Fabric Laser Cutting System

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***ABSTRACT* — AN ORIGINAL CREOL/CECS PROJECT, OUR FABRIC CUTTING LASER SYSTEM BRINGS AN INNOVATIVE APPROACH TO LASER CUTTING. USING AN IMAGE ACQUISITION SYSTEM, A DRAWN ON DESIGN CAN BE CUT USING OUR LASER MODULE, IMAGE ACQUISITION SYSTEM AND MECHANICAL GANTRY SYSTEM. WITH A SIMPLE USER INTERFACE VIA TOUSCREEN, THIS PROJECT CAN BE USED WITHOUT NEEDING AN ADDITIONAL COMPUTER OR LASER CUTTING SOFTWARE.**

***INDEX TERMS* — IMAGE PROCESSING, COMPUTER VISION, HUMAN-MACHINE INTERACTION, PATH PLANNING, DIODE LASERS, LASER BEAM CUTTING.**

I. Introduction

The idea of F.L.C.S. is a solution solver. The design of this fabric laser cutter will appeal to those who do not have advanced understanding of computers or computer software. Instead of needing a cutting software or specific file or a laptop to upload the desired cut pattern, we can instead use image acquisition and processing to differentiate the desired cut lines from the fabric. This product is for those "old-fashioned" hobbyists or even business owners who might want some technology to assist them in physically cutting, without needing the background knowledge needed for operating software and uploading files.

F.L.C.S can be useful for all types of hobbyists, designers, and manufacturers who desire quick cutting of pieces of fabric at the tap of a screen. By drawing using a black marker on light fabric or white on dark fabric, the user can outline the desired shape of their fabric and click the touchscreen module to cut the desired lines once the fabric is inside the machine. It is large enough to have a variety of practical applications in terms of the large area we are able to cut. If needed, the system can run multiple cuts on the object.

II. Laser Safety

When it comes to operating a laser many safety precautions should be taken to ensure safe operation. Laser classes and standards help us identify how we should be using and behaving around our lasers to ensure no one is harmed while making this fabric laser cutter system. We analyzed considerations of the American National Standards Institute as well as Florida Administrative codes. For the laser safety classes, the potential hazard of the laser increases as the number increases from 1 to 4. These hazards are considered in terms of harmful impacts towards our skin and eyes. Products including lasers must have a label listing the classification of the laser.

Class 3 is split into 3B and 3R lasers that include lasers within the visible spectrum. 3R corresponds to lasers with a beam between 1 milliwatt and 4.99 milliwatts of power, so direct eye exposure should be avoided. Whereas class 3B lasers have a beam power of 5 milliwatts to 500 milliwatts, or half a watt, and any exposure to this beam should be avoided. This includes lasers that can harm your skin and materials if held long enough at close range. When considering exposure to beams from any class of laser, include considerations of stray or reflected beams.

Class 4 lasers are the biggest concern, as these need-controlled measures to prevent exposure from the direct beam or a reflected beam. These lasers have the potential to ignite and create fire, causing airborne byproducts or materials. These lasers are greater than a half of watt of power and pose a threat to your skin and materials from burns. Do not stare at these lasers even when the laser dot is on another surface, and the light can be bright enough to cause a sustained afterimage lasting longer than 10 seconds. If this sustained afterimage occurs, laser light is too bright [1]. When operating any laser, it can be useful to have a laser safety officer contact to ask questions regarding your specific setup or design.

Since the laser output of our laser diode will be variable it can range from a class 3 to a class 4 laser. This is why we have taken precautions to have an enclosure system that includes OD6+ laser safety windows and a HEPA filter, as well as implementing a fire sensor.

When comparing laser sources, we considered fiber, CO2, solid-state, and semiconductor lasers. These were the main types used in different types of laser cutting, including cutting metal and non-metal objects. We kept our wavelength range within the visible wavelength spectrum since an infrared wavelength would be hard to align without an infrared viewing card. The most common type of laser used for non-metallic objects are CO2 lasers, while fiber lasers will work with most materials although they are limited in the material thickness they can cut. With the laser engraver we purchased, shown below, we gained a diode laser module. Using a laser diode as our source is convenient as it does not require mirrors to create a resonator cavity, like solid-state lasers, or a chamber for gas, needed for CO2 lasers.

III. System Components

The Fabric Laser Cutting System can be explained by the culmination of its subsystems.

A. Controller

In evaluating potential controllers for this project, multiple options were considered from the Arduino Mega 2560 to the Raspberry Pi 4B. The Raspberry Pi 4B was selected as the primary system controller due to its ability to support a full Linux operating system, enabling the implementation of a touchscreen-based human-machine interface and the execution of multiple software processes. Compared to the microcontroller-based options such as the Arduino Mega 2560 and ESP32-WROOM, the Raspberry Pi provides significantly greater computational capability, memory, and graphical support, which are essential for image processing and user interface management. Although higher-performing alternatives such as the Jetson Nano were considered, the Pi 4B offers a more balanced solution in terms of cost, power consumption, and system maturity in the form of great community support and proven reliability.

B. Touchscreen

Three candidate touchscreen options were considered: the Raspberry Pi Touch Display 2, a set of generic 7-inch HDMI panels (such as the Waveshare and Elecrow 1024x600 models), and a 10.1-inch HDMI touchscreen (such as the ROADOM 1280X800 display). In the end the Raspberry Pi Touch Display 2 was chosen due to its use of a native MIPI-DSI ribbon for video and draws power directly from the Pi's GPIO header, yielding a compact, lightweight assembly with minimal cable clutter. This tight integration also reduces potential mechanical strain on connectors and improves long-term reliability in an enclosed system where space is limited. Since it is an official display, it's supported natively within Raspberry Pi OS so no external USB drivers or calibration utilities are required, ensuring plug-and-play operation and long-term maintainability.

C. Laser Engraver

To complete this project, we purchased a Twotrees TTS-55 laser engraver equipped with a Makerbase MKS LS ESP32 PRO V1.1 motherboard, 5.5W laser module emitting a 450 nm blue beam, and a belt driven mechanical gantry system. These belts are driven by three NEMA17 stepper motors; one for X-axis (left to right) movement and two for Y-axis (forward and backwards) movement.

D. Gantry Carriage

The gantry carriage, originally meant to hold the laser module, is repurposed to mount the mirror which reflects the laser beam downwards towards the target fabric, the aspheric lens which focuses the light into a small point, and two downwards-facing photodiodes which detect the amount of light being reflected off the material.

Using a NEMA11 stepper motor, the height of the lens from the fabric can be adjusted based on the fabric's thickness to ensure the focus point of the beam is at the best height to cut the fabric. The photodiodes are at the same height as the focusing lens. The angle of the mirror can be finetuned using a knob to ensure the beam is directly incident onto the fabric and lens. The height of the entire carriage can also be adjusted on a mounting rail which the carriage can then be friction locked onto.

E. Photodiodes

The two photodiodes mounted on the carriage of the gantry detect the light scattered from the laser spot by the fabric. They are slightly angled facing towards the spot and send these signals to an analog to digital converter which then sends the signal to the Raspberry Pi.

The VTB8440BH photodiodes were chosen since they have a peak spectral response at 580 nm, a high responsivity and made from quality materials like glass and ceramic. Since the reflections from the fabric may be very intense, a frosted material is placed over the photodiodes to diffuse the light to reduce the photodiode's exposure to the scattered light.

IV. System Concepts

To best understand our system, the following flow maps are helpful visuals.

A. Lens System

The optical system shown in Figure 1 uses three lenses and an anamorphic prism pair, all secured by 3D printed mounts, to keep the laser diode beam collimated and enlarged as it approaches the mirror guidance system with the focusing lens. Collimation of the beam is essential because it minimizes divergence, or widening, of the beam as it travels. The initial lens of the system is aspheric followed by the beam expander system composed of two lenses, expanding the beam size incident on the anamorphic prism pair. This anamorphic prism pair helps collimate the beam after it is expanded.

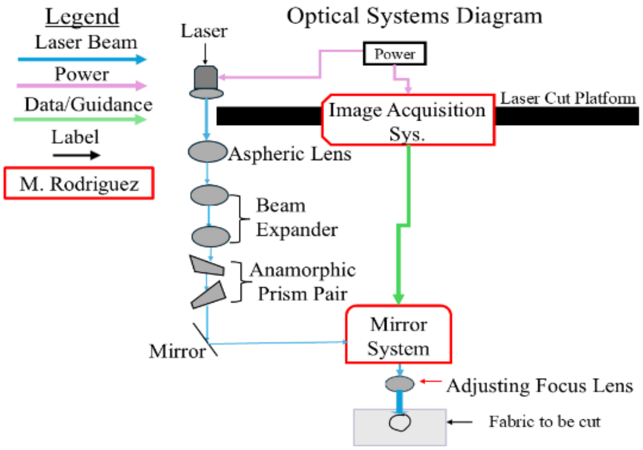

Figure 1: Optical Systems Diagram

To expand the beam, we utilize a two lens Keplerian beam expansion setup. Expanding the beam ensures the beam spot size on fabric will be small because the incident beam on the focusing lens is large. For our system we chose a plano concave and plano convex lens of specific back focal lengths to give us our desired expansion.

Our beam expansion system gives us a magnification or M of -4.9, shown in (1), resulting in a diverging beam of almost 5 times its initial size. High magnification was desired due to the assumption that the initial beam size will be in micrometers.

$$\frac{Back\ Focal\ Length\ (Plano - Convex)}{Back\ Focal\ Length\ (Plano - Concave)} = \frac{125}{-25.4} = -4.9 \quad (1)$$

When combining our lens into an optical system we can utilize Zemax OpticStudio to get an idea of our beam behavior due to our lenses and subsequent coatings. This software does not allow us to account for the initial beam shape due to the use of a laser diode or account for the addition of the anamorphic prism pair. we neglected to include those simulations in this paper.

B. Mirror and Focusing System

To guide the beam from the lens system to the desired spot on the fabric, three E02 coated dielectric mirrors are used to reflect the laser. These mirrors reflect over 99% of light in the visible spectral range and have a high damage threshold for powerful incident light.

The first mirror is stationary, aligned with the vertical lens system, and reflects it horizontally across the Y-axis. The second mirror the beam encounters moves with the gantry rail; traversing across the Y-axis. This mirror reflects the beam 90° from the Y-axis to the X-axis. The final third mirror is mounted on the gantry carriage and is angled downwards; reflecting the beam 90° from the X-axis downwards across the Z-axis and onto the focusing lens underneath.

Since it is extremely difficult to 3D print solid mirror mounts specifically for the exact position and angle at which they need to be placed without aligning them first, these mounts are designed to be shiftable. The user can align the mirrors by shifting their locations and angles and lock them when the mirrors are aligned.

The aspheric lens following the final mirror focuses the beam into a small spot onto the fabric. Since the thickness of the fabric can vary, the lens is able to be adjusted vertically so that the smallest kerf size and finest cuts can be achieved. The lens has a focal length of 17.9 mm so that the carriage can maintain a safe distance from the fabric.

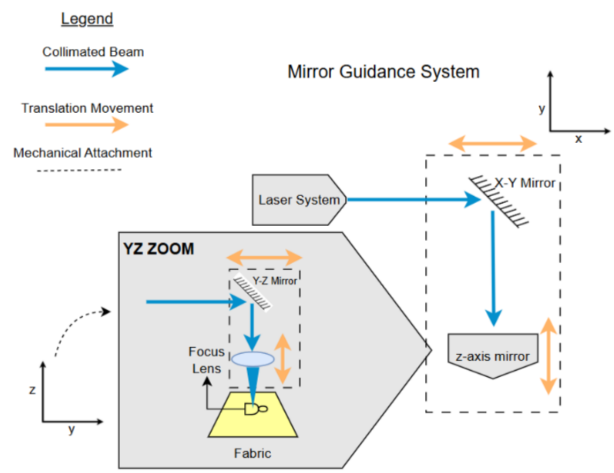

Figure 2: Schematic of the mirror guiding system. The first mirror is integrated in the laser system. The X and Y axis in this diagram are inverted from the real X and Y axis

C. Hardware Flow

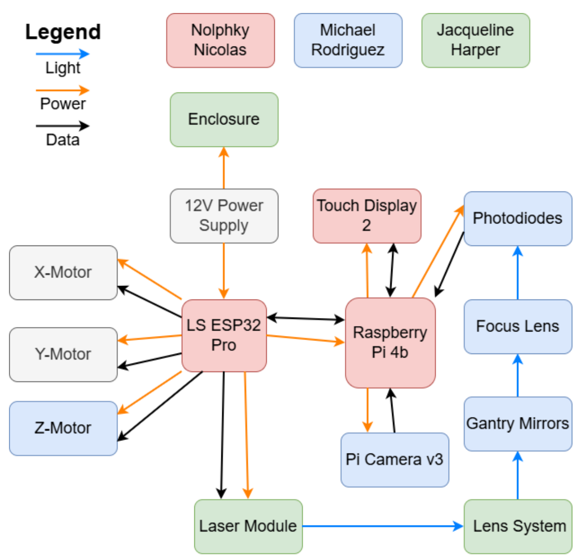

Figure 3: Hardware Block Diagram

Figure 3 shows the hardware block diagram for the overall project design. The hardware block diagram illustrates how power, data, and laser light flows throughout the system. The power supply unit from the laser engraver serves to provide and distribute stable power to all of the components. Each of the subsystems work in tandem to deliver the final product. This Figure is color-coded to establish who in the team will be responsible for that task.

D. *Software*

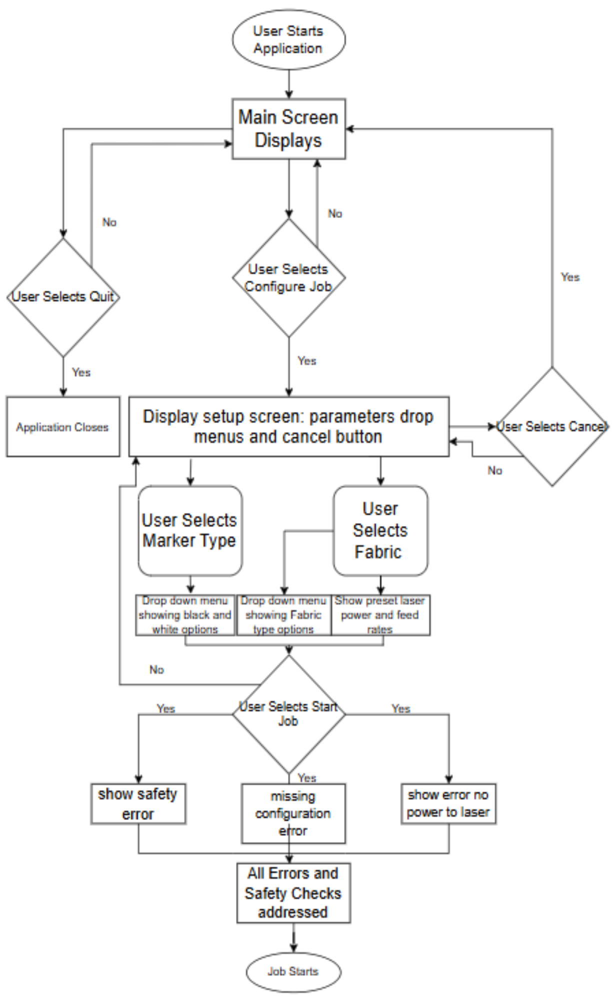

Figure 4: Starting a Job Flowchart

As seen in figure 4 above, the software workflow begins when the user is presented with the application as soon as the pi turns on. From the main interface, the user may either exit the application (effectively turning off the HMI) or proceed to configure a cutting job. Upon selecting the configuration option, the system displays a setup screen that allows the user to define key parameters, including marker type and fabric selection.

Marker type selection enables the system to adjust detection settings for either black or white markers, while fabric selection determines preset laser parameters such as power or feed rate. These inputs ensure that the system is properly configured before execution.

Once configuration is complete, the user may initiate the job. Prior to execution, the system performs a series of validation and safety checks, including verification of required configuration parameters and system readiness. If any errors are detected, appropriate error messages are displayed. Only after all conditions are satisfied does the system proceed to execute the job ensuring a safe environment for the user.

This structured workflow ensures that the user has an easy time starting a job.

V. Software Detail

A major component of the Fabric Laser Cutting System (F.L.C.S.) is the integration of its subsystems through software. The primary functionality of the system lies in its ability to capture and analyze user-drawn shapes and convert them into G-code instructions that control the laser engraver. In addition, a touchscreen-based human-machine interface serves as the primary point of interaction for the user, guiding the workflow from image acquisition to execution. Together, these software components enable a seamless transition from visual input to physical output.

A. *Human Machine Interface*

Our system uses a touchscreen-based human-machine interface (HMI) implemented in Python using the Tkinter framework. The HMI is designed to operate in a kiosk-style environment running on a Raspberry Pi 4B, allowing users to interact with the system without the need for an external computer or program. The interface provides an intuitive workflow for capturing images, configuring parameters, and executing cutting operations.

The HMI is structured into multiple functional pages, including a Home page, Camera page, Job Setup page, Settings page, and Status page. The Home page serves as the central hub allowing access to the other pages. The Camera page provides a live preview of the workspace and allows users to select which marker type they are using and capture images for processing. The Job Setup page allows the user to configure parameters such as laser power and feed rate. The settings page is for app configuration such as switching between dark and light mode, and the Status page provides real-time feedback during operation such as time to completion and errors.

B. *Camera Capture and Analysis*

A core feature of the F.L.C.S. is its ability to convert user-drawn marker traces into cutting paths for the laser to execute. This is achieved through a multi-stage image processing pipeline implemented using OpenCV.

The pipeline begins by simply capturing a snapshot using the Picamera2 interface. Frames from the live preview are resized to reduce computational load and improve responsiveness. Once an image is captured, it undergoes preprocessing to enhance contrast and improve feature detection. Contrast Limited Adaptive Histogram Equalization (CLAHE) is applied to normalize lighting variations and improve the visibility of marker lines.

After the preprocessing stage, the system performs adaptive thresholding to isolate the marker from the background. The system supports both black marker and white marker modes, allowing it to operate on a variety of fabric colors. Gaussian adaptive thresholding is used to dynamically adjust to uneven lighting conditions across the image.

To reduce noise and eliminate small artifacts, morphological operations such as opening and closing are applied. These operations help remove isolated pixels and smooth the detected regions, improving the reliability of subsequent processing steps.

Following noise reduction, connected components or contour detection methods are used to identify potential regions corresponding to marker traces. The system will then extract the most relevant components based on size and structure. In earlier implementations, multiple detected regions resulted in unwanted artifacts. To address this, a filtering approach was introduced limiting the number of detected shapes based on user selection (e.g. one to three primary regions).

Once the relevant regions are identified, a skeletonization process is applied to reduce thick marker strokes to single-pixel-wide paths. This step improves accuracy of path extraction and ensures consistent toolpaths. THe resulting skeleton is then used to generate an ordered sequence of points representing the trace.

C. *G-code*

The extracted path from the image processing pipeline is converted into G-code instructions suitable for controlling the laser engraver. This process involves mapping pixel coordinates to real-world dimensions based on the known size of the cutting bed.

The system assumes a fixed working area and applies a linear scaling transformation to convert image coordinates into millimeter units. The generated path is then translated into motion commands using standard G-code syntax. At the end of each job, the system issues commands to disable the laser and return the gantry to its original starting point.

D. *Serial Communication and Execution*

The generated G-code is transmitted from the Raspberry Pi to the laser engraver controller using a serial communication interface. Communication is implemented using the PySerial library and follows a standard GRBL-style streaming protocol.The G-code file is then transmitted line-by-line. After each command is sent, the system waits for a response from the controller, typically an "ok" or "error" message, before proceeding to the next line.

This handshake-based approach ensures reliable execution. The system also ignores comments and blank lines to streamline communication. Progress updates are periodically provided to the HMI, allowing users to monitor execution status in real time.

In addition to normal execution, the system supports basic control operations such as start, pause, and abort. These controls are critical for safe operation, particularly when dealing with lasers.

E. *System Firmware*

The original ESP32 firmware can accept G-Codes to dictate the movements of the motors connected to the X and Y axis motor pins and the average power of the laser module. A setback in the project though was the lack of support for the Z motor port. A TMC2208 stepper motor driver was installed on the z axis motor drive socket of the board. Though the motor was being powered by the driver, the motor never rotated when G-Codes meant for that motor were sent.

Therefore, it was decided that the board had to be flashed with new software to be able to enable the movement of this additional motor. FluidNC was used to flash the board, which allowed for full customization using a config.yaml file that gave full access to GPIO pins and board behavior. It also included a web UI accessed when connected to the board's Wi-Fi where the file could be uploaded and the G-Codes could be tested.

VI. Testing

The main goal of this project is to successfully integrate our subsystems so they may operate smoothly to carry out their functions. We will be utilizing a photodiode system to measure reflectance returning to the lens system while it is cutting the fabric. The image acquisition system will collect data regarding the location of the fabric to be cut, and this information will be communicated to the mirror system to direct the beam. The power system will supply power to our components, including the laser system which will be dormant until the touchscreen communicates to start a cut.

A. Image Processing

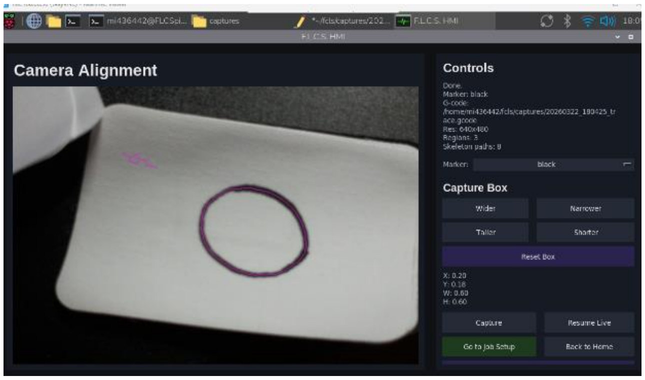

Figure 5: Trace Detection Failure

The performance of the image processing pipeline was evaluated using a variety of user-drawn marker inputs. The system demonstrated reliable detection and tracing for basic shapes such as squares and triangles, successfully converting these inputs into continuous toolpaths suitable for G-code generation.

However, several limitations were observed during testing. The system is sensitive to variations in lighting conditions and background texture, which can introduce noise and result in unintended detections as seen in Figure 5. To remedy these issues, multiple improvements were made, including adaptive thresholding, morphological filtering, and the introduction of selectable marker modes (black or white). Additionally, a constraint on the number of detected regions was introduced to limit the impact of noise when multiple objects are present.

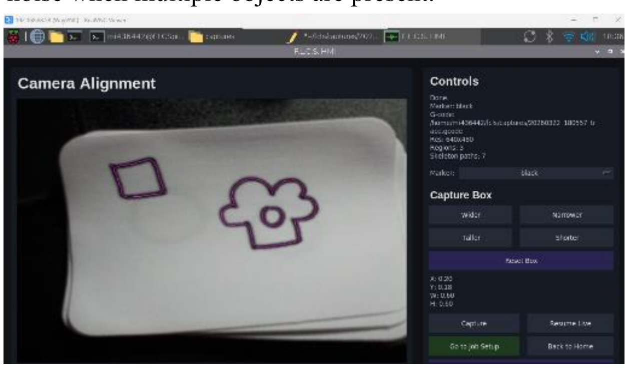

Figure 8: Trace Detection Success

B. Lens System

Prior to purchasing the laser engraver, we were able to see our expansion and shaping system work with a laser pointer, shown in Figure 6. In order of appearance, we have the anamorphic prism pair, aspheric lens, and beam expansion lenses shaping the red dot you see on the right.

Once the laser engraver was purchased, we created a 3D-printed rail that includes a mount for the laser module. The

Figure 6: Initial Testing of Lens System

lens mounts were previously 3D printed which allowed for easy integration. Figure 7 is an example of early integration stages, where we were using a final lens of longer focal length, the LB1945, giving us a larger magnification than needed. This required us to move to what we currently use, the plano convex lens, the LA1613, instead of the LB1945. Additionally, we confirmed the shape of our laser beam was already a circle, meaning we did not need to use the anamorphic prism pair to initially shape the beam as planned. This instead allows us to use it at the end of the system to help collimate the beam if needed.

Figure 7: Early Stages of Laser and Lens System. The laser module is on top followed by the aspheric lens and beam expansion pair. The beam is too large and is onset a white screen

VII. Citing Previous Work

When investigating similar products and projects, we found a senior design project with similar end goals to ours, as well as a multitude of commercially available lasers that cut materials ranging from wood to steel but excluding fabric.

A. APALES- Senior Design 2023-2024

This past UCF Senior Design project named "Automated Parameter Adjusting Laser Engraving System" serves as an example of what we seek to build. This project used specific laser power and scan speed for each distinct material to be engraved. Each unique material was identified by a spectrometer, and the laser's power and speed were adjusted to operate on that material. Shapes could be engraved, but also a particular image could be uploaded to an application to have that engraved [2].

Our laser system will vary because we will cut through certain fabrics using presets determined during testing and we will not be creating a spectrometer system.

C. Open Source Buildlog.net 2.x Laser

The Buildlog 2.x laser is a second generation open-source laser cutter that employs a 2-axis rail-based XY gantry system, with an additional manually adjustable vertical axis. Unlike our proposed fabric laser cutter, the Buildlog 2.x does not have a human-machine interface (HMI). Instead, it relies on tethered computer control for job setup and execution [3]. Our design introduces an onboard Raspberry Pi touchscreen HMI to enable sand-alone operation, real-time job management, and user feedback without requiring a connected computer. In addition, while the Buildlog design delivers the laser via a moving gantry, our project employs mirrors that will steer the beam to the appropriate destination. This approach should reduce the mechanical load of moving the entire laser head and potentially enabling faster operation, though it introduces new challenges in precision alignment and control.

C. Commercial Epilog Fusion Pro Laser

The Epilog Fusion Pro is a professional, industry-level laser cutter that integrates a built-in touchscreen HMI, similar to what we intend to implement in our project. Its 7" display allows a user to select between stored jobs, adjust parameters, auto-focus the laser, and rerun previous cuts directly from the machine without requiring a tethered computer. In addition, the Fusion Pro incorporates an overhead camera system, which provides a real-time view of the work area [4]. These features align with our project goals for our system. By adding an onboard touchscreen interface, our cutter will provide stand-alone job management and ease of use comparable to the Fusion Pro. Although we will not reach the same industrial-grade specifications; we seek to emulate their machine on a smaller and cheaper scale, whilst adding the additional functionality of generating cutting paths directly from user-drawn shapes.

VIII. CONCLUSION

A central accomplishment of the project is the implementation of a beam expansion and directed-optics assembly, which includes a pair of beam shaping prisms, two-lens expander, and a mirror-based gantry system for accurate beam steering. These components allow the laser to maintain a tightly focused spot, with a diameter less than .2 millimeters, across the working area, enabling consistent cutting performance across a variety of fabric types by adjusting the height of the focus lens. In addition to heat management considerations, the PSE students led the characterization and alignment of the optical path, ensuring proper divergence control, safe operation, and compatibility with the mechanical motion system. This was in addition to image-processing logic that allows users to load patterns just by drawing on the fabric.

This project can set a precedent for future laser cutting systems, with its innovative approaches. These approaches include keeping the laser stationary and using image processing to gather data to direct the laser. The fabric laser-cutting system developed in this project has the potential to benefit a wide range of users and creative environments. Small textile businesses could use a compact, relatively low-cost cutter like this to streamline custom garment production, patch creation, or small-batch manufacturing without investing in industrial CO_2 systems. Freelance makers and hobbyists would gain access to a tool that enables precise textile manipulation for cosplay, quilting, wearable art, and personalized fabric design. In prototyping environments, our system's ability to directly interpret hand-drawn lines on fabric provides rapid iteration capabilities, allowing designers to go from concept to physical pattern with minimal preparation time. Additionally, accessibility-centered creative spaces, including community workshops, arts centers, and educational labs, could adopt a system like this to make textile fabrication more inclusive by eliminating the complexity of vector-file generation or Computer Aided Design software. With its simple touchscreen interface and image-acquisition workflow, F.L.C.S lowers the barrier to digital fabrication and encourages creative expression across diverse user groups.

While the system meets its major design objectives, several limitations point toward valuable areas for future work and refinement. Increasing the laser diode power or improving mechanical efficiency could broaden the range of cuttable materials and increase cutting speed, bringing the system closer to industrial performance. More time dedicated to research would allow us to include diverse fabric types, depending on research findings available. Automating material recognition through color analysis, reflectivity measurement, or machine learning would enable adaptive cutting parameters optimized for each fabric type. Specific enhancements to the motion system, such as higher-stiffness gantry mechanics, improved stepper motor control, or closed-loop feedback, would help reduce vibration and improve dimensional precision. Further refinement of the beam-shaping optics could yield a smaller or more stable spot size, improving edge quality and reducing charring. Collectively, these improvements would elevate the system's performance, durability, and overall usability, and they present clear opportunities for continued research and development beyond the scope of this senior design project.

The team faced several challenges throughout development, including losing a groupmate, workflow delays, and uneven subsystem progress, which required adjustments in task distribution and timeline planning. These obstacles ultimately strengthened the project by highlighting the importance of adaptability, documentation discipline, and communication among team members. The completion of this fabric laser-cutting system highlights the importance of being an effective member of interdisciplinary teamwork and represents a significant accomplishment for the students involved, as well as a meaningful contribution to the fields of photonics, electronics, and embedded systems design.

BIOGRAPHY

Jacqueline Harper is a senior at the University of Central Florida graduating in Photonic Science and Engineering with a minor in Engineering Leadership. Jacqueline, or Jacqui, is joining VIAVI Solutions as a R&D Optical Engineer following graduation.

Nolphky Nicolas is a senior at the University of Central Florida graduating in Computer Engineering. Nolphky hopes to pursue a career in research and design for large companies such as Google, Apple, and Microsoft.

Michael Rodriguez is a senior at the University of Central Florida graduating in Photonic Science and Engineering with a minor in Computer Science. Michael, or Mike, is looking to pursue industry or research for a large company following graduation.

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