Automatic Parameter Adjusting Laser Engraving System (APALES)

Nolan McGinley (PSE), Jackson Gilliland (PSE), Felipe Mosquera (CPE), Aly Megahed (CPE), Kavinaash Jesurajah (CPE), Amir Mohd (ME)

Dept. of Electrical Engineering and Computer Science, University of Central Florida, Orlando, Florida, 32816-2450

***Abstract* — The Automatic Parameter Adjusting Laser Engraving System (APALES) integrates conventional laser engraving with material recognition capabilities. Employing reflection spectroscopy, APALES analyzes reflected spectra to identify the material being engraved. After recognition, APALES then retrieves the corresponding laser parameters (power, scan speed) associated with the material, streamlining the engraving process. This eliminates the manual task of adjusting parameters for different materials, enhancing user convenience and efficiency.**

I. Introduction

Developed with the goal of enhancing existing laser engraving systems, the Automatic Parameter Adjusting Laser Engraving System (APALES) blends the domains of optical, electrical, computer, and mechanical engineering to advance the automation of laser engraving operations. Over the past decades, laser engraving has transformed from a novel technology to something much more accessible. Despite this increase in accessibility and other technological advancements, conventional laser engravers lack the capability to identify the material being engraved, a critical limitation given that laser parameters (such as power and scan speed) vary widely depending on the material. Memorizing these parameters for numerous materials can be a pain point for users. APALES was conceptualized to address this shortcoming and streamline the engraving process. By integrating a cost-effective spectrometer into the engraving system, APALES captures the reflection spectrum of the engraving material and uses it for analysis and identification, and ultimately adjusting the laser parameters. Initially designed to recognize and engrave three distinct materials (wood, leather, acrylic), APALES aimed not only for material recognition but also for the production of engravings with intricate details and fine line widths tailored to each material. Furthermore, APALES was engineered to ensure that the material recognition process takes under 5 seconds on average, thus minimizing any potential slowdown in the engraving process and justifying its added feature compared to conventional engravers.

II. System Components

A. Frame

In the development of our laser engraver, precise mechanical components were carefully designed and executed to ensure optimal performance and reliability. The frame of our laser engraver is constructed using 80-20 aluminum T-slotted rails, offering durability, customizability, and ease of assembly. With dimensions measuring 530mm x 470mm, this frame provides a sturdy foundation for accommodating moving components while allowing for flexible configuration. Brackets and hardware such as M6 bolts and nuts simplify the design and construction process, ensuring structural integrity and reliability in the engraving system. These rails offer versatility, enabling easy customization to meet the specific design requirements and allowing for the implementation of unique features. The frame's robust construction ensures reliable performance, making our laser engraver suitable for various applications and industries.

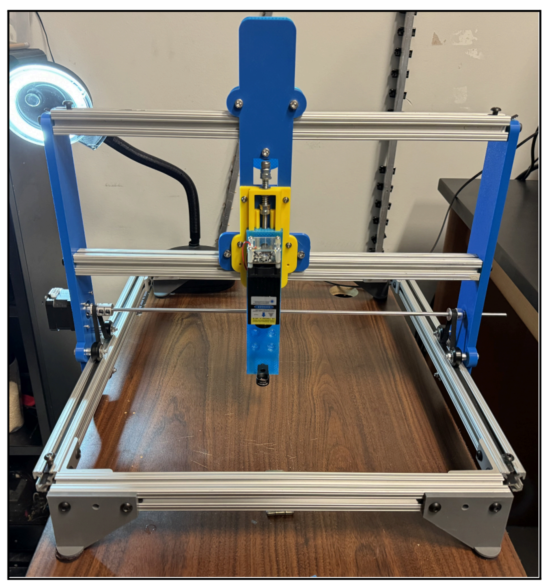


Fig. 1. Design of the APALES frame constructed with the 80-20 aluminum extrusions.

B. Gantry Movement System

The movement gantry system serves as the backbone of our laser engraver's mobility, enabling precise positioning and motion control.

A respective stepper motor is dedicated to the X and Y axes, providing the necessary power for movement. Each stepper motor is equipped with a gear attached to the shaft, driving the timing belt responsible for translating movement to the POM (Polyoxymethylene) wheels. These wheels are strategically positioned to interact with the rail system, facilitating smooth and accurate motion of the gantry towers. As the timing belt rotates, it imparts motion to the POM wheels, which in turn glide along the rail tracks, executing the desired movements dictated by the engraving process.

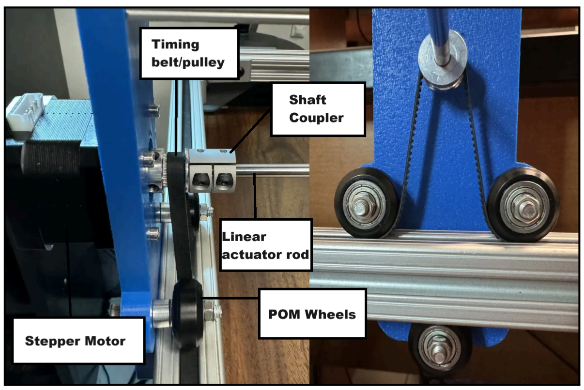


Fig. 2 POM wheel and motor movement mechanism.

Custom-designed gantry towers for the Y-axis are tailored to accommodate the Nema 17 stepper motor, featuring slots for M3 screws for secure mounting. These towers provide robust support and alignment for the POM wheels, guaranteeing stable and controlled movement along the designated axis. At the top portion of the designed tower, there is accommodation for the X-axis extrusion rail. This ensures that the system can withstand continuous operation; they serve as an essential part of the engraving system's vertical mobility, delivering consistent and precise engraving results.

A specialized tower, tailored for the X-axis, further enhances stability of the horizontal movements within the gantry movement system. Designed to accommodate the unique requirements of lateral movement, this tower complements the Y-axis gantry towers with the rail it sits on bolted into the previously gantry towers. By providing a sturdy foundation and optimal alignment for the POM wheels, the X-axis tower facilitates smooth and controlled motion, essential for achieving precise engraving outcomes. Additionally, this tower keeps into account the desired height of the laser diode from the material. This is shown with a designated mounting area for the custom laser/lens mount. This ultimately enhances ease of integration and alignment of the laser itself.

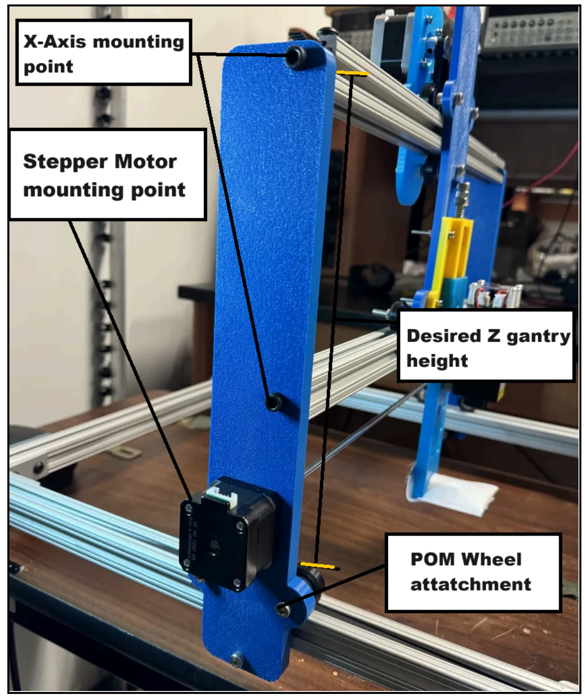


Fig. 3 Gantry Tower design.

C. Designed Mounts/Mechanisms

The process of mounting the laser is intricate, rightfully because of the precision required to operate a laser engraver. There are four parts required to properly mount the laser, lens, and the two spectroscopy components, the LED and the optical fiber. All parts were designed using SolidWorks.

First is the laser gantry panel which is designed to connect the other parts to the gantry system to be moved. Connected to that panel is the Z-axis height adjuster, which is made of two 3D printed sliding parts, an M6 threaded rod, and a barrel nut. The threaded rod is stationary, spring-locked in place, and when it is turned it adjusts the height of the laser. The last printed part is simply a 7.8mm block to raise the height of the laser module's optical axis to the same height as the mounted lens. The laser gantry panel is also equipped with two POM wheel mounts which greatly reduces vibrations in the system and maintains a better engraving resolution.

Together these parts mount the laser on the gantry system and enable the laser’s movement to engrave.

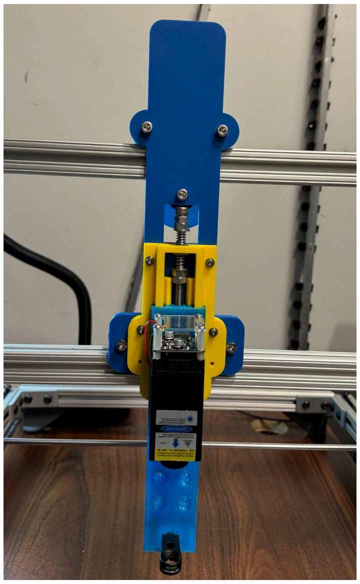


Fig. 4 Laser module mounted on the Z-Axis Height Adjuster, which is mounted on the Laser Gantry Panel

D. Laser System

The laser system was designed with safety and simplicity in mind. The laser diode module operates at 450 nm with a maximum output power of 4W. This is a Class 4 laser and must be operated with extreme caution. We are employing a fire-retardant enclosure which acts as a black box so no laser radiation can escape. Using this enclosure, our Class 4 laser system is now reduced to a Class 1 laser system, according to the Board of Laser Safety.

Our laser system uses 2 lenses to focus the quickly diverging laser beam. The first lens is a biconvex which is attached to the laser module and has adjustable focus. We adjusted the focus to 20mm from the aperture, and are using a single lens imaging system, the 2f System, to focus the light. This lens is a 13mm diameter plano-convex with an effective focal length of 30mm and it is positioned 2 focal lengths away from the image plane of the first lens. The spot is focused again 2 focal lengths away from the lens. We chose to use an extra lens, specifically a plano-convex, to reduce the spherical aberration of the beam. [JG1] The current measured smallest spot size is 56x80 , which is well below our initial spot size requirements.

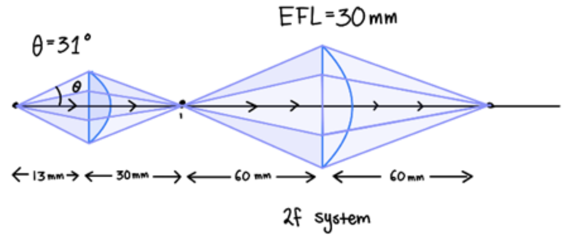


Fig. 5 Design of the optics used in focusing the laser beam

E. Spectroscopy

To accurately identify materials, we designed and constructed a low-cost spectrometer to analyze light reflected from each material's surface. This process mimics the way our eyes differentiate materials based on color and intensity. A custom mount secures the spectrometer to the laser module, which houses a high-power white LED and a fiber-optic cable. This setup directs light at a 45-degree angle onto the material's surface and collects the reflected light through the fiber. The reflected light enters the spectrometer for analysis.

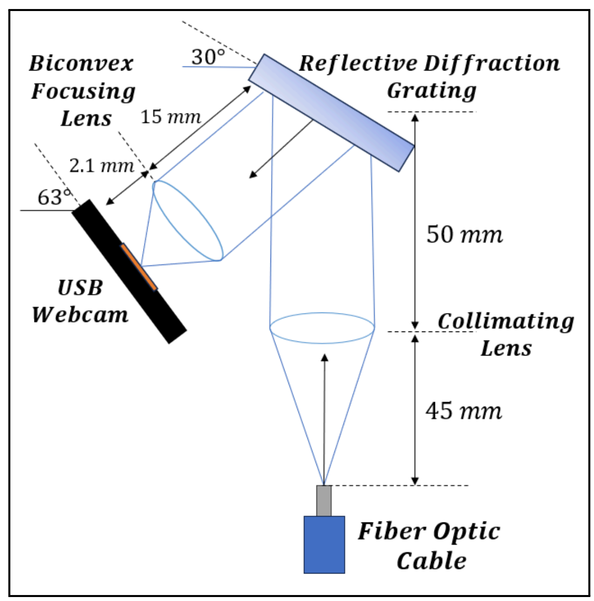


Fig. 6 Design of the optics within the spectrometer with detail on component spacing and orientation

The spectrometer's 3D-printed housing blocks external light from affecting spectrum readings. The housing contains a fiber optic post, a collimating lens, a reflective diffraction grating, and a USB webcam. These components are precisely positioned on a 3D-printed board for accurate and consistent readings.

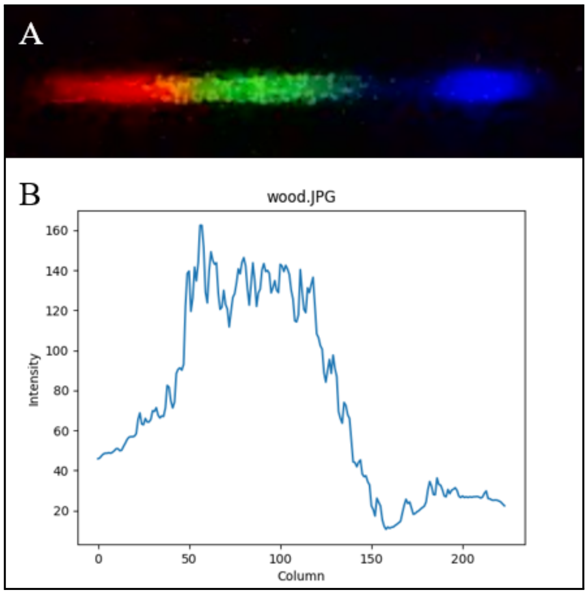


Fig. 7 A) Spectrum of pine wood taken with the spectrometer. B) Associated spectrum of pine wood taken by collecting a 1D slice of the spectrum.

The fiber post precisely positions the fiber, directing light output at a normal angle to the collimating lens. This lens, with a 25 mm diameter and 45 mm focal length, was carefully chosen to maximize light collection efficiency based on the fiber's numerical aperture (NA). The diffraction grating is placed directly after the lens, oriented to reflect a specific spectral mode towards the webcam. The webcam, positioned at an equivalent height and appropriate angle, is optimized to capture this reflected mode of the spectrum.

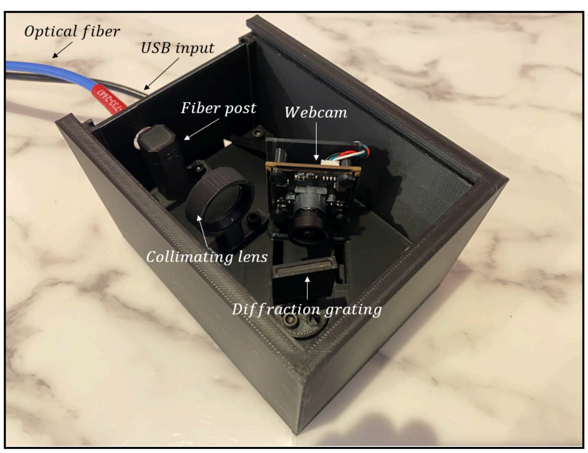


Fig. 8 Spectrometer housed within a 3D printed body, with fiber mount, collimating lens, reflective diffraction grating, and webcam.

The diffraction grating separates incident light into its component wavelengths, creating a spectrum captured by the USB webcam. We selected a reflective grating with a line density of 600 lines/mm for optimal wavelength separation. A reflective grating was chosen over a transmissive grating because it offers greater stability and accuracy in the presence of mechanical shifts, making it ideal for our application.

The fiber used in our project is the Ocean Optics QP400-2-VIS-NIR, which has a core diameter of 400 micrometers, allowing a wavelength range spanning from 400 nanometers to 2.1 micrometers, and extending to a length of 2 meters. We chose this fiber for a number of reasons. Firstly, its wide core diameter improves light throughput, thereby amplifying the sensitivity to reflected light entering the system, consequently improving material identification. Secondly, the robust construction of the fiber ensures durability, while its ample length facilitates seamless integration within the laser engraver, mitigating concerns regarding potential damage or compromise in performance.

In practice when analyzing a new material, the LED on the laser mount activates, and the webcam captures an image of the spectrum. This spectral data is stored for future comparisons. For known materials, the captured spectrum is compared against previously stored data to determine the closest match, enabling material identification.

III. Printed Circuit Board Design

Our primary PCB functions as a CNC controller. The controller board is independent of the spectroscopy system and only functions to control the laser engraver. Both our controller board and the spectroscopy camera interface directly with the PC, which acts as the control hub for the entire system. The PC runs the Python program, which initiates the spectroscopy and classification of the material. It then begins the g-code sender, which communicates with our controller board.

The controller board has the capability to drive three stepper motors in the X, Y and Z axes as well as the 12V diode laser. The primary components of our board include the ATMega328P microcontroller, CH340G USB to Serial converter, JST headers to connect to the power board and headers for the A4988 drivers boards.

Our power solution consists of a 12V DC to 5V DC step down circuit. We use an adjustable switching regulator, the LM2576 by Texas instruments. Initially, we had designed the power solution as part of the same main PCB. The original voltage regulator circuit used the LM2678. However, after breadboarding our original design, we found that it had issues starting up so we switched to using the LM2567. We also decided to split the board into a power board, with the voltage step down circuit, and a main board with all the required parts for the controller.

PCB Details

A. ATMega328P Microcontroller

In our system, we included one of the most commonly used microcontrollers, the ATMega32. This primary controller is a 32-pin MCU that was chosen not just for its common usage which includes a variety of information online regarding it in datasheets or on online forums, but also for its collaborative usage in GRBL. These are hardwired specifically to be the pins used in the ATMega32, which can let us create a makeshift CNC controller. The pins included on an ATMega32 are the same as those used within an Arduino. This microcontroller offers a plethora of features such as its support of various communication protocols such as SPI, UART, or I2C, with these then being used to interface to the project. The MCU will be placed onto our printed circuit board and be used to control the logic being done by the motors, the drivers, and the laser diode.

B. A4988 Motor Controller Driver

As precise control is key in our design, we included drivers known as A4988 that will enable us to control the stepper motors needed. These drivers take in an input voltage of 12V to power the NEMA 17 motor, and 5V to power the logic itself. These then output 1A per motor. The primary reason for choosing these to be placed into our design were for their versatility seen in CNC machines, with it being a commonly used component. This allowed for a larger variety in research and documentation to be easily accessed. With each stepper motor needing its own driver chip to control it, three accounted for in our PCB design.

C. Nema 17 Stepper Motor

Within our project, we had the task of controlling three individual motors for our CNC machine. Therefore, the one chosen was the NEMA 17, as this provided the appropriate torque required, as well as an adequate size for the engraver itself. This made it a reasonable and sufficient choice for our PCB design. Each will be included for each axis, X, Y, and Z movement.

D. CH340G USB - Serial Converter

To completely integrate our system to include the transferring of data, we had to include a component that had the necessary requirement of connectivity. For this, we included the CH340G as the primary component allowing us to communicate between the microcontroller and the computer through the interface of the USB. This USB to Serial converter offered flexibility as well, since it includes a compact size allowing for seamless inclusion on the PCB.

E. LM2576 Switch Regulator

Over the course of this project development, we had several revisions done on the design, how we originated with an LM2678 which ultimately failed us. This led to our new component being chosen, known as the LM2576. This was then breadboarded and confirmed to work, which was then chosen at last. Since our device will be powered completely by a single 12V jack, a converter was necessary to step down the voltage to 5V. The component used can be adjusted to input 7V - 60V [1]. The equations for solving for voltage output and the resistors is shown below:

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right)$$

$$R_2 = R_1\left(\frac{V_{OUT}}{V_{REF}} - 1\right)$$

We can then conclude using these equations that for our project we will then require R1 and R2 to be 1k and 3k Ohm respectively, to get our desired output of 5V.

F. 12V 1.6A 450nm Laser Diode

One of the key components that needed to be included correctly within our PCB design was the pinouts used for the laser. The laser diode we chose is responsible for engraving on our system. The laser has 3 pins in total, 12V, GND, and PWM. Due to this, a 3 pin connector was included into the system allowing streamlined connection to the ATMega32 to control the output of the laser.

G. PCB Summary

For our project, we decided ultimately to include two separate PCBs, as one will be responsible solely for the power input and output to the main board. Both of these were designed originally with AutoDesk Eagle, before then being transported over to be redesigned on KiCad. Every component and circuit placed onto the board has its own purpose. The power PCB takes in a 12V input from a jack, which then further steps it down to be 5V using the regulator. It then has three additional JST connectors, one for outputting 5V, one for 12V, and the final one as a connector for the additional white LED that will be used to maintain an accurate system in the enclosure for the spectroscopy. A master switch was also included into the final design of the power board, ensuring safety continuing to be a priority. A picture of the described power board can be found below:

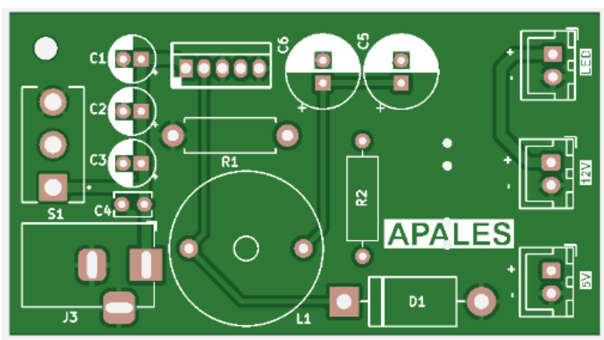


Fig. 9 Final Layout for Power board.

In addition to the board being used for powering, we also design the primary board which encompasses every other circuit required in the system. This includes the microcontroller, the ATMega32, various connectors for the drivers, the CH340G used for converting data, a connector for the laser, various pads for the clocks, etc. Both PCBs were designed with a standard 2-layer board layout, with components being placed on the top layer, either through surface mount or through hole. Below is a picture of the final main board layout:

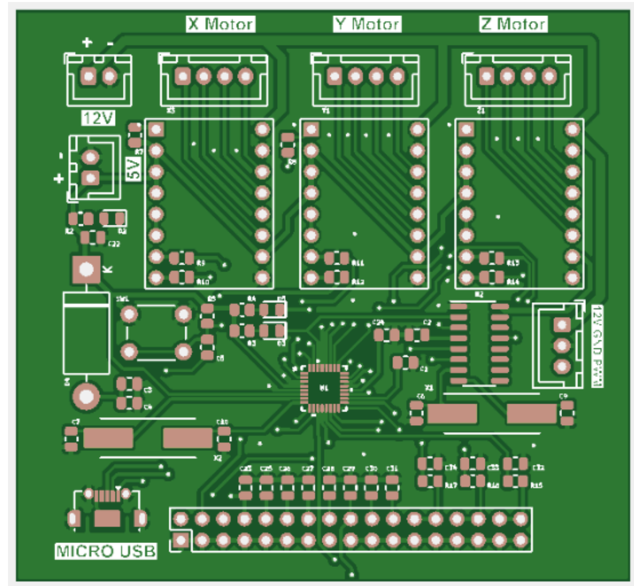


Fig. 10 Final layout for main controller board.

IV. Software Details

A. Spectroscopy Software

APALES uses reflection spectroscopy to identify each material. To accomplish this, we must correspond spectrum data with each material. We can use a computer vision library to assist with this process. OpenCV is a computer vision library for C++ or Python and is used within our code. We use OpenCV for functions like cv2.VideoCapture to capture an image and store it into our computer. Our Spectroscopy system code called *SpectroscopySystemOpenCV.py,* uses plenty of the OpenCV library functions that can boost the resolution up, write data to a file, and affect image colors.

Some add-ons from the OpenCV library are APIs (Application Programming Interface) that can be configured on functions that can help performance. Some APIs boost the speed at which the image is captured on the webcam and processed in a certain resolution. Using the API called CAP_DSHOW, our code changes the time it takes to run from around 12 seconds to less than 2 seconds. This is an enormous improvement and with that being one of our main engineering requirements, it helps.

The Spectroscopy system works in steps. The first step is the OpenCV library uses the camera to take a picture and stores that image into a file. That file is manually changed to a resolution we want. The more pixels in an image, the better results and data we have to use for comparisons. When that is done, we take a snip of that image which is the area where the spectrum lies. That spectrum is then converted to a grayscale image and turned into a text file of 1D array data. Images are in a X and Y image format so to convert the image from a 2D array of data, we can take the average of each column to make it a 1D array. This is saved into a place for our existing materials when we start the system.

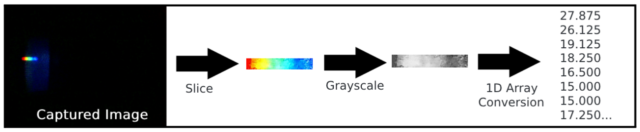


Fig. 11 Steps to convert spectrum image of a material into grayscale 1D grayscale array data.

B. Array Comparison

To measure our system's accuracy, we first must figure out a way to be able to compare data. When the data is stored as explained in IV.B, it is in files in a 1D array format. We must be able to compare the array data with other arrays. To compare the array files to each other and see which one is similar to the reference array we are using to measure, we can use Euclidean Distance. Using the Euclidean Distance formula:

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

Knowing this and that Python's built-in library, *numpy* has a built in euclidean distance function, we can implement this idea into our code to compare the arrays with each other at a precise measurement. The time complexity of the euclidean distance formula is O(n) and the space is O(1). This is decently fast speed unlike O(n^2) which is one of the longest and that O(1) is the fastest time complexity. Running the code called *array1Dcomparison.py,* we can test the speed of the code and see that we can have less than 1 second to get our results. The code cannot compare if the array sizes of each comparison are not the same. That is not a problem for us due to the slice always having the same resolution to compare which means that there will always be the same exact amount of array indexes.

C. GUI Implementation

To combine all the code into one area for the user, a GUI can be used to give the user simple access to use the whole spectroscopy system. The GUI has a menu with a dropdown for the user to select either "New Material" or "Existing Material." The "New Material" option lets the user input details of a material not in the database such as: name, laser speed (mm/min), and S-Max (G-code parameter). That gets stored into a text file with the name of the material and keeps those parameters to send to our g-code to start engraving. The name is also used for the 1D array data text file of the material when the user uses the spectroscopy system. The "Existing Materials" option has a spectroscopy system button as well to do the whole system when the user uses a material already in the database of 1D arrays to compare with. If a match is found then they can start the engraving process. If not, the user can input the details of the material.

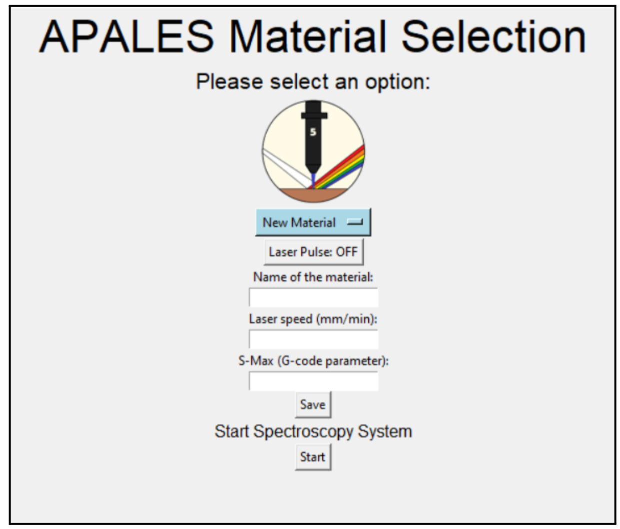


Fig. 12 Image of GUI application in "New Materials" option.

D. G-code Parameter and Sender

The g-code file contains all the data required for the controller to produce the desired engraving. We parametrize the g-code based on the material. There are two parameters that we alter: the feed rate (F parameter) and the laser duty cycle (S parameter). The feed rate is the speed of the tool or laser in millimeters/minute as the machine is moving. The laser duty cycle corresponds proportionally to the diode laser's intensity. This parameter is constantly changing throughout the engraving job. There is a scaling factor associated with the laser ablation threshold of each material.

When parameterising the engraving job, we change the max PWM duty cycle allowable in the g-code based on the scaling factor. Since the g-code is a text readable file, we automate the parameterisation process in our program. It parses through the base g-code file, where max allowable duty cycle is set to 100%. For every instance where the parameter appears in the g-code the program pulls the substring and scales the parameter down according to the material requirements. For example, a material requiring an S-Max of 30% would have the S parameters in its g-code multiplied by 0.3. Similarly, for the feed rate, every instance of the F parameter is updated according to the material requirements. However this is a simple replacement of the substring rather than a scaling update.

Once the g-code is updated for the corresponding material, the Python program begins sending the g-code to the controller board through using PySerial. The g-code file is sent line by line to the GRBL firmware on the microcontroller. GRBL allows multiple g-code lines to be received and sends 'ok' back to the PC through the serial interface indicating when more g-code lines can be received .

VII. Conclusion

In summary, APALES (Automatic Parameter Adjusting Laser Engraving System) required a ton of persistence and significant design in laser engraving technology, offering precision and efficiency in the process through the use of material detection using spectroscopy. Our goal that we strived for was for it to continue streamlining and allowing for a user friendly environment with features such as the detection that allows it to be a valuable tool in the wide industry of laser technology.

As it has been demonstrated within this report, our system known as APALES offers a genuine amount of potential to revolutionize the industry. The team continues to move forward, continued research will be developed to further refine APALES and ensure that it continues being an effective and stable system with a reliable outcome for a variety of applications.

Acknowledgement

The entire team owes a thank you to Everix Optical Filters for supplying our team with the 80-20 aluminum T-slot rails for our frame. This project would not be possible without them!

Many thanks to the Texas Instruments Innovation Lab at UCF. Isaac Joshua, Nathon, and Jared were tremendously helpful in 3D printing most of our parts.

The PCB team consisting of Felipe Mosquera and Aly Megahed would like to give a personal thank you to Jocelyn Ignacio for the additional consultation provided with the development of our printed circuit board.

The Senior Design Team would like to acknowledge and thank Gianni Luna, and for his consultation during the development of our CNC system.

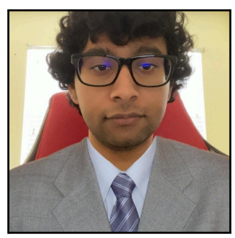
References

[1] Texas Instruments, "LM2576xx Series SIMPLE SWITCHER® Power Converter 3-A Step-Down Voltage Regulator," SNVS107G, JUNE 1999 [MARCH 2023].

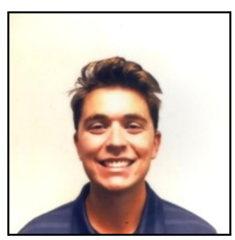
The Team

Felipe Mosquera will graduate and receive his Bachelors of Science in Computer Engineering in May 2024. He is currently working at Duke Energy as an engineering intern and plans on continuing his position within the power industry, focusing on completing his PE and FE exams in the near future.

Aly Megahed is a Computer Engineering major and will graduate with his Bachelor's in May 2024. He plans to work in the embedded software industry.



Kavinaash Jesurajah is a Computer Engineering major and will be graduating in May 2024. He is currently working as an intern at Siemens Energy as a Project Manager. He plans to work in the gas industry and learn to be more experienced.



Nolan McGinley will graduate and receive his Bachelors of Science in Photonic Science and Engineering in May 2024. He plans to work in the fiber optics industry following graduation and complete a masters or MBA program in the following years.

Jackson Gilliland will be graduating with a Bachelor's of Science in Photonic Science and Engineering on May the Fourth be with you. He has accepted a full time position at Everix Optical Filters as an Optical Applications and Sales Engineer.

Amir Mohd will be graduating with a Bachelor of Science degree in Mechanical Engineering. Post-graduation, he is eager to embark on a career in the automotive design and manufacturing industry, utilizing his skills and knowledge to contribute to innovative projects.