Green Laser Diode and Laser Galvanometer for Marking Paper - Enhanced Laser Inkless Printer (E.L.I.P.)

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***Abstract* — The Enhanced Laser Inkless Printer (E.L.I.P.) utilizes alternative technology to build upon the previous design, from which it received its name. The E.L.I.P. utilises a laser galvanometer to direct our laser diode to form solid lines upon paper rapidly. Messages can be sent to the E.L.I.P. via the Bluetooth interface connected to a smartphone.**

***Index Terms* — Diode Laser, Lenses, Bluetooth, Programmable Control Board, C/C++.**

I. INTRODUCTION

Printers have become an essential piece of technology for home and work-related activities. To create an image or include characters on copy paper, ink or toner is utilized. Refilling these printers is a common expense for anyone who uses them, but the used cartridges pose a significant environmental risk. Despite the damage caused and the perpetual cartridge payments, they remain the primary means of refueling printers [1].

The Laser Inkless Printer (L.I.P.) senior design group from Spring and Summer 2021 created a working proof-of-concept inkless printer, using an ultraviolet laser diode to burn into paper and a programmed mechanical gantry system to direct the marking process. [1] Inspired by their work, our group plans to advance the previous design and utilize alternatives that they were unable to test due to constraints.

We plan to adjust the design by testing the use of a green laser diode as the engraving laser and a laser galvanometer to direct the laser. Both were considered by the previous group, but were forgone due to financial and time constraints. Additionally, for proper use of the galvanometer, a correcting lens system was required to maintain laser integrity as the mirrors adjust to create desired characters. We chose to forgo a prebuilt mechanical platform like the previous group, as we lacked an additional student to help manage the integration. This would limit our scanning area, but print speed would increase thanks to the galvanometer. We also designed our own system casing from scratch with 3D modeling.

II. OPTICAL SYSTEM COMPONENTS

Multiple optical components work together in our system to properly receive input and mark paper. This section summarizes each system component and the planned materials used.

A. Laser diode

The laser diode has a wavelength of 530 ± 2 nm, an operating voltage of 4 to 5.5 volts, a forward current of 2.2 amps, and an optical output power of 1.65 watts. The operating range of the diode is from 0 to 65 ℃. As a result of passing through mirrors and lenses, we expect a slight decrease in output power. The estimated results alongside our diode visualization are highlighted below. Input power (Pin) is 1.65, reflectance is 0.98, the transmission coefficient is 0.005, and n is the number of lens surfaces the laser passes through. Overall, our calculated output power is 1.538 W.

$$P_R = P_{in} * R \qquad (1)$$

$$P_T = P_R * (1 - T)^n \quad (2)$$

Figure [1] Laser Diode Specifications

For heat management, the holder we designed for the diode was attached with a copper heatsink via a layer of thermal epoxy. We also included a small fan to help dissipate heat from the diode. The diode is driven by a Wavelength Electronics 2.2-amp driver that will be integrated into our PCB. This, alongside our 5-volt regulator, will provide the necessary power for the diode to mark paper.

B. Laser Galvanometer

The laser galvanometer is our design's primary means of directing our laser to mark desired messages on paper. Obtaining a reliable galvanometer was the highest financial cost for our project, as there were few cheap and understandable alternatives online. Thanks to a fellow student's previous employment at the company, we were able to get in contact with ScannerMAX. They specialize in designing galvanometers and were able to help us in the part selection and ordering process.

The two 6 millimeter mirrors can direct the beam through a 45-degree optical field of view. The mirrors are dielectric to reflect visible light. Also included in the package was the motor control board and the power supply for the galvanometer. The 土 24-volts 150-watt supplies the necessary power to the MachDSP, the board that powers and controls the motion of the mirrors.

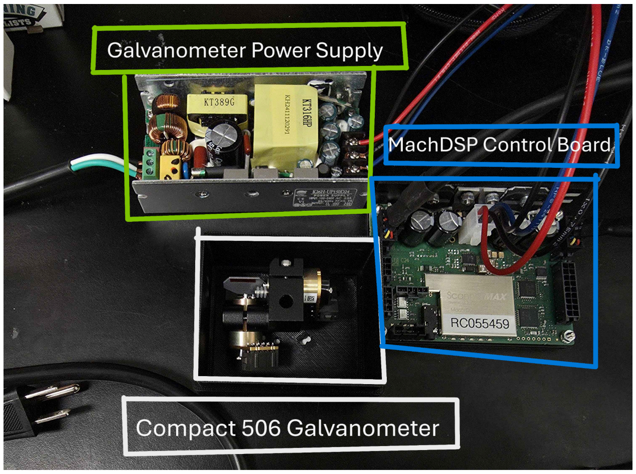

Figure [2] ScannerMAXCompact 506 Galvanometer Package

C. Lens System

The f-theta lens is the most crucial part of any laser galvanometer system intended for engraving. As a laser beam moves, the focal point shifts, resulting in significant power loss. An f-theta lens maintains focus by creating a "flat field" for the laser, ensuring little to no power loss from angle deviation [2]. However, a reliable f-theta lens is priced beyond the scope of our group's budget. After further research, faculty consultation, and AI assistance, a schematic was developed that theoretically replicates the beam correction capabilities of the f-theta lens. Initial tests were promising as paper marking was still possible when powering the laser diode through the mirrors and lenses.

Our lens system consists of three lenses: a biconcave, an achromatic doublet, and a positive meniscus. The biconcave captures the lens as it's angled from the mirror, the achromatic doublet recollimates the beam before final focusing through the positive meniscus lens. Each lens is held vertically in its own holder, with a separation of 10 mm between the biconcave and achromatic, and 50 mm between the achromatic and meniscus. The combined focal length of the lens system is approximately 115 mm.

The estimated output spot size utilising our effective focal length and values of 5 mm for initial beam diameter (D), 4 for the M^2 factor, and 530 nm for the wavelength was approximately 0.25 mm. The equations utilized for the effective focal length, the estimated output spot size, and a 3D representation of our "f-theta" lens are highlighted below.

$$f_{BA} = [1/f_{biconcave} + 1/f_{achromatic} - dBA/(f_{biconcave} * f_{achromatic})]^{-1} \quad (3)$$

$$f_{eff} = [1/f_{BA} + 1/f_{meniscus} - dAP/(f_{BA} * f_{meniscus})]^{-1} \quad (4)$$

$$d = 4/\pi * (\text{入} * f_{eff} * M^2)/D \quad (5)$$

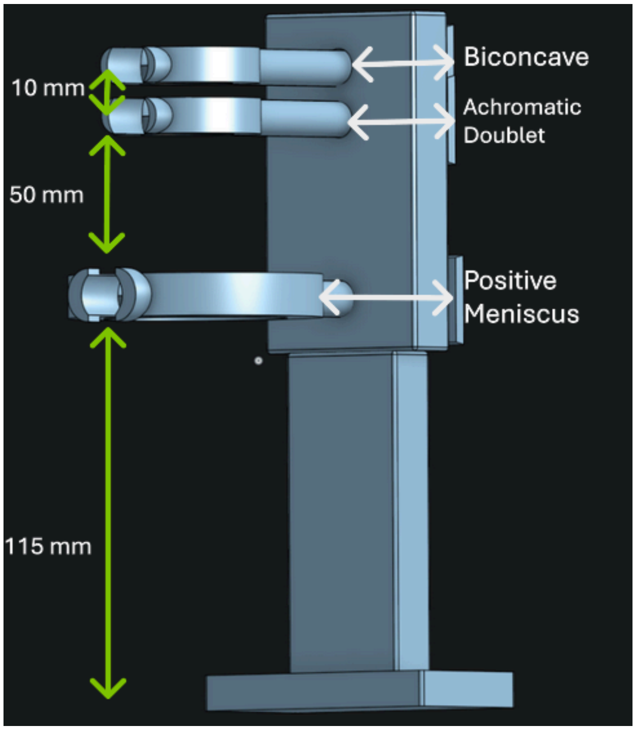

Figure [3] 3D Model Representation of the "F-Theta" Lens.

D. Chosen Paper

Based on the previous group's research, they highlighted how their blue laser diode light would be best absorbed by yellow-tinged paper, as yellow is a complementary color to blue [1]. Following this logic, we opted to use a magenta colored paper to best absorb our green light. The Astrobrights: Interstellar Pinks copy paper provided a range of colored magenta copy paper to use in testing. The thickness of our paper is 0.0045 to 0.005 in. and weighs 89 g/sm.

III. Power Supply

The E.L.I.P. power system is designed around a multi-stage AC-to-DC conversion chain capable of cleanly supplying all subsystems from a single wall outlet. A 120-volt AC input feeds into a transformer, which steps the voltage down before passing through a bridge rectifier. From there, an LM2679SD buck converter, recommended by faculty advisor Dr. Weeks, regulates the output to 12 volts at up to 4 amps. This intermediate voltage is then distributed to two downstream LM2596T buck regulators, one producing 3.3 volts for the ESP32 and its peripherals, and one producing 5 volts to power the LCD and laser diode driver.

The LM2596T was selected over linear alternatives such as the LM7805 due to its significantly higher efficiency, and over the TPS5430 due to the team's prior familiarity with the part, reducing development risk. Each regulator was implemented on its own dedicated PCB, connected to the main MCU board via 1x4 pin headers, allowing for modular testing and replacement.

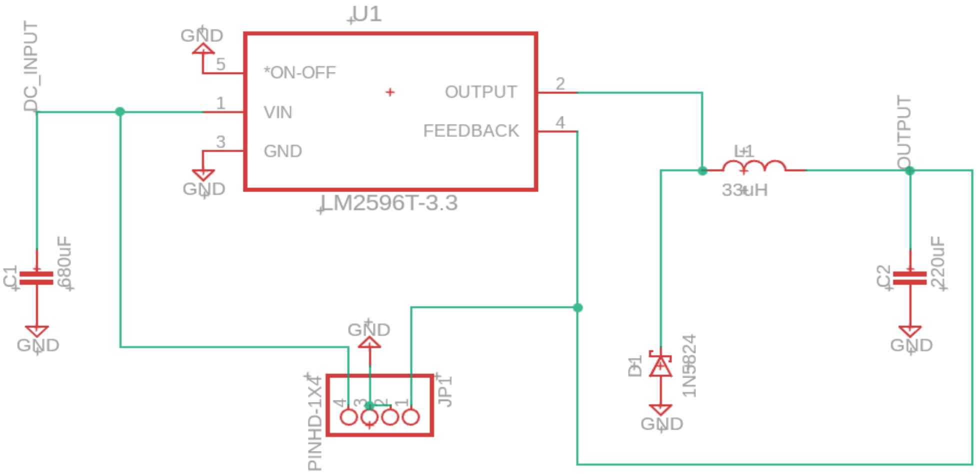

Figure [4] Regulator PCB Design

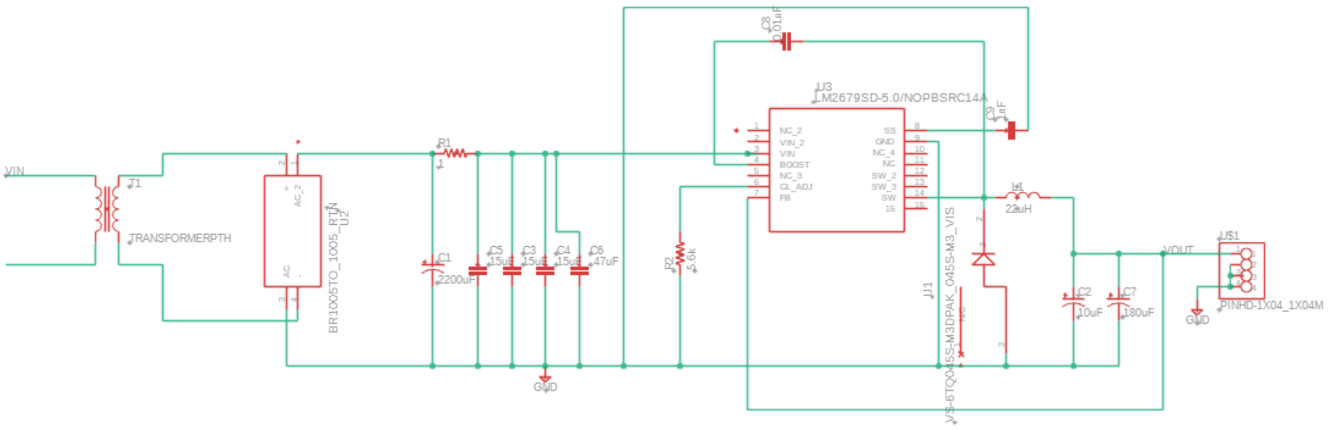

Figure [5] PSU PCB Design

For the power supply, we are using a 120V/12V 4 amp transformer connected to an LM2679, which will output 12 volts and 4 amps that will then be regulated to 3.3 and 5 volts, respectively. Both the regulators and the power supply are connected to the MCU board using header pins.

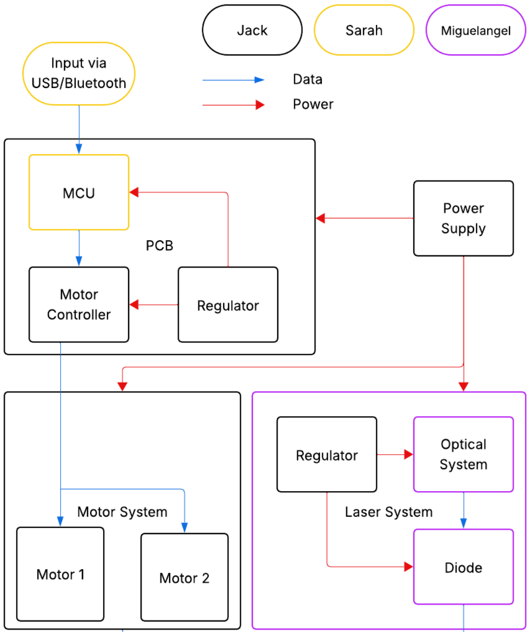

Figure [6] Project Hardware Block Diagram

The hardware goals for this project are to maintain stable output voltages in the PSU and regulators, ensure the components don't overheat, and ensure data is able to be reliably transferred between the MCU and Motor Controller. In terms of system overview, data is fed into the MCU via USB/Bluetooth, which then transfers that data to the Motor Controller, which in turn uses it to move the galvo motors into position.

IV. Safety Regulations

According to the American National Standards Institute, our 1.65 watt laser diode falls under Class 4: prolonged viewing can and will pose significant danger to the user without proper protection. For the final design, we plan to surround it with a protective laser shield that covers the desired wavelength. Direct or indirect eye contact with the laser is ill-advised unless protective eyewear is utilized.

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

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

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

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

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

Reverse-polarity protection and short-circuit safeguards were added to protect the user and the electronics. Thermal limits were also considered — heat sinks and small fans keep hot components within safe temperatures. Surfaces accessible to users stay well below the 70 °C limit recommended in the standard.

Thermal management emerged as an important consideration during early breadboard testing of the power system. While the LM2596T regulators operated within acceptable ranges, testing of the full laser diode circuit revealed that the system generated more heat than initially anticipated, necessitating additional cooling measures beyond the originally planned heatsink and small fan attached to the laser diode holder. To address this, additional fans were incorporated into the design. The galvanometer system is powered separately by its own ±24V 150W supply included with the ScannerMAX Compact 506 package, which feeds the MachDSP motor control board that governs mirror positioning. This separation of the high-power galvo supply from the logic and laser circuitry helps reduce noise and simplifies protection design for the lower-voltage subsystems.

Our initial testing showed that

V. Software Development

The software architecture of the E.L.I.P. system is centered around reliable wireless communication, real-time control, and safety-critical execution. The ESP32 microcontroller utilizes the NimBLE Bluetooth Low Energy (BLE) stack to interface with external devices, while the nRF Connect mobile application is used as the primary testing and command interface.

A. BLE Communication Architecture

The ESP32 operates as a BLE peripheral device, advertising a custom GATT(Generic Attribute Profile) service that enables bidirectional communication between the user interface and the embedded system. The BLE service includes a write characteristic for transmitting control commands and print data.

Using nRF Connect, a user can establish a connection and send formatted packets directly to the ESP32. These commands include:

- Motion Commands: Define X-Y positioning data for galvanometer control.
- Print Job Data: ASCII or buffered data representing characters or patterns.
- Control Signals: Enable/Disable laser, start/stop print jobs
- Emergency Commands: Immediate halt for safety conditions

Upon receiving a BLE packet, the ESP32 parses the data within the BLE task and places the processed command into a FreeRTOS queue for execution, ensuring separation between communication and real-time control.

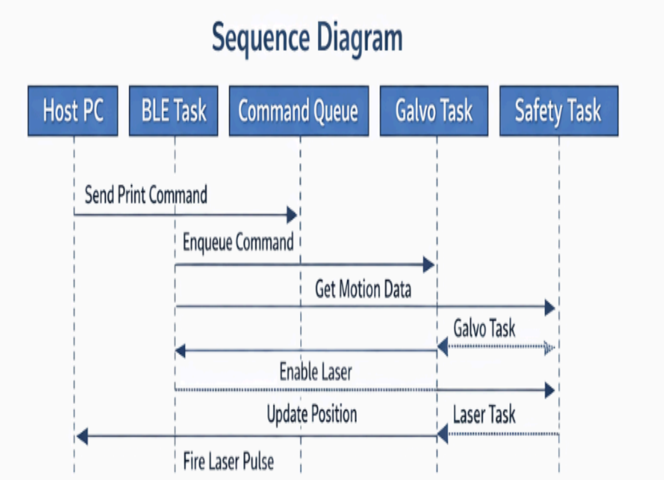

Figure [7] Sequence Diagram

This workflow aligns with the system execution pipeline shown in the sequence diagram (*page 30 of CDR)*, where BLE input is first received, queued, and then processed by control tasks.

B. Integration with FreeRTOS Task Structure

The BLE subsystem is integrated into a multi-tasking environment using FreeRTOS. The system is divided into independent tasks:

- BLE Task: Handles connection events, packet reception, and command parsing.
- Galvo Control Task: Converts command data into mirror positioning signals.
- Laser Control Task: Controls laser enable/disable timing synchronized with motion.

- Safety Task: Monitors system conditions and overrides execution if necessary.

This modular structure ensures deterministic behavior and prevents communication delays from interfering with time-sensitive galvo movement. As shown in the system flow, commands flow from BLE -> Queue -> Control Tasks -> Execution.

C. Command Processing and Data Handling

Commands transmitted from nRF connect follow a structured format to ensure consistency and reliability. The ESP32 firmware supports two primary modes:

1. Direct Command Mode
    - Simple ASCII commands (e.g., START, STOP, LASER_ON, LASER_OFF)
    - Used for debugging and manual control
2. Buffered Print Mode
    - Data packets representing full print jobs
    - Stored in memory and executed sequentially

Each received command undergoes:

1. Validation (format + safety checks)
2. Queueing (FreeRTOS queue insertion)
3. Execution (handled by control tasks)

This pipeline ensures that invalid or unsafe commands are rejected before affecting hardware.

D. Laser Enable/Disable Control via BLE

A critical component of the system is remote laser gating, which is controlled exclusively through validated BLE commands. The firmware enforces strict conditions before enabling the laser:

- BLE connection must be active
- System must be in PRINT state
- Safety checks must pass

If any condition fails, the laser is immediately disabled. The system transitions to a fault state upon any violation. Additionally, BLE-based emergency stop commands allow the user to:

- Instantly disable the laser
- Halt galvo motion
- Force system reset to a safe idle state

E. Real-Time Performance Considerations

To meet system requirements (≤1 s response time and synchronized motion control), several optimizations were implemented:

- Use of low-latency BLE write operations (Write Without Response)
- Separation of BLE and control logic via FreeRTOS queues
- Minimal parsing overhead within the BLE interrupt context
- Priority-based task scheduling for motion and safety tasks

These design choices ensure that BLE communication does not introduce jitter into the galvo control loop, which is critical for maintaining print accuracy and resolution.

F. Contribution to System Integration

The BLE and nRF connect integration enables a fully wireless control pipeline, allowing the system to receive, process, and execute print jobs without direct physical input. This significantly improves usability while maintaining strict safety and real-time performance constraints.

This software layer directly supports the system objective of user-friendly operation with wireless command capability.

V. TESTING RESULTS

Before finalizing the PCB design, all major subsystems were validated through breadboard testing/prototyping. The LM2596T buck regulators were assembled and tested independently on breadboards. We confirmed stable 3.3 and 5 volt outputs under load before integrating them into the main MCU board.

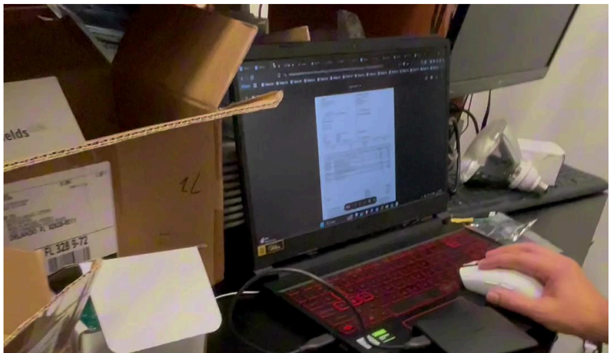

Figure [8] Senior Design I System Testing

The test diode was powered through the breadboarded regulator circuit, successfully producing a visible 530 nm green beam and confirming that the power supply system was capable of driving the diode within its operating range.

A low-cost galvanometer sourced from Amazon was also purchased to test how a galvo could be integrated into our main system. We powered it with the given PSU to ensure we had experience with galvo power supplies before the main ScannerMax galvo arrived.

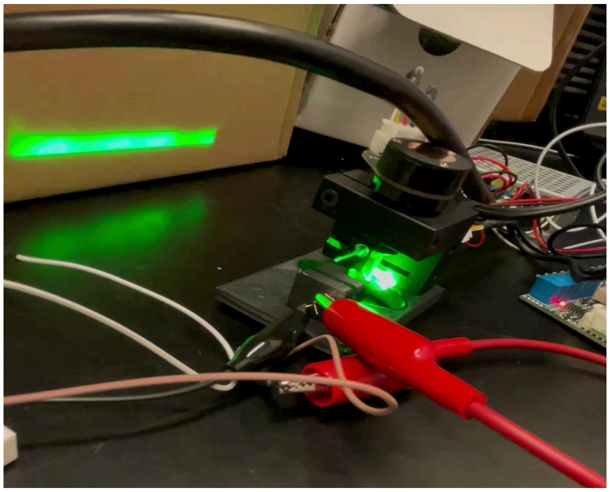

Figure [9] Senior Design I Diode thermal testing

During testing, the system's thermals were shown to be an important consideration. While the regulators were operating within acceptable temperature ranges, running the diode at full power revealed that it generated more heat than we initially anticipated. This caused the 3D-printed holder we were using to melt near the diode. These findings informed our hardware plans, including needing more heatsinks and fans than originally planned.

Later in Senior Design II, the lens system required a significant change. Rather than shine the diode directly on the mirror, we initially had an aspheric lens to help collimate the diode. However, the resulting spot size was more of a solid line that would not mark, rather than a dot. Removing the aspheric lens and moving the diode closer to the galvanometer mirror resulted in a fairly solid dot with some successful marking. The white areas on the following piece of paper were formed from slightly adjusting one of the galvanometer mirrors as the laser passed through our lens system.

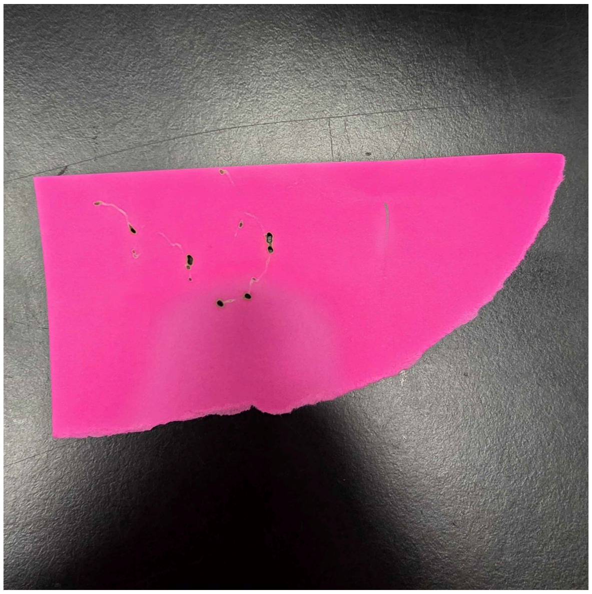

Figure [10] Senior Design II Paper Testing Results

VII. Conclusion

The aforementioned systems and components within this paper combine to further advance the design of the original Laser Inkless Printer. Our efforts led to an improved system utilizing alternative technologies previously disregarded due to past constraints.

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BIOGRAPHY

Jack McCain is currently a senior at the University of Central Florida. He plans to graduate with a Bachelor of Science in Electrical Engineering with a focus on renewable energy. This is his 5th year at UCF, and he plans to work in and around Orlando. His primary interests are mathematics and power systems related to renewable energy sources.

Sarah Siverio is currently a senior at the University of Central Florida, pursuing a Bachelor of Science in Computer Engineering. She plans to graduate and continue her career in the Orlando area, focusing on engineering-related roles. Her primary interests include circuit design, embedded systems, software development, and data management. Through her academic coursework and project experience, she has developed a strong foundation in both hardware and software integration, with an emphasis on real-time systems and efficient data processing.

Miguelangel Otero is currently a senior attending the University of Central Florida. He is pursuing a Bachelor of Science in Photonic Science and Engineering. After graduating, he plans to continue his education and pursue a Master's degree in Photonic Science and Engineering.

REFERENCES

[1] *SD2 Final Document - Group 2.docx*. (n.d.). Google Docs. https://drive.google.com/file/d/1-9XSiKTDrBUXfLMQIur1FekS7HH15aY3/view

[2] "Thorlabs." *Thorlabs.com*, 2026, www.thorlabs.com/f-theta-lenses-tutorial?tabName=F-Theta%20Tutorial.