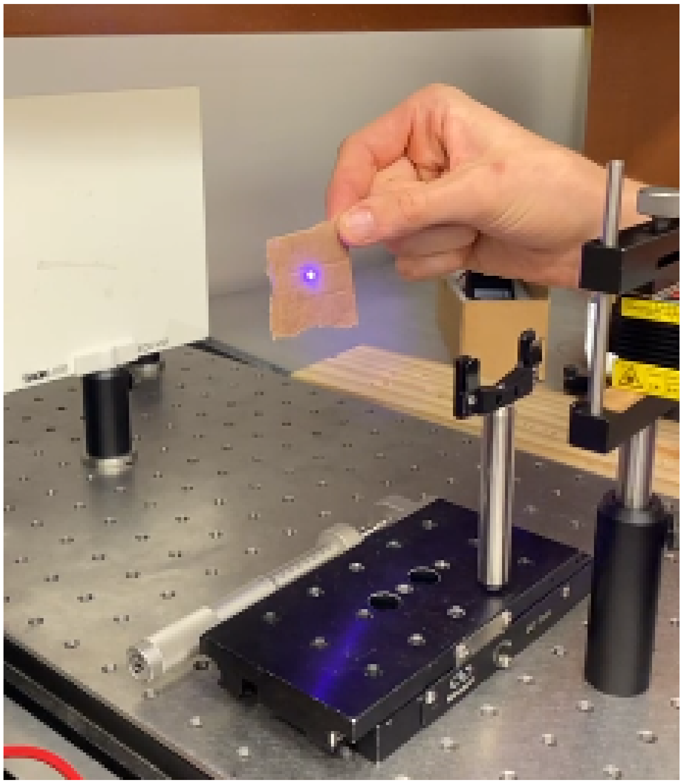


Figure 55: 405nm 0.5W Cardboard Engraving

On the other hand, the 450nm 5W laser, with its obviously higher laser engraving power, excelled in cutting through the tougher, more robust materials i.e: plywood, and genuine leather more effortlessly. While it showcased exceptional efficiency on plywood and genuine leather, achieving somewhat deep and pronounced engravings on the materials, the overarching challenge was to strike a balance to avoid excessive burning, charring and contrast. Leather specifically, striked a noticeable contrast between the two differently powered lasers, with the 450 nm 5W laser outputting quicker engravings.

This thorough testing phase for the various lasers not only highlighted the importance of the laser power in relation to the material interaction, but also played a pivotal role in our decision making process for determining the optimal parameters. In the context of our scale of the laser engraving project, the meticulous evaluation led us to conclude that the 405nm 0.5W laser was the optimal choice, and here's why:

<u>Precision:</u>

First and foremost, precision was a paramount in our project. The 405nm 0.5W laser, with its inherent lower power output, demonstrated a finer degree of control during its engraving. This level of control makes it ideal for our project considering the smaller scale of our laser engraver system. This precision is especially evident when working with materials like cardstock paper and cardboard, where the goal was not to burn through it or cut, but rather delicately engrave.

Efficiency:

Additionally, this 405nm 0.5W laser demonstrated remarkable efficiency producing detailed, high contrast engravings engravings on a smaller-scale. The lower power output was shown to be advantageous in preventing excessive materia burning, charring, as well as contrast on materials, such as leather, preserving the integrity of the service, while choosing the desired depth of engraving.

Safety and Operation:

Another key point was the small ways or offered notable advantages in terms of safety and operation. Given the smaller workspace of the CNC platform and the proximity of the laser to the lens and that of the material the lower power of the laser minimizes the risk of unintentional damage and hazards due to burning. It ensures a safer working environment for intricate details on our laser engraving process.

7.3 Spectroscopy System Testing

In this phase, we did discuss the methods we did use to test the performance of the spectroscopy system. In order to reliably predict the identity of materials before the start of the engraving process, proper testing needs to be done to ensure the spectrometer is calibrated and set up properly.

7.3.1 Alignment

The first phase of the testing process begins with alignment. Once all of the components within the spectroscopy system are collected, the next step is determining the correct alignment amongst all of the parts. Initial testing will be done with angles and distances calculated using the diffraction grating equation and then adjustments will be done by hand afterwards for any minor corrections. The overall goal of alignment within the body of the spectrometer is to get one mode of the spectrum to fall onto the sensor of the camera. The camera will be operational during alignment to see a preview of the camera output while determining the proper placement to get the best spectrum preview.

The initial phase of testing for the spectrometer body involves establishing optimal positions and angles for the slit, diffraction grating, and camera components. Once the best alignment is determined, these positions and angles will be recorded, and preliminary testing will commence using a temporary enclosure made from disposable materials like cardboard. Notably, the fiber optic cable will not be integrated into this preliminary testing but will be incorporated later in the process. For the initial tests, a slit will be fashioned from plastic, affixed to an aperture on the temporary spectrometer body. The diffraction grating and camera will be firmly secured using adhesive to prevent any shifts. A mix of light sources, including an LED flashlight, a color-changing LED, and a desk lamp, will be utilized to gauge changes in spectrum output.

Analysis of the webcam's image and the spectrum generated via Python code will guide subsequent adjustments to the slit size and code parameters. The Python code will include a segment that extracts a 1D slice from the image at specific coordinates. we did iteratively experiment with different combinations of slices and test averaging multiple rows of pixels. Furthermore, various noise reduction techniques will be explored to refine and smoothen the spectrum.

The subsequent phase of testing will focus on the LED and fiber optic cable. By systematically testing different angles for the LED and fiber, as well as varying LED power levels, our aim is to identify the optimal configuration for the spectrometer. The primary objective here is to maximize the amount of light entering the fiber, thereby enhancing the signal for analysis. Testing the fiber will involve utilizing multiple fibers with varying core radii to compare results. Larger core radii collect more light, although they can be challenging to find with the appropriate ST connector ends.

7.3.2 Calibration

An important step to making an accurate spectrometer is to set wavelength values to the indices in the array sliced from the webcam image. Since the diffraction grating splits the incoming light into component wavelengths and reflects them at an angle according to the incoming wavelength, the light hitting the webcam will already be sorted by wavelength and by position meaning the position on the webcam corresponds to the wavelength of light hitting the pixel. While not entirely necessary, it can be useful to mark each pixel as a certain wavelength such that the intensity seen by a given pixel corresponds to the prevalence of a certain wavelength of light. The way we did calibrate the spectrometer is to use a prebuilt spectrometer and a light source to find its peaks (ideally a source with multiple peaks). we did record the peaks and then use our spectrometer to analyze the spectrum of the light source. The location of the peaks on the sensor should correspond to the wavelength of the peaks. Then assuming the spectrum from our system has a linear relationship to the real spectrum we can calculate the wavelength of each pixel on our sensor.

7.3.3 First Demo

Within the first demo, completed on Thursday, October 12th, we demonstrated the use of a spectrometer for material identification as a proof-of-concept. Within this demo, an Ocean Optics spectrometer along with a white light generator were used to capture the reflection spectrum from wood, leather, and fabric. The spectrometer used a fiber optic cable which we mounted roughly three inches above the surface of the table at a 45 degree angle. The white light generator used a thick bundle of fiber optic cables which were also mounted about three inches above the table at a 90 degree angle with respect to the spectrometer fiber. Each material was placed between the white light output fiber and the spectrometer fiber where white light illuminated the surface and the spectrometer collected the reflected light to be analyzed. The spectral outputs were shown to be visually very different and can be seen as a proof of concept that we can differentiate different materials by looking at their spectral signature.

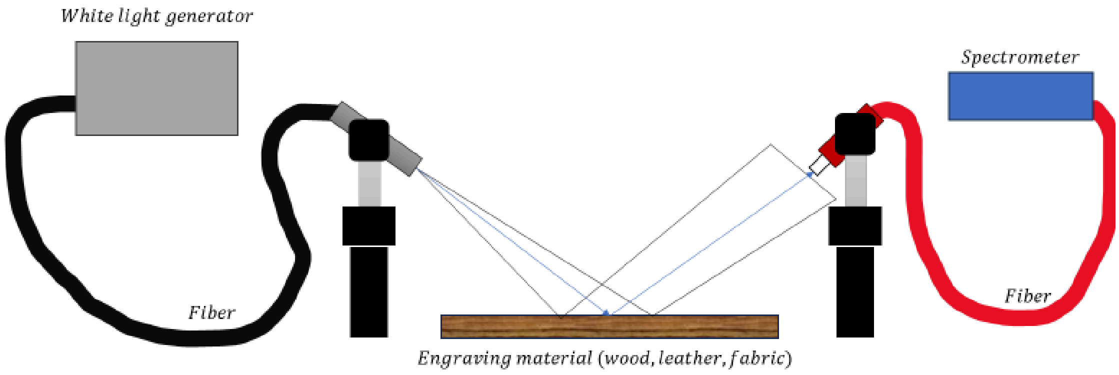


Figure 56: Schematic of Initial Demo

Shown above in Figure 55 is the schematic of the initial demo. The output shown for wood, leather, and fabric each had different spectrums varying in peaks and intensity. Wood and leather had a similar shape but had drastically different levels of reflected light. By showing that the spectrums are noticeably different, it proved that materials can be differentiated by using a 1D array created by extracting the reflection’s spectrum.

Moving forward, we learned that assuming our spectrometer is accurate enough, the ability to differentiate these three materials using a spectrometer is feasible.

We also learned that using an optical fiber as the method for light collection is very convenient and should be incorporated into our design. Additionally, the light source used should be fairly bright as the materials we used absorb/scatter lots of light. This design will be incorporated into the first prototype mounting the light source and collection fiber with a 90 degree angle separation.

7.3.4 Final Demo

Upon the time of this entry, the final demo (for CREOL) has not been completed as of yet. Nonetheless, for the final demo, we plan on using the same principles from the initial demo but from building our own spectrometer. In the initial demo, we used a pre-built Ocean Optics spectrometer to show that with high-end equipment, materials can be identified by their spectral signature. In this demo, we did build a basic spectrometer using a plastic housing, a CD diffraction grating (to be replaced by an actual diffraction grating once arrived), and a USB webcam. The setup of our final demo is shown below.

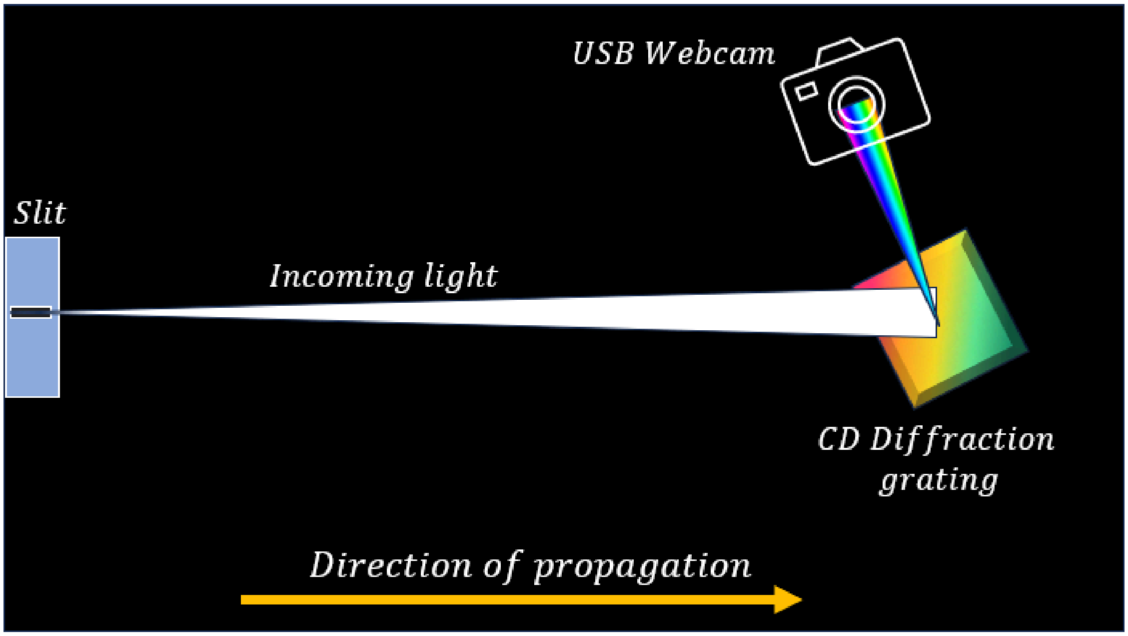
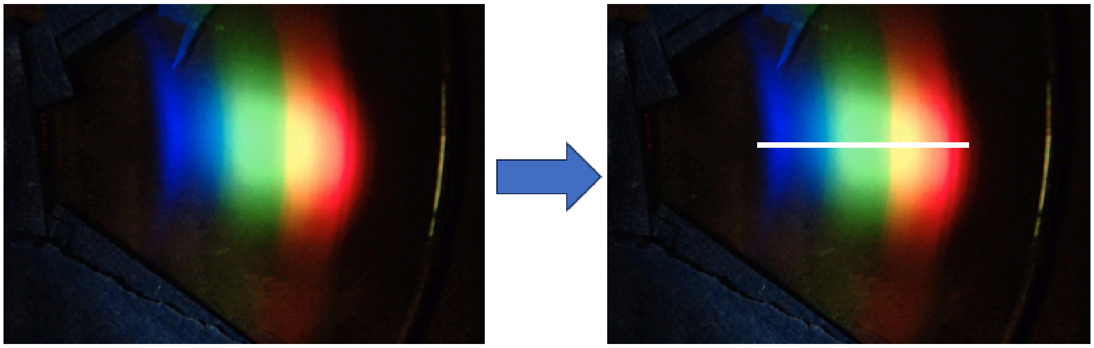
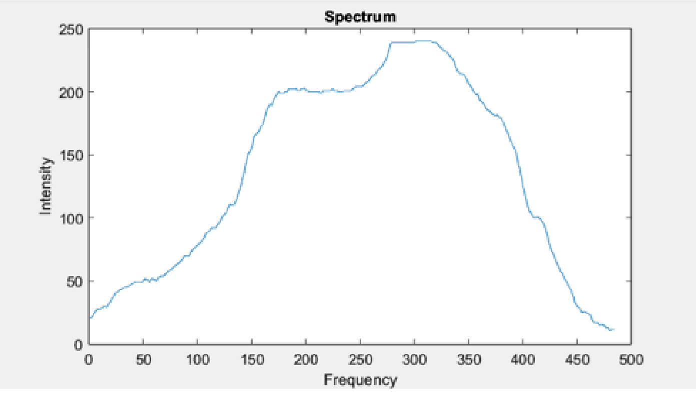


Figure 57: Setup of final demo

As shown above, light will enter into the body of the spectrometer through a slit that will be covered with a piece of tissue paper to act as a diffuser. The incoming light will pass through the slit and hit the diffraction grating where the first mode of the spectrum will be captured by the webcam. The webcam will capture an image and will be read by a MATLAB code where a slice will be taken and its spectrum plotted. This procedure is detailed below.



Captured image *1D slice taken*



Plot of 1D slice as spectrum

Figure 58: Steps to plot spectrum using webcam image of diffraction grating

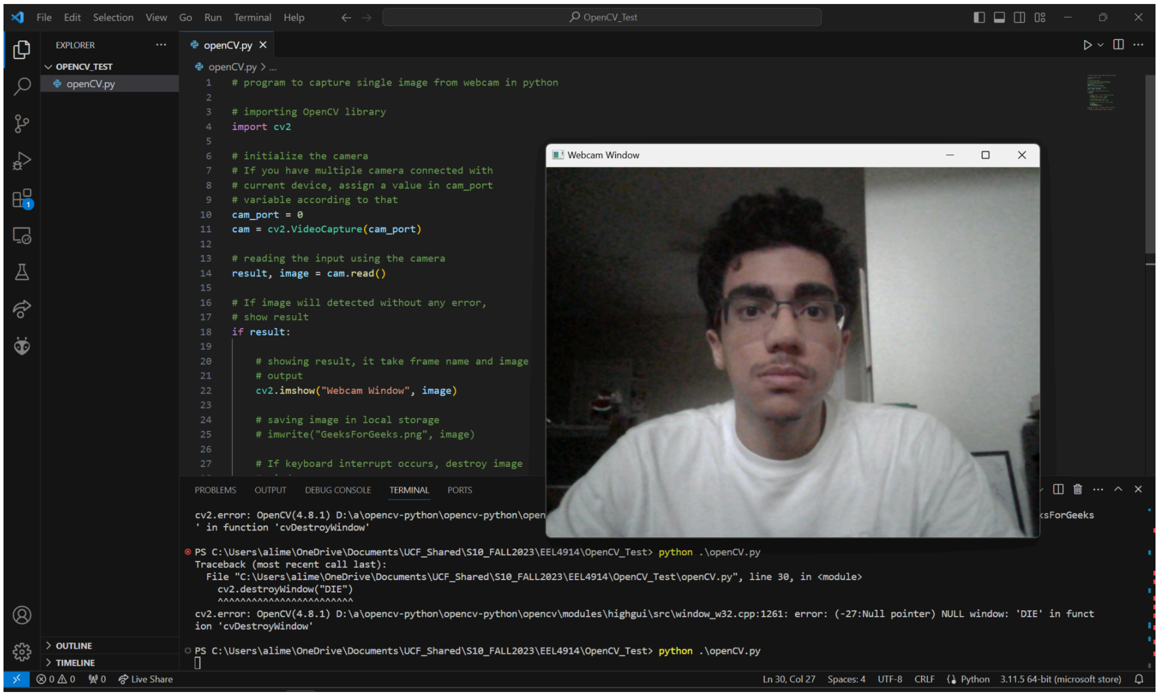
Shown above is an actual image taken using a simple setup we created at home using a CD as a diffraction grating. The setup was created using a cardboard slit and each component adhered to a desk with the room lights out to prevent background noise. In the final demo we did use a very similar setup but in an enclosure to block out background noise and to keep each component stationary. From some basic at home testing, the CD is suitable as a diffraction grating but is very sensitive due to the curving of the lines. Once our real diffraction grating arrives, we did do further testing to analyze the change in performance.

7.4 Webcam Software Testing

We'll be using Python with the OpenCV package to get the data from the webcam and perform the necessary image processing. As mentioned in section 3.10.12, OpenCV is a Python package used for computer vision algorithms. It also supports the ability to pull footage and take images from the webcam directly in the Python script. While doing some research on the Python package, I (Aly) did some rudimentary testing on the software using my laptop with an integrated webcam.

I used a rather simple example to get an image of myself to be captured and displayed directly in the Python script. I already had Python 3 installed on my Windows system. I used the pip install utility to get the open-cv package. I looked into the function calls from the cv2 module and prepared a script to initialize the webcam and take a snapshot. If the photo is successfully taken, it's displayed in a new window and saved to the working directory.

After making sure the library was working properly with my webcam, I tested the image conversion into an nd array. Similar to the cam.read() function, there are existing functions in the cv2 module that automatically convert the image (MatLike) object into an nd array. The function parameter used in the conversion 'COLOR_BGR2RGB' results in an RGB value for each pixel. OpenCV uses BGR by default for the image objects so the conversion makes sure the nd array reads it as RGB instead. This will be important later when looking at the image of the diffracted spectrum.



```python
# program to capture single image from webcam in python

# importing OpenCV library
import cv2

# initialize the camera
# If you have multiple camera connected with
# current device, assign a value in cam_port
# variable according to that
cam_port = 0
cam = cv2.VideoCapture(cam_port)

# reading the input using the camera
result, image = cam.read()

# If image will detected without any error,
# show result
if result:

    # showing result, it take frame name and image
    # output
    cv2.imshow("Webcam Window", image)

    # saving image in local storage
    # imwrite("GeeksForGeeks.png", image)

    # If keyboard interrupt occurs, destroy image
```

```
cv2.error: OpenCV(4.8.1) D:\a\opencv-python\opencv-python\open                                                  sForGeeks
' in function 'cvDestroyWindow'

PS C:\Users\alime\OneDrive\Documents\UCF_Shared\S10_FALL2023\EEL4914\OpenCV_Test> python .\openCV.py
Traceback (most recent call last):
  File "C:\Users\alime\OneDrive\Documents\UCF_Shared\S10_FALL2023\EEL4914\OpenCV_Test\openCV.py", line 30, in <module>
    cv2.destroyWindow("DIE")
    ^^^^^^^^^^^^^^^^^^^^^^^^
cv2.error: OpenCV(4.8.1) D:\a\opencv-python\opencv-python\opencv\modules\highgui\src\window_w32.cpp:1261: error: (-27:Null pointer) NULL window: 'DIE' in funct
ion 'cvDestroyWindow'

PS C:\Users\alime\OneDrive\Documents\UCF_Shared\S10_FALL2023\EEL4914\OpenCV_Test> python .\openCV.py
```

Figure 59: Testing OpenCV capturing webcam footage

7.5 Camera Module Testing

For our camera module, we plan to use the HiLetgo OV7670 CMOS Camera Module. This camera module was going to be used to capture an image of the material we did be engraving and use that image to take the data for material detection. Some of this is explained in section 6.1.1, in more detail here due to prototyping and testing. As mentioned in 6.1.1 that data outputted by the camera onto our computer will be used as input data for another process.

During the testing procedure and prototyping phase, we used 2 ways to test these camera modules. One way was installing a software application onto our Arduino IDE called ArduImageCapture 1.1. ArduImageCapture is a plug-in software we add onto our Arduino IDE. It is added onto our Arduino tools folder and This software uses the COM connected to the Arduino and camera module and then we can tweak the option of the image. We can change the baud rate of what the image capture will be as it sends the data. The default baud rate is set as 1000000 or 1Mbit/sec for the 320x240 resolution of the image. To test the camera module using the Arduino IDE and ArduImageCapture 1.1, we must wire the camera with a breadboard and Arduino Uno. we did need 2, 10k ohm resistors, a 1k ohm resistor and a 680-ohm resistor. We wire every port from the camera module except HREF port.

Now that all the wiring is completed, we plug the Arduino Uno into the computer and run the code. Some of the code to test the camera module must be modified to be able to send the image data and files through a USB cable. There are 3 different modes in the code for each UART example. we did use EXAMPLE 3 since that sends images through USB cable which is what we are testing. We test ArduImageCapture 1.1 just running the tool without the Arduino plugged in and we see a red screen which means it works. Now we give power to the camera and Arduino and then when we run the tool again, we should see a green screen. Once that is done, we did plug in the digital and analog pins and run the tool again to get an image sent over for us using the baud rate.
When running the ArduImageCapture 1.1 tool, we were able to get it running and show the red screen. Once it was time to power the system the green screen never appeared on the ArduImageCapture tool. The camera was not able to send an image to the tool therefore we were not able to get the full image to run either. Wiring was not an issue, and neither was code or power.

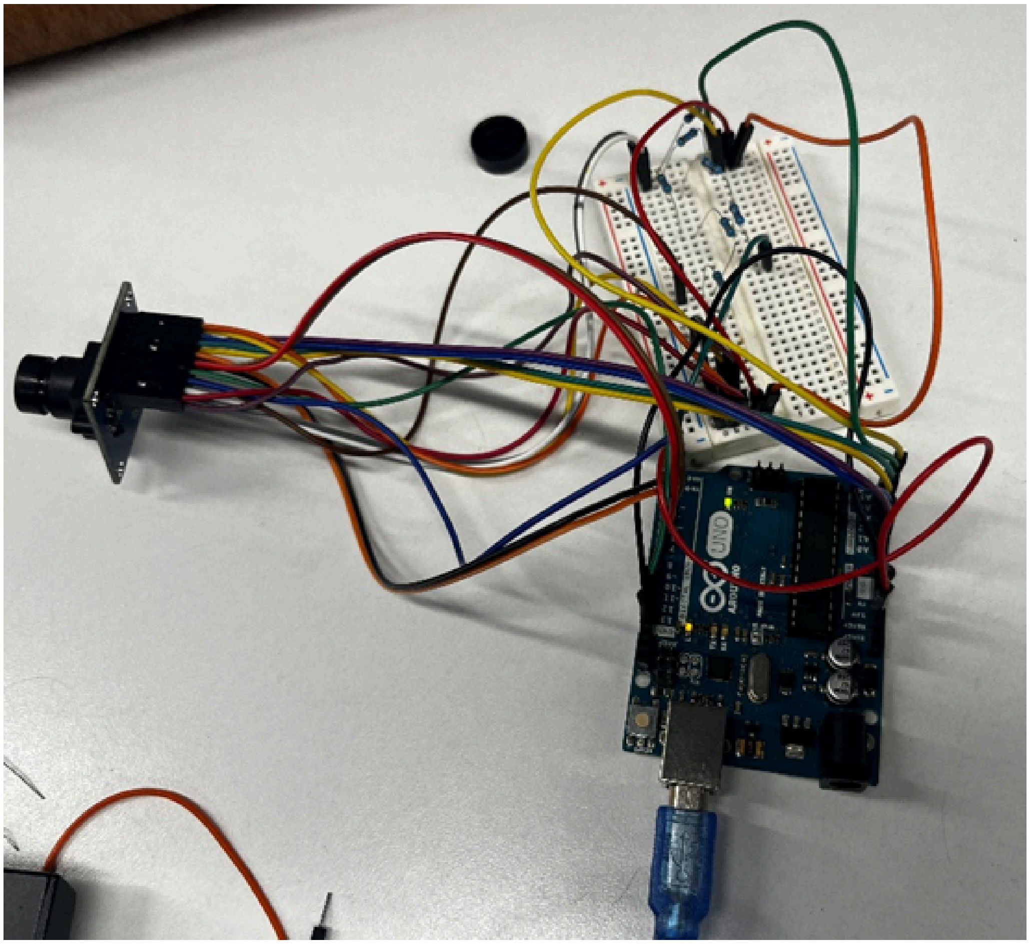


Figure 60: Image of connections between OV7670 Camera, Breadboard, and Arduino Uno for testing. Test 1.

We tried another method which involves another circuit schematic we used that involves all the pins used. This method uses all the pins of the OV7670 camera connected to the Arduino Uno and using the schematic design here with 2, 4.7k ohm resistors and 2, 10k ohm resistors we connect this into the computer. Instead of using ArduImageCapture 1.1 for this test, we use CMD and Java.

We install Java software that allows image capture to work with the camera and send image files over to our computer. The file that uses the OV7670 camera connection is the ‘arducamp.rar’ file we extract to get the other files that are needed. We move some of those files into our program files folder and then we run the code on the Arduino IDE for our camera to work. One other file we need is a file called ‘comm’ for our Java folder which is used to have the communication between the hardware and software. Now we open the CMD in our computer and run the file using the command ‘java code.SimpleRead’. That should let the camera take a picture and send it into our program folder and store the images there as well. When running the command, we got an error message saying, ‘unable to find SimpleRead’. Which was a problem. Wires were checked and power connections to make sure enough was going through without causing a short circuit.

With the OV7670 camera module being tested two ways and different schematics still not being able to work, we discussed and thought of a different solution (as described before in 6.1.1). We decided to use a different camera, maybe a webcam to take a picture of our material for the material scan. This solution also decided that we can use the custom PCB we are designing for the sensors of our project rather than the OV7670 camera module, material scanning, and material database. This solves the problem that can cause more issues that we must think about such as how we can take that image that the computer gives us and input the data of the image as an array to use material scanning. Doing that automatically and making sure we use the specific image we just captured as well. Sounds more complicated when trying to think how it would work and the connections between everything and if we decide to automate this process. With this pinout having multiple connections it made it a little harder to keep and connect all the pins together. This makes the hardware interface more complicated. Using this camera module makes it more complicated than using a webcam with a single USB connector and existing software drivers on windows.

We can use another camera module as well that involves less wiring and that is simpler. We can try to test and use the BUBCOS 5megapixel USB Camera Module CMOS OV5640 Sensor instead which involves less step up and works well. This Camera module can be used for Windows, Android, Linux, Laptops, and other desktop computers and it is a very useful camera that can reach good resolutions. The OV5640 Sensor can do 2592x1944 at 15fps, 1080p at 30fps, and 640x480 at 90fps with clear images. When existing materials exist that can be used than setting up a camera with less resolution and more steps to use as inputs for other procedures.

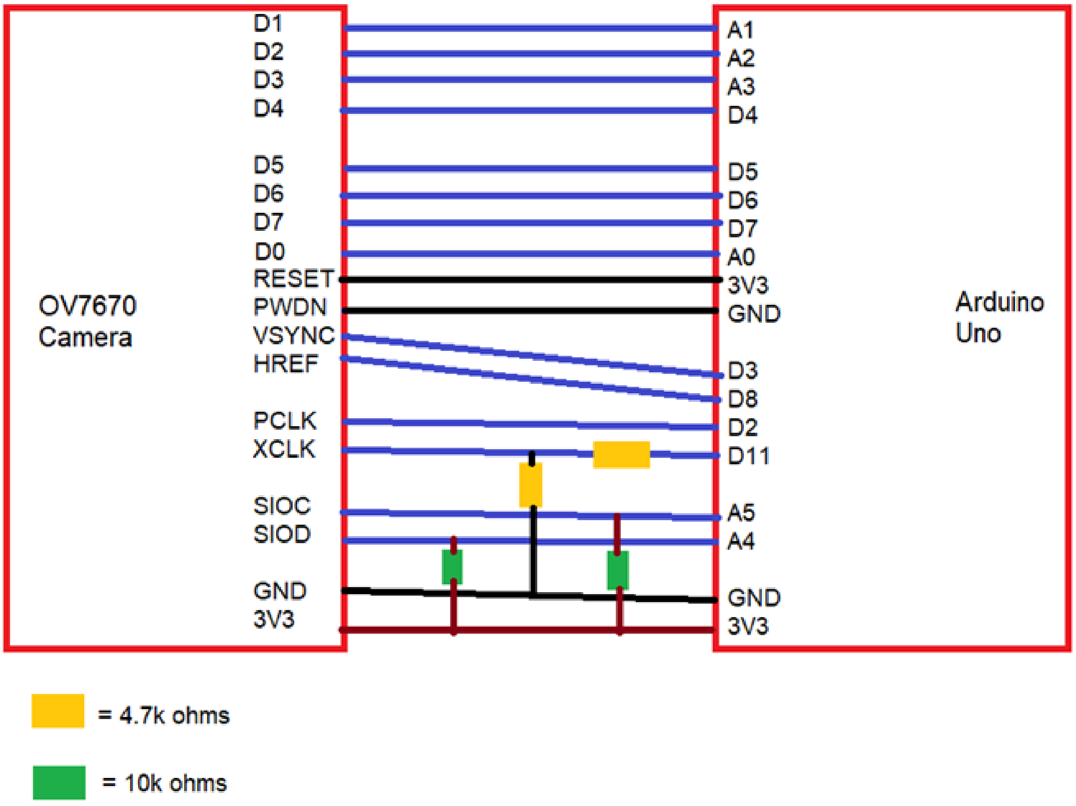


Figure 61: Schematic for connections between OV7670 Camera and Arduino Uno

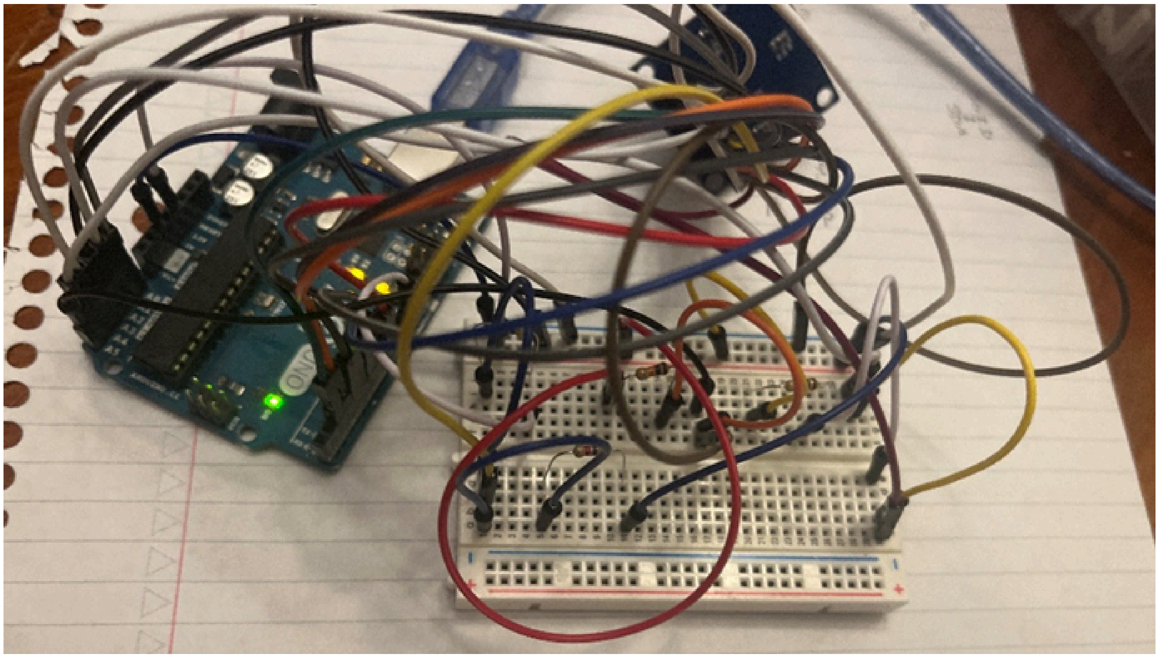


Figure 62: Image of connections between OV7670 Camera, Breadboard, and Arduino Uno for testing. Test 2.

7.5.1 OV5640 Sensor and Camera Testing

Since we were using a web camera for demoing, we were going to use an OV7670 Camera. Due to the OV7670 having issues when testing we had to discuss another camera module to use. We came to the conclusion of using the OV5640 Sensor and Camera module. The OV5640 is used for cameras in laptops, computers, and android devices. As mentioned before in other sections, this camera is useful for many reasons and used for devices. The resolution for these cameras are high with good frames per second (mentioned in section 7.5: 2592x1944 at 15fps, 1080p at 30fps, and 640x480 at 90fps). The camera set up for testing is simple as well using a USB2.0 wire and connecting that with the computer to show us what is being shown on the lens. The issue with this camera is that it can show clear images and the camera always is trying to autofocus even when not necessary. With this being an issue, we can try to modify the camera and program it to try and not autofocus every single moment possible.

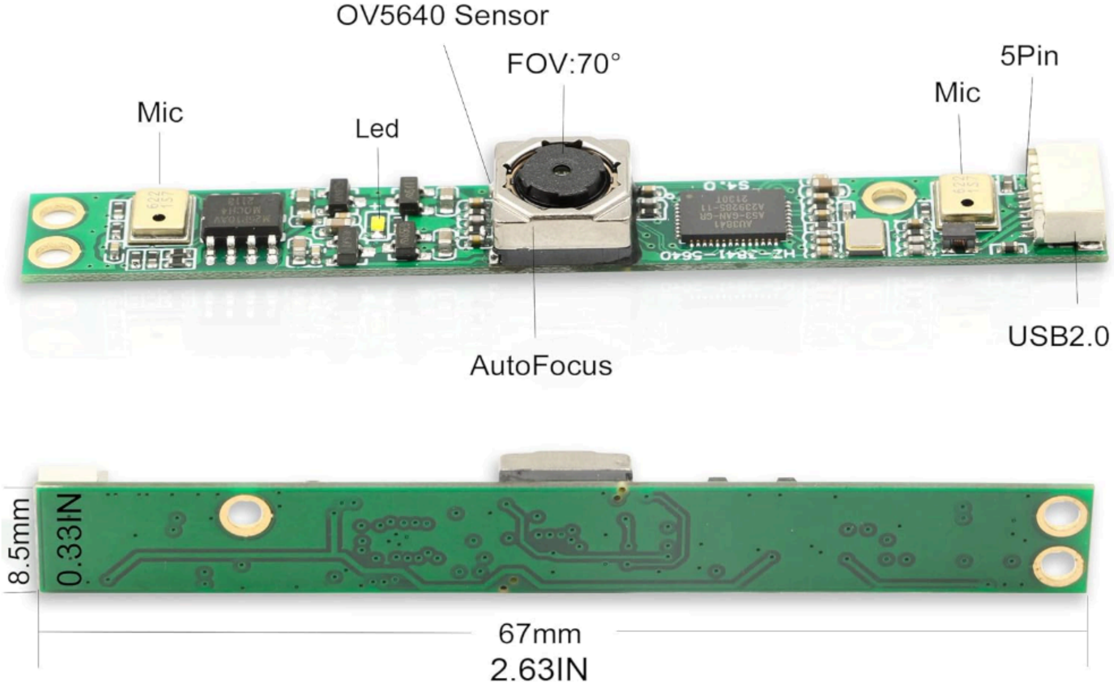


Figure 63: OV5640 Sensor and Camera Module System.

7.6 Distance Sensor Testing

When discussing the laser module and system, we had to think about if the laser is too close or far from the material to engrave. If an item is thick, then it can be close to the laser module. We need a system that can move the Z-axis bed to make sure the material and laser have the right distance to the laser. For this we decided to use a sensor and a buzzer. For thoughts on the sensor the option is a distance sensor. We can use an ultrasonic sensor or something better such as a ToF (Time of Flight) sensor. This sensor uses a laser to detect the distance between the laser and object. The sensor can measure about 150mm to 200mm and can be more. This sensor is more accurate to use than the ultrasonic due to bouncing waves to measure while this is just a laser. With this sensor we can use it to detect if the material is too close and when we move it to the right distance, a buzzer can detect the right distance to start the engraving process.

Figure 1. VL6180 block diagram

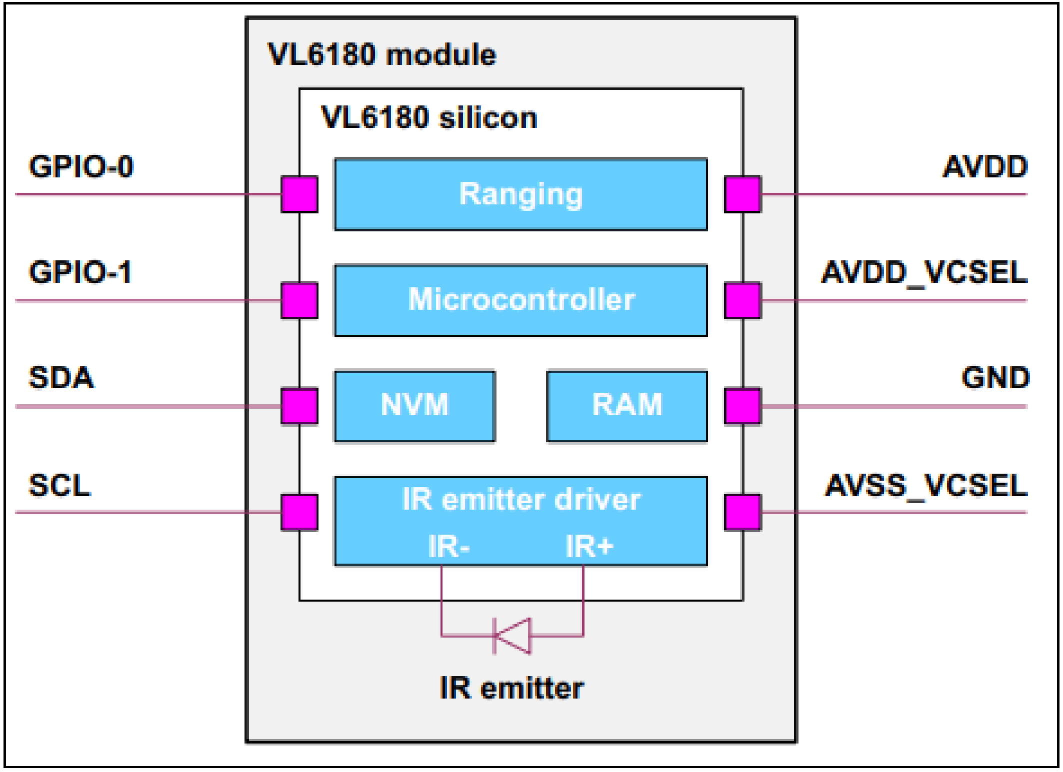


Figure 64: VL6180 Block Diagram from datasheet.

We chose the Adafruit VL6180X as our distance sensor. Wiring the Adafruit VL6180X to the breadboard for testing and we must make sure it can measure as well. To measure it, we can either use I2C to send the measurement data back onto our output screen on the Arduino IDE since this ToF sensor is compatible with Arduino or we can use an LCD screen to output the distance.

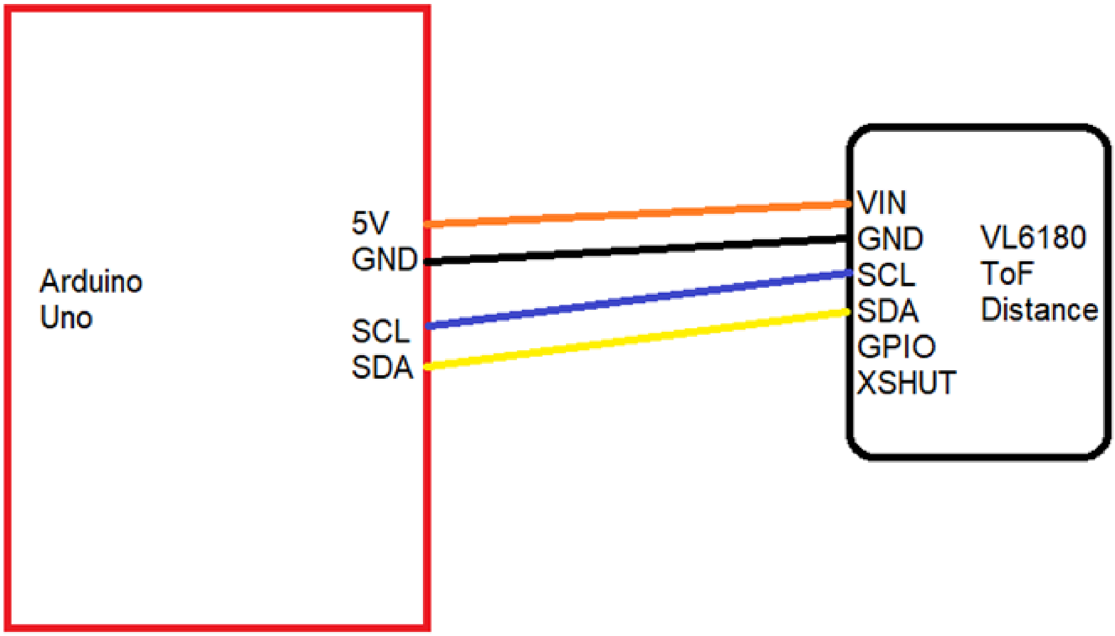


Figure 65: Schematic design of connections for VL6180 ToF Distance Sensor and Arduino Uno.

For testing we just connect VIN, GND, SCL, SDA to the corresponding Arduino Uno pins. VIN is the power pin, and the chip uses 2.8 VDC. Since our Arduino uses 3.3V or 5V we would need a voltage regulator, but the neat thing is that the chip has a built-in voltage regulator to convert the 3.3V-5V. GND is the ground voltage and the other two pins, SCL and SDA are I2C logic pins. SCL is an I2C clock pin and SDA is an I2C data pin, and these will be connected to the I2C clock line and I2C data line respectively. The other two pins that will not be used in the testing and might be used later are control pins. GPIO pin is used to late the sensor to let it know if the data is ready and the XSHUT/SHDN pin is a shutdown pin. The shutdown pin is set as pulled high and if we want to make the sensor shutdown, it must be pulled low.

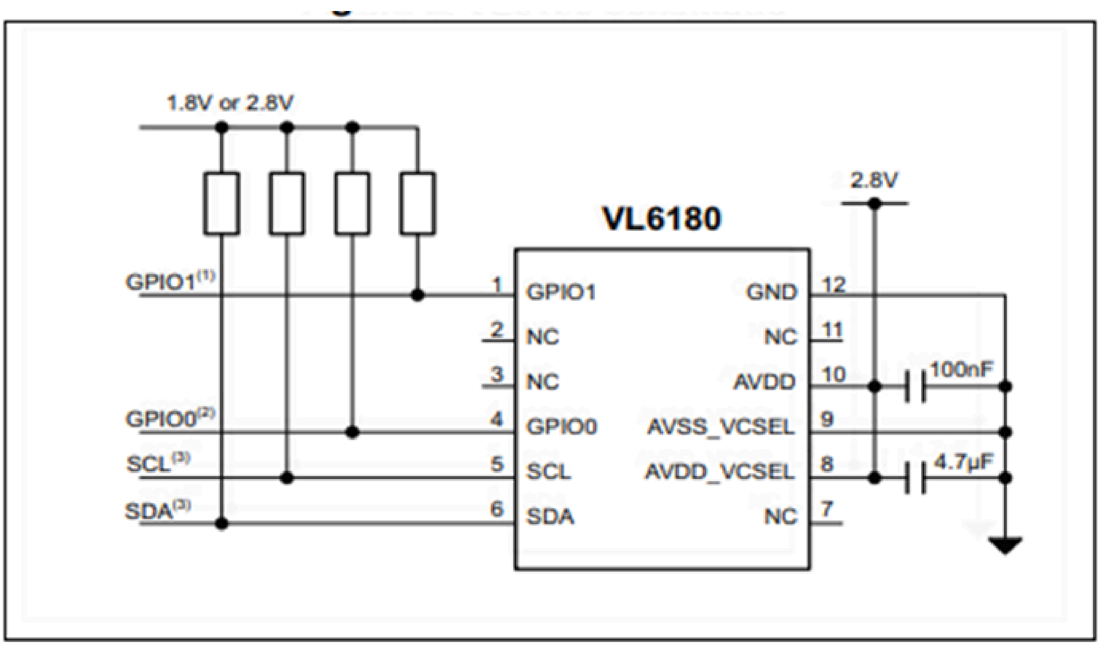


Figure 66: VL6180 Schematic Diagram from datasheet.

Once that is done, we give the system power by plugging it into the computer via USB. We know when the sensor has power when we see the area of the VL6180 has a green light in the ‘on’ area. Now we download the Adafruit VL6180 ToF Distance library built into the Arduino libraries that gives us all the necessary libraries for the sensor to work on the Arduino IDE and connect.

Now we make sure the right COM port is used and we upload the code. Once compiled and uploaded we open the serial monitor where the output of the data from the sensor will be. We make sure to change the baud rate to the correct rate which is 115,200 baud and we get an output of the sensor on our monitor. We get data of Lux and range. Lux is the light reading data and range is the distance data of the object. We can change the lux gain to be adjusted for low and high levels of light. Low light will need more gain and vice versa. Using an object, finger, or anything to test if we get range data from the laser touching anything onto the serial monitor is important and using my finger on the laser gave me data instantly of each moment and output onto the monitor. When testing data, we can get up to 206mm of distance from an object to be detected which is plenty for the material and laser distance.

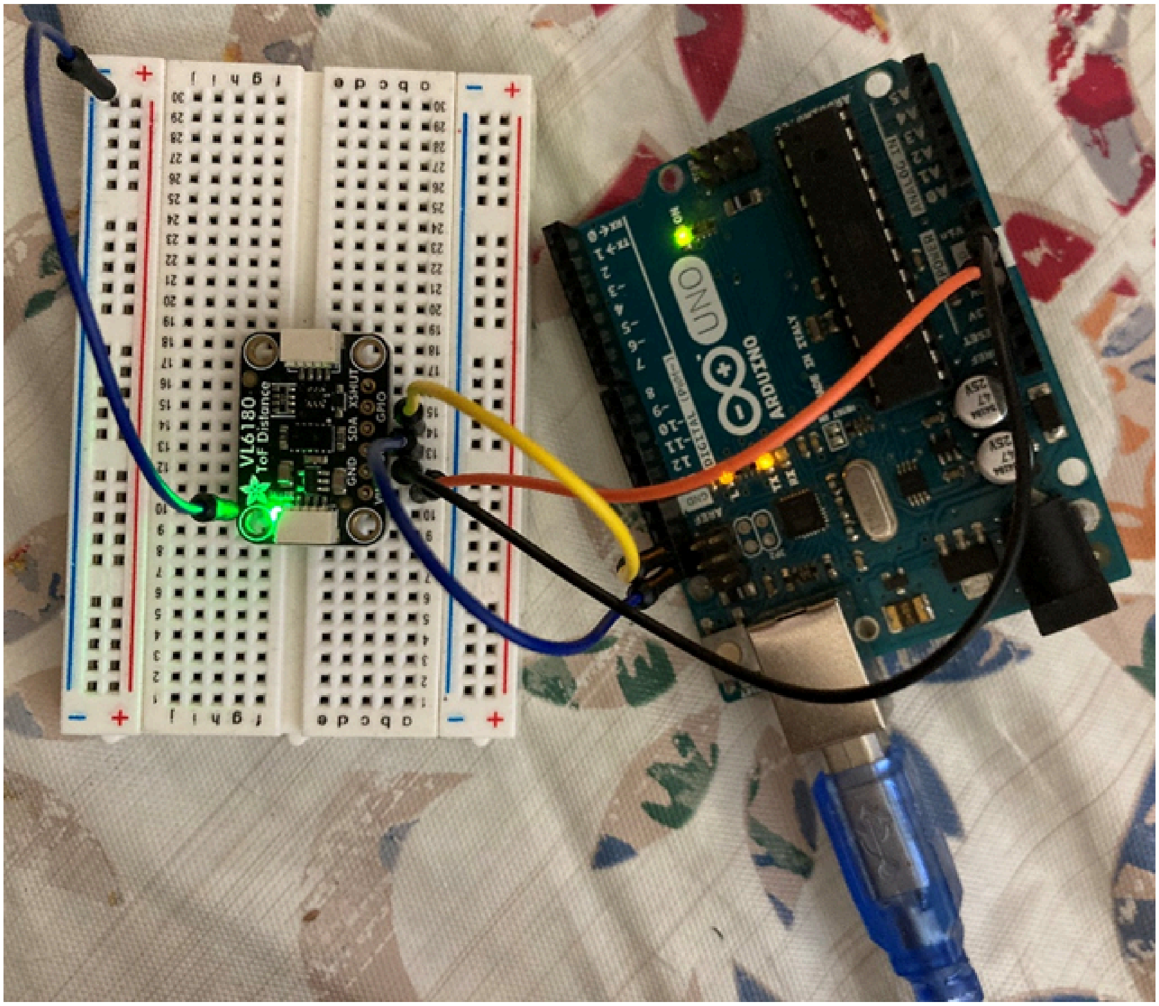
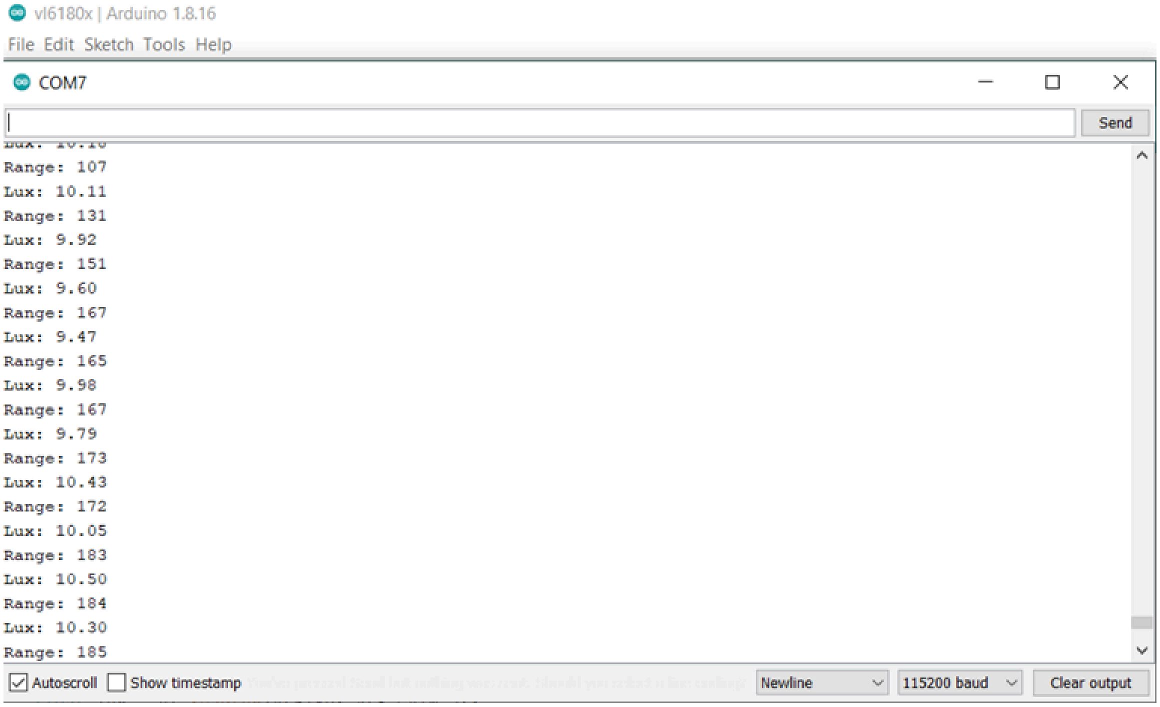


Figure 67: Image of connections with VL6180 ToF Distance Sensor, Arduino Uno, breadboard, and USB.

Testing the VL6180 ToF Distance Sensor worked, and it can be used for our laser module and can be modified. To make sure we reach the right distance we want with a material we did engrave as mentioned above, we can set a limit and add a buzzer to indicate that.



```
Range: 107
Lux: 10.11
Range: 131
Lux: 9.92
Range: 151
Lux: 9.60
Range: 167
Lux: 9.47
Range: 165
Lux: 9.98
Range: 167
Lux: 9.79
Range: 173
Lux: 10.43
Range: 172
Lux: 10.05
Range: 183
Lux: 10.50
Range: 184
Lux: 10.30
Range: 185
```

☑ Autoscroll ☐ Show timestamp Newline 115200 baud

Figure 68: Data output of the VL1680 ToF sensor from Serial Monitor (Lux and Range data for 115,200 baud).

7.7 Facilities Used

To test out our designs for experimentation and prototyping, we did need to utilize a variety of environments. Primarily, we did utilize the senior design labs in both CREOL and the engineering building located on the UCF campus. The CREOL lab is located on the second floor and contains equipment such as oscilloscopes, multimeters, function generators, power supplies, as well as various optical devices such as prisms, fiber optic cables, and diffraction gratings. The electrical equipment will be used to test the laser, using the function generator to vary the duty cycle and determine the optimal laser power for each material. Additionally, for soldering and desoldering for the PCB and other electronic equipment, access to the senior design lab in the engineering building will be necessary and utilized.

Located within the engineering building is the L3 Harris lab which contains an industrial laser cutter and multiple 3D printers. The industrial laser cutter will be used to compare the software as well as functionality to be used as inspiration for our own project and to compare results. The 3D printers will be used to print out many of the parts required for our project such as the mount for the laser and the casing for the spectrometer.

Testing for the spectrometer will be done in part within our residences and in part in the CREOL senior design lab. Since the spectrometer does not require access to any technical equipment outside of a personal computer, assembly and testing can be done from home. Building the prototypes will require access to the 3D printers located within the engineering building but assembly can be done anywhere.

For the operation of the software required for our project, that will be done on each of our devices within our own residences. For software that is not directly installed on our personal computers, we may need to access school computers from the engineering building for access to MATLAB and Solidworks. Students also have access to programs via UCF by using a VPN called Citrix when not on campus, programs such as Solidworks and MATLAB were

8 Administrative Content

To create a precise product that will be able to meet not only our standards but those of the IPC, we did need to lay out a foundation on the budget we did maintain, as well as the limitations that come with this. In this section we did highlight and go over some of the brief descriptions on the separate categories of budgets we did have, as well as number and value everything that will be needed, to give one total price point.

8.1 Budget and Funding

One of the most essential portions of this project is being able to create an outline for the materials and have price estimates that we did be using. Having a budget and a list will allow us to stay under the ceiling. Within each division of the budget shown below, we further go into detail about the specifics of what exactly is needed for each discipline. This comprehensive list will focus on the three main disciplines that we are working under, including Computer, Mechanical, and Photonics.

Optical Components:

In regard to the optical portion of our project, we did create two separate optical systems: one for engraving and one for materials detection through reflection spectroscopy. The laser system will require a high-powered diode laser module with a heat sink, a mirror, and a focusing lens. The materials detection system will consist of a broad-spectrum white LED light source, a series of collimation and focusing lenses, a diffraction grating, and a USB CMOS sensor to capture spectral data.

We already bought the laser diode module off Amazon, this was the first component purchased back in September. We are using the 5W 405nm laser diode from LaserTree and the laser was $60. The diode comes with a lens attached with a focal length of roughly 20mm. The focusing lens we are using is a Newport 6.25mm diameter N-BK7 lens with an effective focal length of 12.7mm. Pairing with the computer engineers, we purchased an Adafruit VL6180X time of flight distance sensor with a sensing distance of 5 mm to 200mm, this was purchased for $14 but we bought two to have a backup in case we need a replacement. For the spectrometer, we did be purchasing two focusing lenses to focus the reflected light onto the diffraction grating, and another lens to focus light from the diffraction grating to the camera sensor. we did need a high powered white LED to provide enough light to get the reflected spectrum focused onto the diffraction grating. A diffraction grating with a grating of 500 lines/mm is needed for sufficient dispersion of light. Finally, a CMOS detector will be implemented to detect the spectrum from the diffraction grating.

As of the time of this entry, we are exploring a spectrometer design without any lenses. Others have demonstrated successfully that a spectrometer can be built without any lenses but testing has to be done to prove this in our case. Due to the nature of fiber optic cables being small in core surface area, they do not collect much light and may lead to a low SNR if not collimated upon collection and exit from the fiber. If lenses are needed, we did use a pair of fiber collimators which range from $70-$150 each. Due to this steep cost, we did try and find used options online from sites such as Ebay which should reduce the price but still give us acceptable performance.

Computer/Electrical Components:

In our computer portion of the group, as we did have three core members, we did need a variety of items included into our budgets, rather than being specifically geared towards just hardware, we did need the source of online applications as well.

This project requires several components for the development of a sophisticated laser engraver system. Some of these parts include an Arduino Nano microcontroller chip, priced at $20, which helps to form the central processing unit for seamless control and operation. we did also need the inclusion of custom PCB components, along with printing costs, with a quantity of one, amounts to $25, ensuring the creation of an efficient printed circuit board. To enhance the user interface, we did have a 2.4-inch TFT LCD display module with touchscreen capability as part of the order, costing a total of $30. The software aspect is covered by both Windows Engraver Software and MCU Software, which are provided free of charge. This comprehensive set of components, including the microcontroller chip, custom PCB, LCD display, and software, is therefore curated to facilitate the development of a fully functional and user-friendly laser engraving system.

Mechanical Components:

Within our mechanical portion of the project, a bulk of our budget will be given in relation to materials needed to construct the framing that will encapsulate the project itself. This includes but is not limited to, the frame to hold the lasers, the bed itself, and an enclosure that will be used as a safety mechanism.

In terms of mechanical components that are fundamental for the construction of a laser engraver system, we did include the framing and material component, crafted from 6061 Aluminum framing material, is priced at a total of $150, providing a sturdy foundation for the entire project. In addition to this, the

hardware aspect, valued at $200, ensures the integrity and durability of the system as a whole. To accommodate the assembly, a miscellaneous package, encompassing screws, bolts, wires, and other essential components, is included at a cost of $50, to create a secure final product. This comprehensive selection is not only used for listing all materials, but also culminating in a final total that reflects the investment we make for the reliability of our laser engraver.
When tallying up all the costs needed in our three disciplines including framing materials, PCB, and various optical and electrical components, we end with a final price of $805. This final cost reflects the commitment we are promising in delivering a fully equipped laser engraving system that meets the standards we are striving to achieve in terms of performance as well as reliability.

Total Cost: $805

8.2 Work Distributions

To be able to accomplish and fully flesh out our project, we did need to distribute the work accordingly, in regards to everyone's respective major. Not only this, but we did also fine-tune so we can have each individual being the primary resource in the aspects that they excel at while being the secondary for other portions. The split is seen below:

Computer Engineering

Felipe Mosquera	● The main PCB must be compact enough to fit onto the side of the CNC machine. Microcontroller unit must have the ability to interface with the user via LCD display and pushbuttons ● The Microcontroller platform must have the ability to interface with the laser and stepper motors of the CNC machine, using PWM ● CNC laser must be able to engrave intricate patterns/images on each of the material types, and must conform to safety standards (power limitations, fire prevention)

Aly Megahed	● Software must be able to process data from the reflection spectroscopy system and classify material with an 80% accuracy rate. ● Microcontroller software must be able to interface with laser engraving software on a PC
Kavinaash Jesurajah	● Create a database that will be able to communicate with the PCB board and the software and hold the information of all the materials ● The user interface must contain a simple menu to verify CNC is ready and begin the engraving process with user inputs taking less than 5 seconds. ● UI must include confirmation of classified material after receiving data from the spectroscopy system.

Table 16: Computer Work Description

Photonics and Optics Engineering

Jackson Gilliland	● Integrate high-powered diode laser module with focusing lens compatible with the CNC platform. ● Design lens system to focus laser light to a spot size of less than 0.05 x 0.05 mm^2. ● Design and integrate a laser time-of-flight distance sensor to auto adjust z-axis height and autofocus the laser to minimum spot size on material.
Nolan McGinley	● Design and integrate a reflection spectroscopy system within the enclosure. ● Create an optical system for capturing reflected light from engraved material and focusing it onto a camera sensor for spectral matching.

Table 17: Photonics Work Description

Mechanical Engineering	
Amir Mohd	- Design a robust structure of the CNC platform, hardware mounts, and enclosure for safety. - Integrate the corresponding optics (laser module, material sensors, and focusing system) flush into the mechanical frame. - Understand the various material properties for adequate and proper laser parameter selection.

Table 18: Mechanical Work Description

8.3 Project Milestones

This section covers project milestones for the senior design project. The project milestone table discusses each week with the milestone of that week. The milestone is assigned to each person or a group with a start and end date. Then, the progress of the milestone is either TBD, in progress, or completed. This section allows a clear way to know what is due and when for everyone and keeps track of each task. Project milestones are used for groups and projects for companies as well and handy for many businesses.

Senior Design 1: (First 16 Weeks): Project Detailing and Report					
Week(s):	**Milestone:**	**Assigned To:**	**Start Date:**	**End Date:**	**Progress:**
1	Form Groups	Everyone	8/22/2023	8/24/2023	Completed
2	Project Ideas	Everyone	8/24/2023	8/28/2023	Completed
3-4	D&C Document & Meetings	Everyone	8/28/2023	9/15/2023	Completed
5-16	60 Page Draft Document	Everyone	9/19/2023	11/3/2023	Completed
5-16	Final Document	Everyone	9/19/2023	12/5/2023	Completed
5-16	Type of Laser to use and power	Jackson	8/24/2023	12/5/2023	Completed

5-16	Materials used to build and test	Everyone	8/24/2023	12/5/2023	Completed
5-16	Idea and plan for material scan	Nolan	8/24/2023	9/13/2023	Completed
5-16	PCB design and creation	Felipe	8/24/2023	12/5/2023	Completed
5-16	Software required to program	Kavinaash and Aly	8/24/2023	12/5/2023	Completed
5-16	Microcontroller for project	Aly and Kavinaash	8/24/2023	12/5/2023	Completed
5-16	Communications between devices	Aly	8/24/2023	12/5/2023	Completed
5-16	Safety measures and precautions	Everyone	8/24/2023	12/5/2023	Completed
5-16	Electrical control, power, and heat control	Everyone	8/24/2023	12/5/2023	Completed
5-16	Mechanical control system	Amir	8/24/2023	12/5/2023	Completed
5-16	Material scanning and testing	Nolan	8/24/2023	12/5/2023	Completed
5-16	Platform movement and area calculations	Amir	8/24/2023	12/5/2023	Completed
5-16	Comms b/w microcontroller, PCB, platform, and laser	Kavinaash and Aly	8/24/2023	12/5/2023	Completed
5-16	User-Interface Implementation	Kavinaash	8/24/2023	12/5/2023	Completed
5-16	Power Calculations	Jackson	8/24/2023	12/5/2023	Completed
5-16	Test and research image processing for engraver	Nolan	8/24/2023	12/5/2023	Completed

Table 19: Senior Design I Milestones

Senior Design 2: (Second 16 Weeks): Project Construction and Final Report					
Week(s):	**Milestone:**	**Assigned To:**	**Start Date:**	**End Date:**	**Progress:**
17-18	Build a Prototype	Everyone	01/08/2024	01/19/2024	Completed
18-19	Troubleshooting	Everyone	01/15/2024	01/26/2024	Completed
20-26	Edit and Finalize Design	Everyone	01/29/2024	03/15/2024	Completed
24-25	Build Final Design	Everyone	02/26/2024	03/08/2024	Completed
26-27	Presentation Demo	Everyone	03/08/2024	04/13/2024	Completed
28-29	Final Report	Everyone	03/25/2024	04/18/2024	Completed
30	Presentation (Final)	Everyone	TBD	TBD	TBD

Table 20: Senior Design II Milestones

9 Conclusion

The journey from the beginning of Senior Design 1 has been a journey of learning in a different manner than what we experienced in previous years of university. We were given very minimal guidance and were forced to take our own initiative to complete a preliminary design for our project. At the beginning, we were unsure what our project would be, and even less sure about how we would go about this daunting task of designing and building a working machine.

This class has given us the opportunity to grow in ways we had not imagined while working our way through our undergraduate studies. Our project is our own design and we are proud of the hard work that has been put in to create a road map for construction of APALES in Senior Design 2. Many hours were spent researching and learning about different ways to make this project possible, and we believe our work will lead us through our future challenges. We are aware changes will be made to our design as we are building towards the final product, but it is impossible to get the design perfect the first time and adjustments are constantly being made throughout the construction process. There will be many unforeseen challenges, but we are confident we did be able to handle them and push on to continue our mission to build a working laser engraver with automatic parameter adjustment.

9.1 Results

As our second semester of senior design comes to a close, we are at the penultimate milestone of our undergrad career. As we highlight and give a detailed description on each of our individual roles as well as the system as a whole and its functionality. This section of the report is to give an air to the idea of the intricacies and challenges that were faced during the construction process. Many hardships were faced throughout this process, given that this is a course that should reflect and simulate what an actual engineering environment should encompass, including its team based effort while simultaneously having much individual work that should be faced with less guidance and knowledge.

APALES in its current state, is a functioning laser engraving system that runs through the use of spectroscopy for its material detection. We hope the following sections can give an insight on the amount of effort and dedication that has been poured in by our team members in allowing this system to reach its latest potential. This also should be able to give information on what steps are left in reaching the stretch goals we had set for ourselves.

9.1.1 Jackson Gilliland - Laser System

My role in this project was to design and integrate the laser and focusing system. Ever since my freshman year as a photonics engineering student, I was very excited to see what kind of optical system I would be designing for my senior design project, and I think the implementation and designing of a laser system is a great culmination of multidisciplinary work to represent my multiple years as an engineering student.

I did extensive research on different types of lasers that can be used for this application, from solid-state to gas and diode lasers, but from the beginning I knew which option would best suit our system and application. The root of the laser system needed to be easy to operate and power to enable ease of use and integration with the rest of the system. The laser diode module is just that, easy to power and operate with a triple-pin connector with PWM input. This enabled me to seamlessly work with the computer engineers in the group and streamline the power control of the laser.

Focusing the laser turned out to be more of a challenge. The laser diode module comes with an adjustable lens attached to the front, which I originally wanted to remove because there was very little information on it in the laser module user manual. The only information was a very rudimentary diagram explaining that when the mount was adjusted to 2mm away from the surface of the module, the laser would focus at 20mm past the surface of the lens mount. I did not trust this lens to create the best quality beam spot to enable the best engraving detail. My original laser focusing design, as seen in Figure 69, removed that adjustable lens, and incorporated two identical lenses to collimate and focus the laser diode while creating an identical image of the laser diode emitter. The beam quality is the best at the emitter, so an image of the emitter would create the best spot. This design was, however, not achievable at our price range because a lens with the correct diameter to focal length ratio was upwards of $300 dollars, way out of our budget… and I needed two. The divergence angle of the laser diode was too large to be captured by the lens diameter and still be placed at its focal length for collimation, and we would have lost a large amount of light power. I was forced to move forward with a different design for focusing, and possibly introducing unknown aberrations because of the uncharacterized lens.

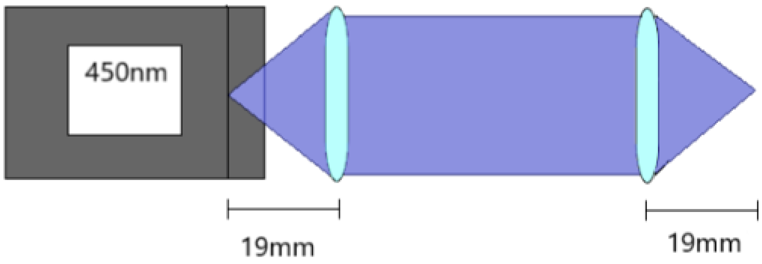


Figure 69: First iteration of laser focusing system

The laser design that was implemented is shown in Figure 69. The 31 degree half angle represents the divergence angle of the laser diode emitter. This is captured by the adjustable lens which then focuses to a spot 30mm after the surface. This focusing distance was not long enough to account for the spectrometer optics on our mount, so I had to extend the focus using a single lens imaging system. I used a lens with a focal length of 30mm, and this extended the focal plane to give the spectrometer system space. The system uses two plano-convex lenses, and there is noticeable spherical aberration on the focus spot. The spot is very small, 80x60µm^2, and is shown in Figure 71. This spot size was calculated by using the number of pixels and multiplying by the pixel size. The small spot size enables our very small linewidths.

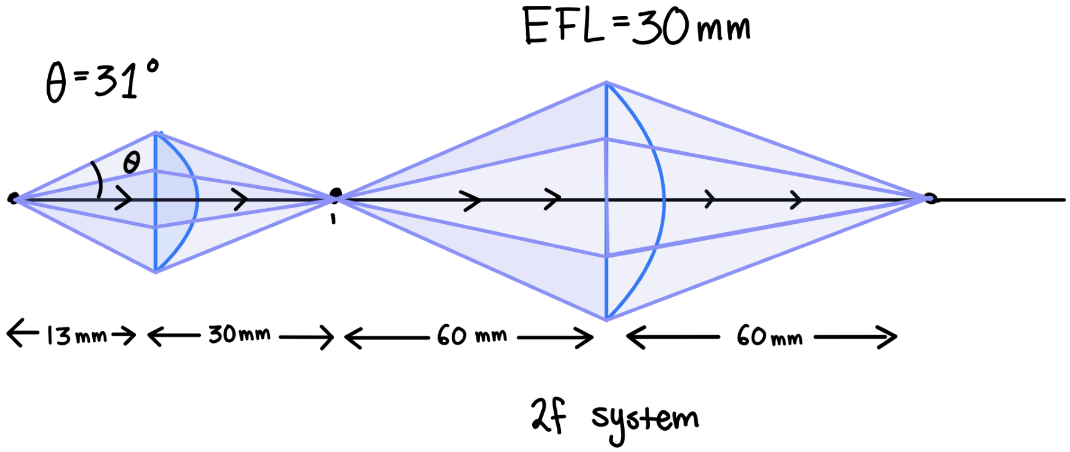


Figure 70: Laser focusing design implemented in APALES

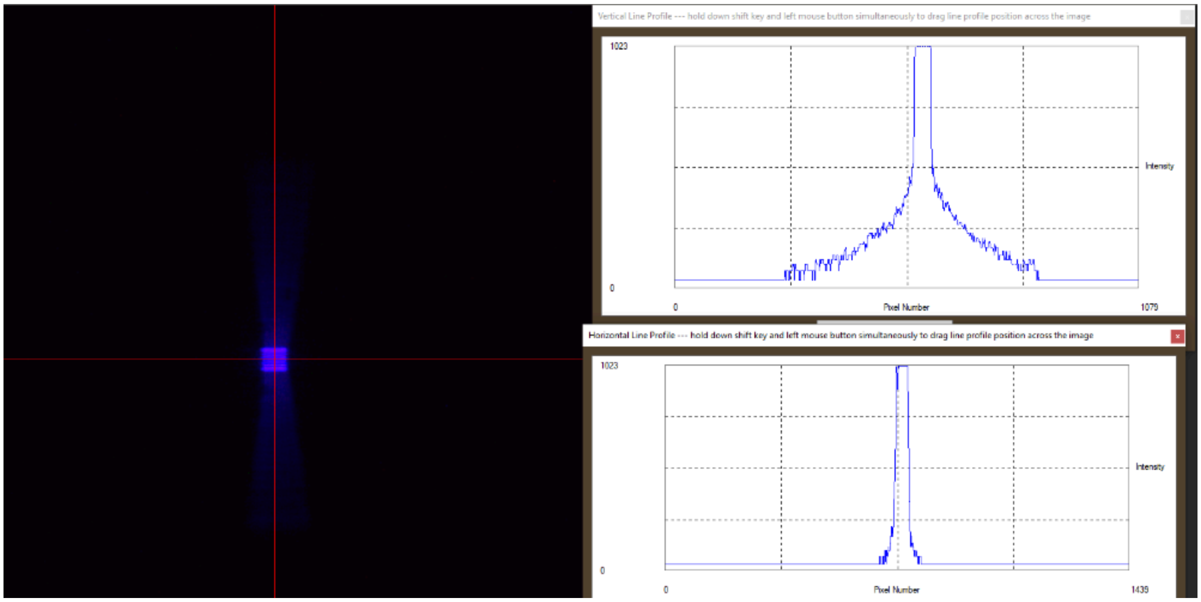


Figure 71: Horizontal and vertical beam profile at minimum spot size. Calculated to be 80x60µm^2.

This very small spot size enables us to create very thin linewidths on our materials. These linewidths are showcased in Figure 72, where it has been shown that we met our advanced goals in having a linewidth of less than 0.25mm on all materials.

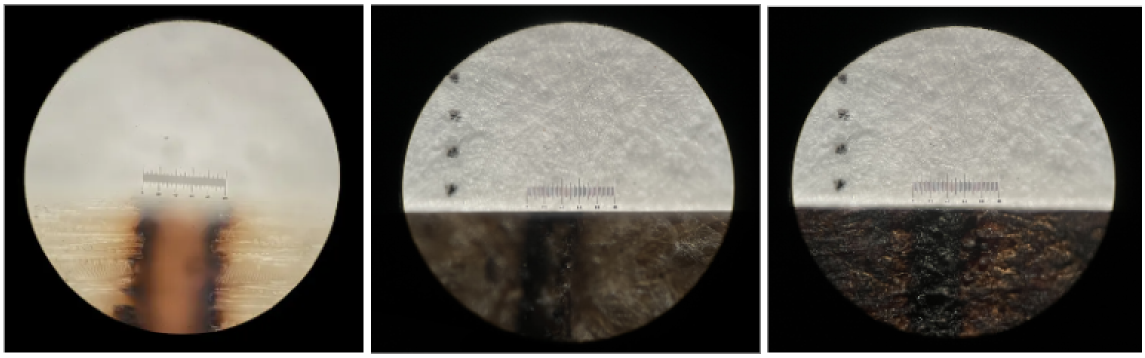


Figure 72: Examples of linewidths compared to a ruler of 250µm. Each is less than or equal to 0.25mm.

In addition to designing the laser focusing and implementation, I designed the laser mount and Z-Axis Height Adjuster in SolidWorks. These were 3D printed and implemented into our system, and can be seen in the mechanical engineering section. This entire process was a great learning experience, and was a great opportunity to display my interdisciplinary engineering skills.

9.1.2 Nolan McGinley - Spectroscopy Design/Integration

During the Fall semester of Senior Design I, I did lots of research to determine the optimal components, their placement, and orientation for the spectrometer. With this knowledge, I created the initial design. As the Spring semester began, I eagerly ordered the necessary components and embarked on the creation of the first iteration of the spectrometer.

However, the initial design encountered various hurdles. Despite these obstacles, I persisted in refining the design, resolving issues one by one. Yet, ultimately, large changes were required. I opted for a different camera, lens, and eliminated the slit. Throughout the process, I redesigned the spectrometer approximately six to eight times, eventually ended up with a product that met my expectations.

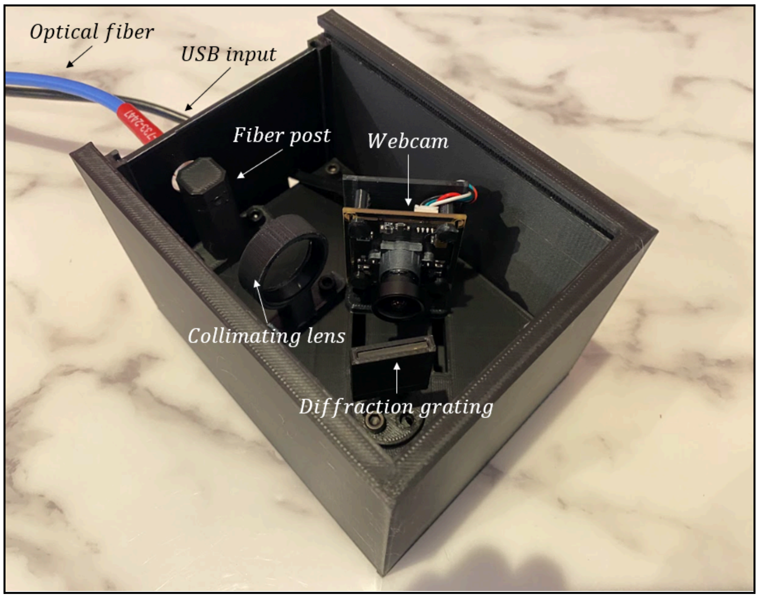


Figure 73: Final Design of APALES Spectrometer

Fortunately, I had access to my own 3D printer, which proved invaluable in rapidly producing new designs and testing them with minimal delay. Through this hands-on experience, I gained lots of experience in mechanical design, 3D modeling of custom parts, optical design, and coding to seamlessly integrate the webcam with my spectrometer.

Although my role did not explicitly involve the use of CAD or Python programming, I embraced the challenges and expanded my skill set to ensure the project's success. By adapting to the evolving demands of the project, I not only achieved our initial goals set in Senior Design I but also gained invaluable lessons along the way.

9.1.3 Amir Mohd - Mechanical Design

Since the conceptualization of the APALES project in SENIOR DESIGN I, the mechanical components of the project served as the backbone ensuring that all the other components and essential characteristics were met with precision. Incorporating my acquired knowledge of 3D modeling, material handling and fabrication, as well as design of mechanisms have all been put to the test in creating a functional CNC laser engraving system.Throughout the development of our system, each mechanical component underwent rigorous design, testing, and iteration to ensure optimal performance and integration within the system. Whether it being the iterative design process of proper POM wheel spacing on the gantry towers, to the many versions of the Z-axis mechanism, there was a healthy amount of hours spent on Solidworks, machine shop, as well as the Innovation lab to 3D print our ever-evolving designs.

The Gantry system, serving as the foundation of our setup, specifically presented me with challenges in achieving the desired balance between strength and weight. Making it to where only one singular motor was used to propel the Y-axis,also brought many mechanical challenges and obstacles. Incorporating a linear actuator rod that translated the movement of the singular motor to the opposite gantry tower served its purpose, while also providing efficient torque and speed for the system to function well. Iterative refinement was crucial to optimize the design of these towers changing the placement of the X-axis beams to even the placement of the motor housing. Ultimately, this resulted in a robust structure capable of supporting the laser head and ensuring precise movement along the X and Y axes.

The Laser Mount, designed to house the LaserTree 4W 450nm laser diode, faced challenges when designing in ensuring secure mounting and alignment with the focusing lens. The focusing of the laser was essential to obtain clean and proper engravings with the desired focal point we intended. Success was achieved through constant model refinement and integration with the manual Z-axis Adjustment Mechanism, resulting in accurate focusing and precise engraving capabilities.For the Z-axis mechanism itself, incorporating hardware such as M6 bolts, barrel nuts, and a spring-loaded assembly, we specifically crafted a mechanism enabling precise adjustment of the laser mount within a 30mm range along the Z-axis.

The culmination of my mechanical engineering degree was epitomized by the successful development and integration of these mechanical components into our CNC laser engraving system. This achievement not only showcased my dedication to thorough design, testing, and iteration but also underscored the invaluable lessons learned throughout my academic journey. Each challenge overcome and success achieved served as a testament to my growth as an engineer and my ability to apply theoretical knowledge to real-world projects. As I reflect on this accomplishment, I am reminded of the importance of perseverance, attention to detail, and innovative problem-solving, qualities that will undoubtedly continue to shape my career in engineering.

9.1.4 Felipe Mosquera - PCB Design

Over the course of the past few months, a strenuous amount of research and development has been incorporated into my schedule to achieve the amount of progress that has been accomplished for my role within this senior design project. I was responsible for incorporating a Printed Circuit Board into our system that will offer the powering capabilities within our laser engraver system.

During the design process, many iterations of the board were created before we decided on the final optimized version we currently are at today. The original thought was to include a board that was responsible for raising and lowering the Z-axis component of the system to adjust for the parameters required for each build of a job. With time, the priority was then shifted to have a board that will instead encompass what is generally required for a laser engraving system, such as drivers for each of the motors, with the power being done within the same board, as well as all components for the laser and any additional connections needed. After this original version was done with a power circuit built using the LM2678, many troubles had risen due to this converter having very infrequent output of the correct 5V required. To circumvent this, per Dr. Weeks' suggestion, we instead used an LM2576 adjusting switching regulator that was more commonly found within the engineering building. After breadboarding, the correct output was provided then later designed as a separate board, ensuring that if any outages were to occur, they could easily be singled out and fixed without potentially shorting the main board.

After the power board was completed, the main board incorporating our primary circuit for the system was developed afterwards. During this next iteration, many steps were taken to ensure a smoother and more efficient board layout. The wire traces were thickened to allow the components which required a higher voltage to travel correctly through the system. The entire board had many of its components rearranged to have an optimized layout for pins to ensure minimizing the amount of vias that would be included in the board. This resulted in the final board design being compacted to be a much more reasonable size of 73.3mm by 68.3mm. With this, the next process of soldering had occurred, as our two boards had been finalized and ordered. At this point, our final two boards were tested with a Digital MultiMeter (DMM) to confirm that they are outputting the correct voltages in every pin that was necessary. With the 12V input, we had the outputs of 12V and 5V successfully being outputted throughout our entire system. Several LEDs were included to ensure that there is a visual indicator for the voltage outputs. Here we then fell into trouble, as our micro usb had fallen off with the traces exposing the copper underneath. Thankfully, Dr. Weeks had then helped in attaching to the pins on our CH340G directly the pins necessary for the USB type-A, those three being D+, D-, and GND. With this, we were able to then finally have our system fully built. Although the building process was complete, we continued to have trouble in having the device be recognized within our console. We had several sessions of troubleshooting trying to find a solution for this serial converter being unable to be recognized, but continued to be met with no resolution. Although the system was entirely complete with the PCB being designed, optimized, soldered, and powered correctly, we were unable to have the board run the software. Even with this, I believe that the problem lies within the specific CH340G that we own, with Dr. Weeks believing this to be it as well. We can undoubtedly say that through a small amount of further development, this small problem could have been resolved with an additional component being tested on.

Regardless, my participation within this senior design project still provided me with both a challenging and rewarding role that pushed me to my limit. I was able to still have a PCB successfully designed that had powered the entire system, which demonstrates my skills and knowledge that has been gained through the senior design term. This achievement, in addition to the problem solving that has been applied, shows my growth as an engineer. While it did not reach its full functionality, this entire experience still goes to show some invaluable insights that will further guide my future in refining the current design.

9.1.5 Kavinaash Jesurajah - Software Integration and Programming

Aforesaid before, there were many plans and thoughts that we wanted to implement into the software system of our project. Many of those ideas changed and for the better as well and we discuss that here. We compared softwares in section 3.10.1 and we chose to use the ATmega328P. This is the case as we started prototyping, designing, and creating our PCB.

Our IDE we thought of using is the Arduino IDE and which is needed for the PCB to flash the GRBL file. When creating our code and our prototype of our functions for the project, we decided to use Visual Studio Code as well. Visual Studio Code is very useful for us when we started to design our prototype code. Doing investigation work on our spectroscopy system, we found out that the python language has a computer vision library which is perfect for our system. This library has functions that our Arduino webcam can be used for. The libraries in the computer vision library called OpenCV, have functions such as *cv2.VideoCapture*, *cv2.imwrite*, *cv2.cvtColor.* These built in library functions capture an image, write data to a file or folder, and convert colors. They are needed for our spectroscopy system and helpful to create the data we need to do testing. Our material identification through spectroscopy (section 3.10.2) we did go through a similar path we were planning on doing. We did create a spectroscopy system that reads an image and creates a 1D array correlated to the material it is connected with. Using the OpenCV library and other functions in the python language, we create a spectroscopy code that takes an image using the OpenCV library and snips part of the image we want that has the spectrum and stores that image. Using the OpenCV function, *cv2.cvtColor*, we can change the color of an image. We use this to change the colored captured image that is of our spectrum that is snipped to a grayscale image. Using the grayscale image gives us data values of each pixel of a grayscale which is less complicated and we can use it to identify each material and compare them. To compare each material data in the database we can use a function in the python library. The formula we did use is the euclidean distance formula. Using this formula we can compare each array with the reference array and see which is the closest as a precise measurement.

$$d(p,\ q) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2}$$

As we mentioned in section 3.10.4, we said we want to implement a user interface for the user. This being a user friendly application or GUI where the user can interact with to start the job, add the material, compare the materials, have port selections, and more things for our system. This is useful and better than a person having to run every single file of code while we can have an application do it all in one area. Error handling is important (section 3.10.5) and that is why there are base cases we must implement. If there is no COM port selected for our controller to send the data to start the job, we must let the user know. If something can or might go wrong we must let the user know as well. Instructions are important and let a user know what to do during each situation and using the application as well. In the APALES application, we created instructions that let the user know what to do in each selection. For our laser engraver, we send the job as instructions of G-Code to tell the system what position and parameters needed. We are using UART to communicate with the controller to send the data of positioning and inputs for the laser to move and start the job. We use python to send this data and in chunks to get the job done. The idea of having data of each material as a 1D array is good and that data needs a database. We want a database to store our material parameters and information to keep track for later. We can recall and search in the database to do a comparison or use the data in it to configure the laser. The ideas were either a MySQL, MongoDB, or a database without a DBMS. Using OpenCV and python, we thought of a plan to keep everything in python for simplicity and connection. We went with creating a database without DBMS and just storing the data of each material in a folder as our own "database." This makes it easier as we can call a function to search the folder and any data of any material or all of them to compare or use.

Knowing all of this, seeing the changes and decisions of our project lean towards more python and using computer vision library OpenCV. This makes the design more straightforward having everything in one area and being about to pull and connect with each other to use the files we need. Ideas and plans change like in engineering projects when learning more about the software we want to use and the plan we want to initiate. My thoughts nearing the end of the project, at first it was thoughts and plans on what should be used and not. As we progressed more and more to see our plans laid out and used, it became clear on the task and our tools to use.

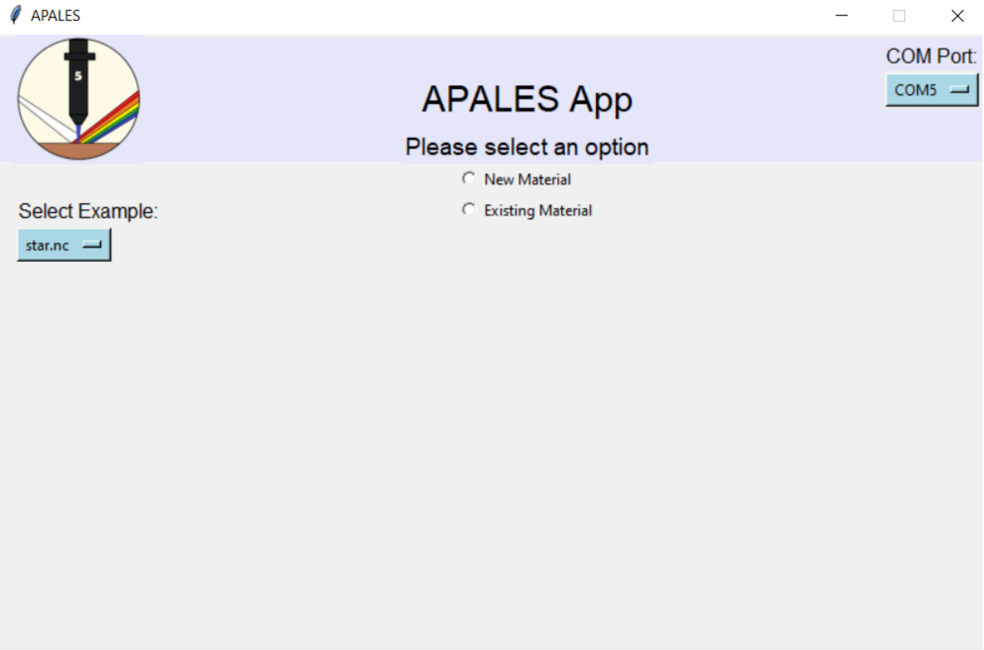


Figure 74: Screenshot of APALES Application.

9.1.6 Aly Megahed - PCB and Software Design

I've learnt a lot throughout my experience during this semester. My time working on Senior Design 2 was mainly split between working on the PCB and the software app. The majority of the time was spent on the former. With the aid of Dr Weeks, both Felipe and I learned a lot about PCB technologies and more specifically the electronics typically used in CNC applications. Namely, this was the driver boards, A4988 boards in our case, and the PWM output for typical 3-pin diode lasers. I learnt about how circuit boards are layered and printed, how the top and bottom layers are interconnected. I learnt how to solder both through hole and surface mount components.

From Senior Design 1, our initial consideration was to design a board with independent Z-axis height adjustment. We were going to use a time of flight LIDAR sensor to measure the distance from the laser mount to the surface of the material to be engraved. The original mechanical design of the gantry tower would have included a Z-axis motor to set the height of the laser from the material. The idea was to keep the laser spot size consistent across boards/sheets of different materials, since they would have varying thicknesses. At the start of Senior Design 2, we consulted with Dr Arthur Weeks and found that independent Z-axis adjustment didn't make much sense to implement. Most CNC software supported the functionality to adjust the Z-Axis height before starting the engraving job. GRBL, the firmware we'd planned to use with the Arduino (ATMEGA) chip, supported that functionality through special g-codes.

This aspect of setting the Z-axis automatically wasn't critical to our design. Additionally, the weight of the gantry system, designed by Jack and Amir made it more difficult to support a Z-axis motor in the first place. We decided to prioritize the X and Y axes control of the system and design a CNC controller board sporting the Arduino chip running GRBL.

Designing a whole CNC controller was more feasible than expected. When designing our initial version of the PCB, we used schematics of existing controller boards as reference. Despite being unsuccessful, our first iteration of the board taught us a lot about how to prototype/breadboard.

While working on the software for the project, we split our roles between working on the GUI and the backend (underlying code modules: spectroscopy and classification, gcode parameter setting). It was a little difficult at first but we managed to structure our Python modules in a way that made sense. The main modules I worked on were the g-code parameter and sende as well as the frontend, while Kav and Nolan worked on the spectroscopy image capture and analysis. It was a little tough using Python's built-in library Tkinter for managing the GUI layout. It took me a while but we were able to connect the widget with the backend.

As we neared the final demo and showcase, we decided to implement some more features to our app. Namely, we decided to add a graph to display intensity over wavelength from the 1-D images captured by the spectrometer. We also decided to add an image preview feature to show what image would be re-produced by the engraving job. Overall, I think the app was a successful project.

10 References and Appendix

List of Tables

List of Figures

References

1.) https://www.ti.com/lit/ug/slau367p/slau367p.pdf?ts=1697726524908&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FMSP430FR6922

2.) https://juggerbot3d.com/3d-printing-materials/abs-filament-review/

3.) https://juggerbot3d.com/pc-filament-review/

4.) http://radiocom.dn.ua/image/data/pdf/ATMega16-16PU_Atmel.pdf

5.) https://ww1.microchip.com/downloads/en/DeviceDoc/doc4316.pdf

6.) https://circuitdigest.com/tutorial/what-is-pwm-pulse-width-modulation

7.) https://prodigytechno.com/i2c-protocol/

8.) https://tritekbattery.com/uart-communication-protocol/

9.) https://www.corelis.com/education/tutorials/spi-tutorial/

10.) https://howtomechatronics.com/tutorials/g-code-explained-list-of-most-important-g-code-commands/

11.) https://all3dp.com/2/grbl-software-guide/

12.) https://github.com/grbl/grbl

13.) https://github.com/grbl/grbl/wiki/Frequently-Asked-Questions

14.) https://jtechphotonics.com/?page_id=2012

15.) https://inkscape.org/about/

16.) https://lasergrbl.com/

17.) https://howtomechatronics.com/projects/arduino-cnc-foam-cutting-machine/

18.) https://howtomechatronics.com/projects/simplest-cnc-machine-with-minimum-parts-possible-diy-laser-engraver/

19.) https://winder.github.io/ugs_website/

20.) https://www.mongodb.com/docs/manual/core/databases-and-collections/

21.) https://phoenixnap.com/kb/mongodb-vs-mysql

22.) https://www.protoexpress.com/blog/ipc-2221-circuit-board-design/

23.) https://blog.matric.com/ipc-class-definitions-class-1-2-3-electronics

24.) https://support.snapmaker.com/hc/en-us/articles/4404753371415-4-Laser-G-code-Generator

25.) https://www.veracode.com/security/integrated-development-environment#:~:text=TurboPascal%20may%20have%20launched%20the,programming%20language%20through%20the%201980s.

26.) https://www.thinkautomation.com/histories/the-history-of-databases#:~:text=The%20advent%20of%20computers%20in,Management%20System%20developed%20by%20IBM.

27.) https://www.linkedin.com/advice/0/what-pros-cons-using-arduino-ide-vs-other-development#:~:text=One%20of%20the%20main%20advantages,debug%20and%20visualize%20your%20data.

28.) https://www.mathworks.com/products/connections/product_detail/code-composer-studio.html#:~:text=Code%20Composer%20Studio%20comprises%20a,profiler%2C%20and%20many%20other%20features.

29.) https://www.elastic.co/what-is/large-language-models

30.) https://chat.openai.com/

31.) https://www.bing.com/search?q=Bing+AI&showconv=1&FORM=hpcodx

32.) https://bard.google.com/chat

33.) https://www.edinst.com/blog/what-is-a-spectrometer/

34.) https://byjus.com/physics/difference-between-emission-and-absorption-spectra/

35.) https://www.rp-photonics.com/white_light_sources.html

36.) https://www.stellarnet.us/what-is-a-spectrometer-slit/#:~:text=The%20slit%20is%20an%20opening,slits%20also%20decrease%20signal%20strength

37.) https://www.edmundoptics.com/knowledge-center/application-notes/optics/introduction-to-optical-prisms/

38.) https://www.edmundoptics.com/knowledge-center/application-notes/optics/all-about-diffraction-gratings/

39.) https://www.westfloridacomponents.com/IC667APH03/TCD2557D+CCD+Linear+Image+Sensor+IC+Toshiba+-+Refurbished.html

40.) https://www.mdpi.com/1424-8220/19/12/2833

41.) https://canon-cmos-sensors.com/120mxs-120mp-cmos-sensor-evaluation-kit/?keyword=&creative=430938097856&gad=1&gclid=CjwKCAjwkY2qBhBDEiwAoQXK5XxNM1Rk1OIsMj7Sb7PgH-8QQdR3elUiVthUIiu9jO75Loih64gMPhoC2NUQAvD_BwE

42.) https://news.mit.edu/2021/smart-laser-cutter-system-detects-different-materials-0819

43.) https://www.geeksforgeeks.org/mongodb-vs-mysql/

44.) https://www.comsol.com/blogs/calculating-the-emission-spectra-from-common-light-sources/

45.) https://circuitdigest.com/microcontroller-projects/how-to-use-ov7670-camera-module-with-arduino

46.) https://www.newport.com/t/laser-diode-technology

47.) Hofer, Lucas & Dragone, Rocco & MacGregor, Andrew. (2017). Scale factor correction for Gaussian beam truncation in second moment beam radius measurements. Optical Engineering. 56. 043110. 10.1117/1.OE.56.4.043110.

48.) https://www.canva.com/

49.) https://www.multisim.com/

50.) Bessel-like beam paper https://www.researchgate.net/publication/327871745_A_new_method_of_out-of-focus_millimeter_wave_imaging_in_fusion_plasma_diagnostics_using_Bessel_beams
51.) https://learn.adafruit.com/adafruit-vl6180x-time-of-flight-micro-lidar-distance-sensor-breakout
52.) https://circuitjournal.com/arduino-OV7670-to-pc

53.) https://circuitdigest.com/microcontroller-projects/how-to-use-ov7670-camera-module-with-arduino

54.) Giancarlo M Luna: CNC System Consulting

55.) https://phydemo.app/ray-optics/simulator/

56.) https://www.researchgate.net/publication/327871745_A_new_method_of_out-of-focus_millimeter_wave_imaging_in_fusion_plasma_diagnostics_using_Bessel_beams

57.) https://labs.engineering.asu.edu/zhao/wp-content/uploads/sites/30/2014/08/2012-Acta-Development-of-gallium-nitride-based-light-emitting-diodes-LEDs-and-laser-diodes-for-energy-efficient-lighting-and-displays.pdf
58.) https://www.st.com/resource/en/datasheet/vl6180.pdf