Distance-Monitored Inkless Laser Engraver (D-MILE)

Ethan Teodosio (PSE) , Sean McCormack (PSE), Franklin Ivey (ECE), Ifran Tello (EE)

College of Optics and Photonics, Dept. of Electrical and Computer Engineering, University of Central Florida, Orlando, Florida, 32816

***Abstract* — The Distance-Monitored Inkless Laser Engraver, henceforth referred to as the D-MILE, was aimed at solving several unique problems at the same time. While the primary function was to create a device which could use a laser to safely etch onto various materials besides solely paper, it also served other purposes as groups in past semesters have attempted a similar project before. As such, it was our goal to create a working project that met our own ambitions, but also served to learn from past lessons and improve upon previous results while also expanding in directions we felt valuable. Going forward, we hope to explain the manner in which we went about designing and constructing the D-MILE while also going into its features.**

I. Introduction

Built upon our study of the previous iterations of this project style, the D-MILE is a mix of both optical technologies and computer and electrical work. In addition to the focuses of our respective majors, there was also significant mechanical work that went into the design and implementation of our own mechanical gantry to enable the various technologies. When we were designing the D-MILE, we had several noteworthy intentions with the project. Primarily, we wanted to display the viability of alternatives to consumable printing solutions. We believed that storing ink to use a printer was irritating, and despite potential improvements in quality, the change to toner did not meaningfully fix this issue, especially as products could potentially limit consumers to their own brand of toner or ink, which is prohibitive to the free market. As well as being an alternative to ink or toner which would not run out, laser etching had an even better focus for us; accessibility.

A laser etching printer would be capable of printing standard text or braille text with a tactile feedback due to material removal, rather than just dying the paper. Between these two major points, we felt we had sufficient motivation to choose this project, and moved on to what was our primary concern throughout the entire project; safety.

The D-MILE uses a Class 3R 405nm laser for etching, this wavelength combined with the optical power it produces, can be heavily damaging when viewed. As such, in compliance with safety standards, we have taken steps to ensure that the beam is blocked from accidental viewing, and testing was always conducted with proper safety goggles equipped.

II. System Components

There are many different system components within D-MILE. Some of these subsystems include: a frame, a full XYZ movement system, laser etching, distance sensing, fire detection, and workspace detection.

A. Frame

The Frame that D-MILE is built out of is 80-20 rails. These are aluminum T-slotted rails that are great for applications such as this. The rails are durable and you are able to cut them to the length needed. 80-20 rails also have very useful brackets and hardware that make designing and building a frame very easy. This frame is also very sturdy and robust which is important when having moving parts.

Figure ##; The Frame that D-MILE is built off of.

The outside of the frame is covered by plastic. The plastic is painted to make sure no stray laser beams are able to seep through. The front of the printer has a viewing window so the user is able to watch the print and make sure it is working. This viewing window is made of plastic that is for laser shielding. The wavelengths that the plastic covers is from 250nm to 520nm. The laser operates at 405nm, so this shielding works well as a window into the machine while protecting the user in the process. Lastly, this also means the user is able to use the printer inside their home without having to wear laser safety goggles.

B. XYZ Movement System

The purpose of the XYZ movement system is to allow for full functionality. This is done by moving the laser in both X and Y directions while leaving the print bed to be able to move in the Z direction.

Movement along the X and Y axis is done by pulling a central point across a gantry constructed of aluminum rods and linear bearings using timing belts and two stepper motors. The gantry uses a technique used in many 3D printers and CNC machines known as ‘CoreXY’. Using this technique, the motors are stationary with the frame, resulting in less mass to move. Compared to other configurations of timing belts for an XY stage the CoreXY technique provides better force distribution for stable movement, which is a primary concern for the D-MILE system’s accuracy. Plastic parts from a 3D printer were used to connect the required rods, bearings, pulleys, and stepper motors together into a complete XY gantry. 3D printed parts were chosen to reduce cost and increase the speed at which the system was designed.

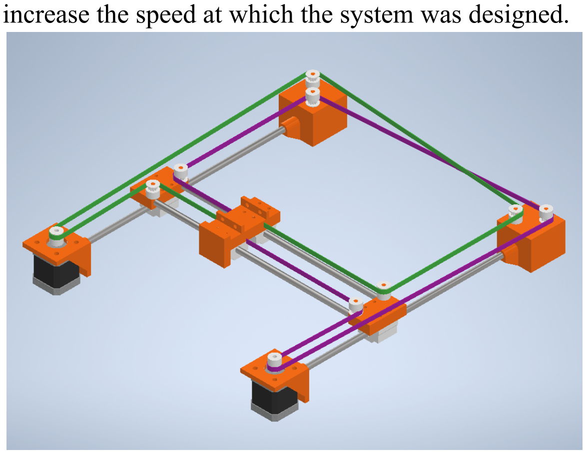

Figure ##; The XY movement system design, using a CoreXY belt configuration.

The Z movement is done with the use of a timing belt, threaded rods, a motor, idlers, bearings, and pulleys. This is done by having two timing belts move due to issues with friction. Having two timing belts was chosen due to the fact that tensioning one belt proved to be difficult, as well as the fact the motor kept slipping. To combat this issue we decided to run two timing belts connected to one motor.. At the top of the threaded rod is a bearing that helps with stability and making sure that the print bed does not come off the threaded rods. The bearings also are important for keeping the print bed from bending as it is moved up or down. This makes it so the print stage can move up and down due to the fact that it is attached to the threaded rods. The threaded rod is connected with a shaft coupler to a 5 mm steel rod. This rod is connected to the pulleys that have the timing belt attached.

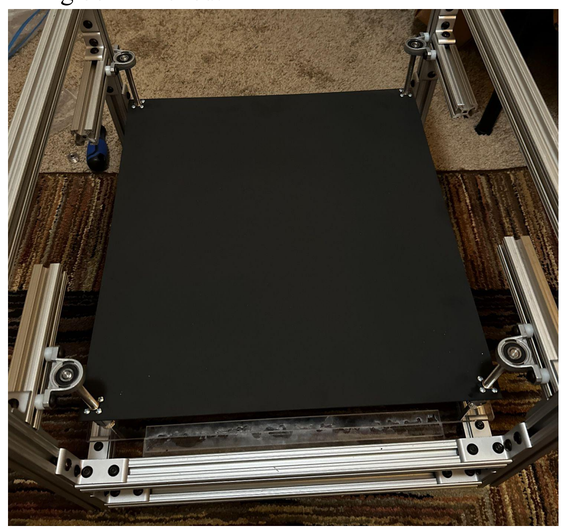

Figure ##; The Z stage movement system connected to the print bed and frame.

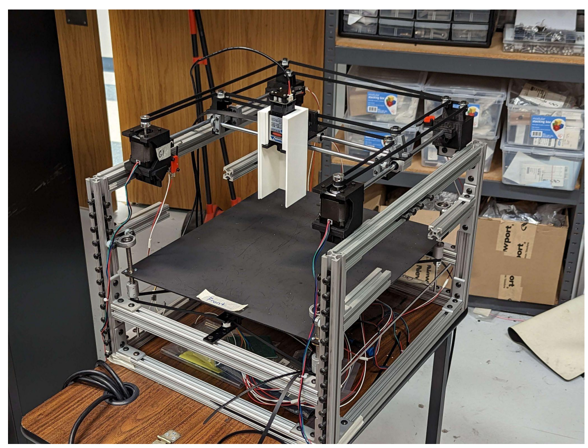

Figure ##; The Frame, Z stage, and XY gantry assembled together during integration testing.

C. Laser Etching System

For the purposes of laser etching, we are employing a 405 nm wavelength laser that operates at over a watt of power at base, but has been adjusted to function at lower input settings to match our desired output. The laser is a class 3R for safety purposes, and we have taken several preventative measures to maximize the safety of our project. The output of the laser is a gaussian beam profile, which results in a U-shaped channel etched into the material. This profile was chosen over the stephat profile to allow for a gradient to form on the edge of the prints. In the case of printing on wood, we felt that this added to the visibility and overall look of the project without causing issues with reaching our desired resolution. On paper, the bleed caused by the gaussian profile over the stephat is visible but non-impactful due to the significant decoloration with respect to the center of the etch.

The laser starts with input settings of 5V Peak to Peak and a 50% duty cycle, with these settings, the output power of the laser is calculated to be around 250mW. This was calculated indirectly, as the laser is powerful enough to threaten to damage a sensor were we to read the value directly. Instead, we moved the focus further away to broaden the beam shape and then passed it through several filters with a known transmission percentage, and from there adjusted the measured result by the various factors listed to arrive at the presented calculation.

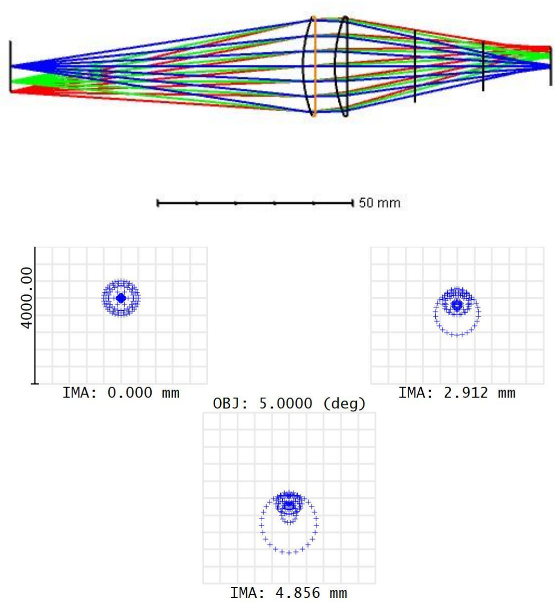

Figure ##-##; Total Optical Design in Zemax, Spot Size Diagram in Zemax for On and Off-Axis Rays.

Our beam is focused down to a point under our resolution goal of 12/72" and does so using two plano-convex N-BK7 lenses. Both lenses are identical and have focal lengths of 38.1mm and focus the laser light down in a total track length under 150mm. The spot size for on-axis rays is measured at under 0.3mm, while the Airy width is 1.529µm. The spot size is much lower than our set goal, but not diffraction limited. More lenses, or more complex lenses, could further lower the beam spot size under the diffraction limit but we felt this process was unwise as that is only in theory through Zemax, and the amount of money and time required to get custom lenses was not worth it for our project's goals while remaining within budget. We also found that we could adjust the number of lenses and the distance between the lens or lenses and the laser to move the effective focal length of our optical system to better match the physical limitations imposed by the mechanical gantry and minimum position of the Z stage.

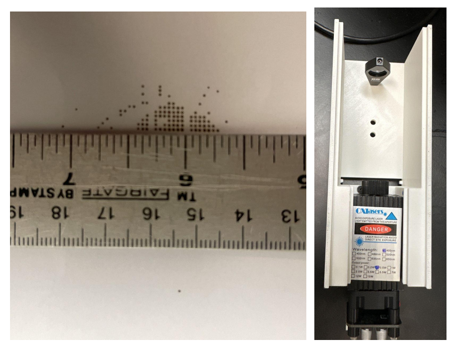

Figure ##-##; Original Laser module initial results and the original laser holder.

During integration testing of the laser, the originally spec'd laser ended up breaking. This occurred days before the showcase and caused a last minute change in design. We ended up using a spare laser module that we were able to find. However, this laser module is a different shape, power, and wavelength as the originally tested laser. This new laser was a Class 4 450nm wavelength laser with at least 1W of power. The biggest challenge was mounting the new laser as the focal length is around 5cm, far lower than the original laser's optical track length of 17cm. This problem ideally would've been solved using optical components, but due to the timing of the laser breaking, we opted to make a mechanical adapter to mount the laser instead.

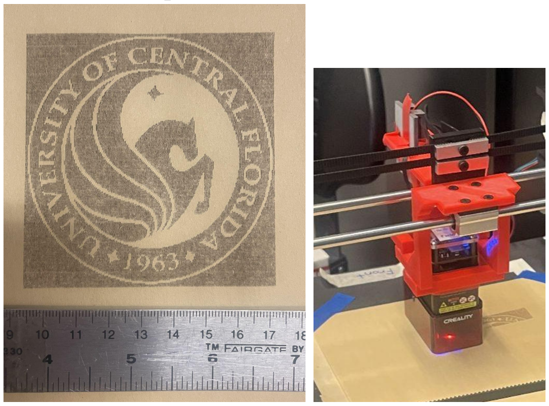

Figure ##-##; Backup laser module initial results and the new laser holder that was printed

To get the results you see in the figures above, we found that we could modify the position of the laser and lenses to adjust beam spot size, and then adjust the frequency, duty cycle, and power to the laser to further adjust the engravement rate and depth. From there, we can freely modify the pixels per step on the motors to change the spacing between points and change the pulse duration to change etch depth and spot size.

D. Distance Sensor

The distance sensor that exists in D-MILE is a very simple design for simplicity reasons. It consists of an IR LED and a photodiode. From there we created two collision detectors using a basic comparator circuit to compare the voltages that are received from photodiodes. This allows us to tune the collision zones to specific distances, from here we are able to place one pair on each side of our spot size and this lets us know that the print bed is within the required spot size for printing. This will stop the z stage from moving and allow the print to occur.

This system also works on knowing which direction to move the print bed to help get it in focus. If the print bed is too low the system will recognize this and move it up, however if it is too high it'll also realize this case and move it down. This is a convenient way for the system to operate.

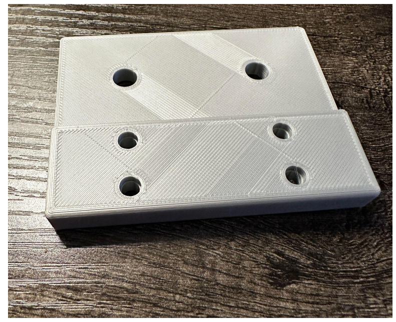

Figure ##; 3D print for the IR LED and Photodiode to mount to the frame of D-MILE.

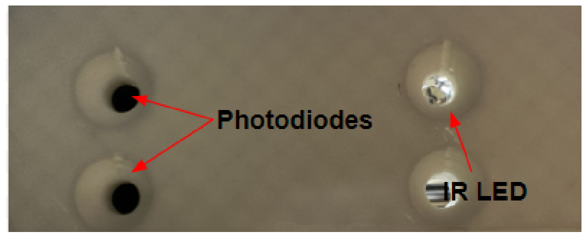

Figure ##; How the distance sensor will be setup for D-MILE to measure the height of the print bed.

E. Fire Detection

For fire detection we created an optical fire alarm. This is made by having an IR LED and photodiode, these can be pointed at each other directly. When smoke of fumes enter the chamber that the LED and photodiode are held in, the fumes cause the IR light to scatter. This means the intensity that the photodiode is sensing will drop significantly, when this occurs it'll trip the optical fire alarm causing D-MILE to stop the current task until it is safe to proceed. This sub system was tested using fog due to the fact that we did not want to use smoke and risk anything breaking on D-MILE. The purpose of this subsystem is with the hope to stop the machine before catastrophic failure were to occur, if the user sets the laser power too high for the material that they are etching.

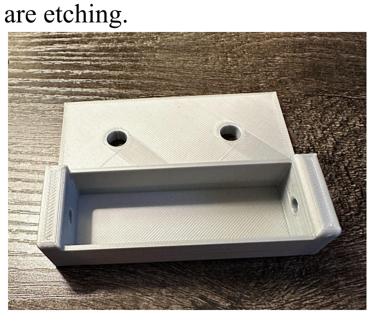

Figure ##; How the fire detection sensor will be setup for D-MILE to make sure smoke is detectable.

F. Workspace Defining System

When you turn the printer on it will give you an option to view the printing area onto the material you are printing. As seen in the figure below the purpose of this system would just be used for telling the user where the edge of the print is with a visible laser. This is done using a 650 nm laser pointer.

This would let the user make sure there is material under all corners. With this information it will help the user decide if they want to continue with the print or move the material beforehand. This should stop any instances where the print is too small/large, or where the printer goes off of the material and is attempting to etch on the print bed instead of the material.

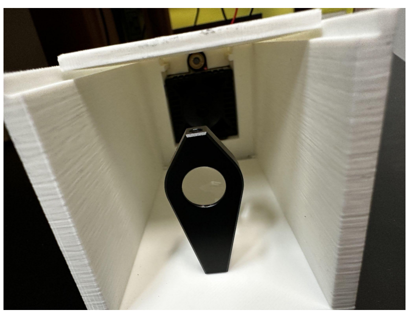

Figure ##; 650 nm laser pointer mounted inside of our laser holder.

III. System Concept

The D-MILE was fundamentally conceived to function similarly in nature to a 3D Printer. The logic was that the print head, in our case the laser etching and distance sensor, would move about the XY plane and check the bounds of the print bed to ensure there were no issues, and then to check the planes distance in the Z direction to confirm whether or not it was within the known focus of the beam. If it wasn't, then the stage would adjust, rather than the focus of the laser. From there, a program would take images or text documents and translate them into a series of XYZ movements to be made by the printer, alongside knowing how long it had to spend on any given spot, while also being able to modulate the laser on and off. This would allow the laser to etch while moving and also to move without etching, and that this system would be limited by the DPI of the motors, rather than the responsiveness of the laser itself. It was from this concept of the project that each of the systems that were put into place were derivatives of.

Hardware Detail

A. STM32F479VGT6 Microcontroller

A 100-pin microcontroller that will be the main master control of our entire device. The STM32 was chosen mainly due to its impressive flash memory size, up to 2MB, which we had decided would be optimal to have for our purposes. The STM32 line of microcontrollers was also chosen for the comprehensive libraries that have been developed and are included with ST's software packages. A key peripheral that will be utilized is a 12-bit Analog-to-Digital converter, since our distance-sensing features require us to read analog signals. Another feature of note is the USB On-The-Go peripheral, which supplies hardware support for the USB protocol. Using this, it becomes possible to create a virtual COM port for serial communication. The STM32 MCU also provides dedicated peripherals for standard embedded communication protocols, like SPI, I2C, and UART. The SPI peripheral will be used to interface with a micro-SD card for added storage. This STM32 will be on our printed circuit board and will use digital logic to control our motor controllers, laser diodes and drivers, and read analog inputs.

B. DRV8825 Motor Controller

To enable control of bipolar stepper motors needed in our design, the right choice of motor controller was needed. The DRV8825 can take an input voltage of 8V to 45V and can output over 2A into a stepper motor. The DRV8825 was chosen due to being well known in use of CNC-type machines and it is well-documented, making it much easier to implement into our PCB design. One of these controller chips can control and power one motor at a time, so three of these are needed.

C. NEMA 17 Bipolar Stepper Motor

The NEMA 17 bipolar stepper motor is the stepper motor of choice for movement of our machine. It is housed in a 1.6 in x 1.6 in x 1.8 in device and weighs approximately 14 ounces. This motor was chosen for its exceptional price and quality of fine movement Each axis of movement of our design will be requiring one of these motors, so three for the X, Y, and Z-axis movement.

D. LMR15420 Adjustable Buck Converter

Since our device will be powered by a single 12V DC jack, voltage regulators are needed to step down the input voltage to be used for lower-power devices on our board. The LMR15420 is a switching regulator whose output can be adjusted with the use of resistors. It can take an input voltage from 6V to 36V DC and step it down to a voltage decided by the resistance of a voltage divider network. The equation to decide resistors is given by:

$$R_b = \frac{V_{out} - V_{ref}}{V_{ref}} R_t$$

With R_b and R_t being the bottom and top feedback resistors respectively, and $V_{ref} = 0.6$. We can calculate that for a desired output of 5V, $R_b = 22.1\text{k}\Omega$ and $R_t = 162\text{k}\Omega$. This regulator was chosen due to being the recommended IC when using the TI WEBENCH Power Designer tool and general ease of use.

E. AZ1117 3.3V Linear Regulator

The AZ1117 is a linear step down voltage regulator. It can take a maximum input voltage of 18V and output a 3.3V regulated voltage. A 3.3V rail is required for powering the STM32 microcontroller and for digital logic and analog signal purposes. The reason this regulator was chosen over another LMR51420 was due to price and noise. A second switching regulator was not necessary, and so this linear regulator was chosen.

F. TSV912 Op-Amp

The TSV912 is an IC with two op-amps. Op-amps are used in our circuit to serve as distance sensing circuits for the distance-monitoring portion of our design. The TSV912 for our purposes will be powered by 3.3V in order to achieve an output that can be used as an analog input into our microcontroller. Four distance sensing circuits will be used, so two of these op-amps are needed in our design. These same circuits and op-amps are responsible for our fire detection system as well.

G. 12V 405nm 500mW Laser Diode + Driver

This power laser diode and its driver will be responsible for the engraving and printing. The device we have in particular comes as one with both the diode and a current source driver. This makes it much easier to utilize the diode as we did not have to design a complicated and precise current source for the laser. Instead, we can control the driver that came with the diode with 2 pins for power (12V and GND), and a single pin for PWM control. The STM32 can output a PWM signal that can control the power output of the laser diode.

H. Printed Circuit Board Summary

The custom-designed PCB for this project was made in AUTODESK EAGLE. All circuit components mentioned previously have a place and purpose on the board, with the exception of external components such as laser diode drivers and stepper motors. The PCB was designed to take a single power input of 12VDC from a female DC jack. The main components/subcircuits of the PCB include: STM32 microcontroller (1); DRV8825 motor controller circuits (3); AZ1117 linear regulator (1); LMR51420 switching regulator circuit (1); TSV912 op-amp and distance sensing circuits (4). A master switch is directly tied to the 12VDC input that will allow us to shut off all power to the board manually if needed.

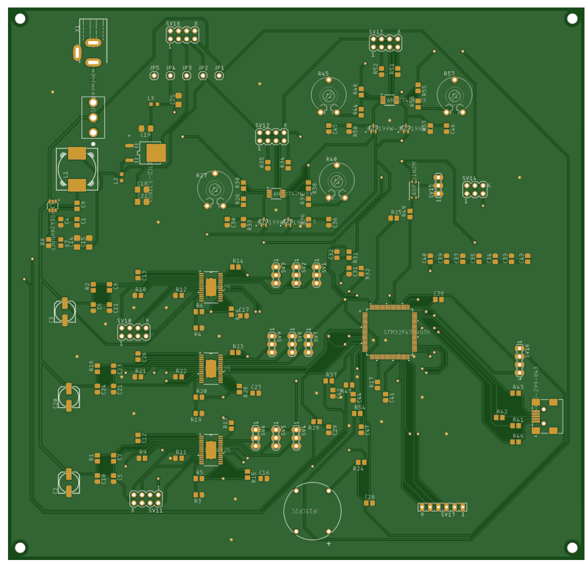

Figure #: Custom PCB Layout Preview Image

The PCB is a standard 2-layer board with components only on the top layer. All external connections are standard 2.54mm pin headers with the exceptions being the 12V DC jack and a single mini-USB connector. The board size is 180 x 172 mm.

Software Detail

A. Firmware

The firmware was coded within ST's IDE created for the STM32 line of microcontrollers, STM32CubeIDE. Subsystem drivers were written on top of the IDE's auto-generated code to initialize and configure the device. This allowed for easy and accurate configuration of the necessary on-board peripherals, freeing up development time. The included FatFS middleware was used to handle print file storage on an SD card.

The main goal of the firmware is to accurately control the print process with simple control loops, and to enable run-time configuration of system parameters. The overall design methodology was to create a separate driver for each sub-system with all driver parameters stored in a globally defined struct. Program flow is controlled by commands received over a USB connection. This can either be through a serial command-line interface, or through the document processing software's backend. To accommodate for both use cases, a flexible shell controller is needed.

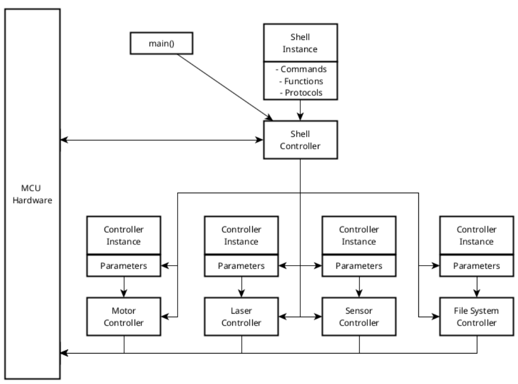

Figure ##; Overall firmware structure

To allow for multiple types of communication, the shell interface consists of two components: a main shell function and an interchangeable shell instance. The main shell function is responsible for a simple control loop as shown in figure ##.

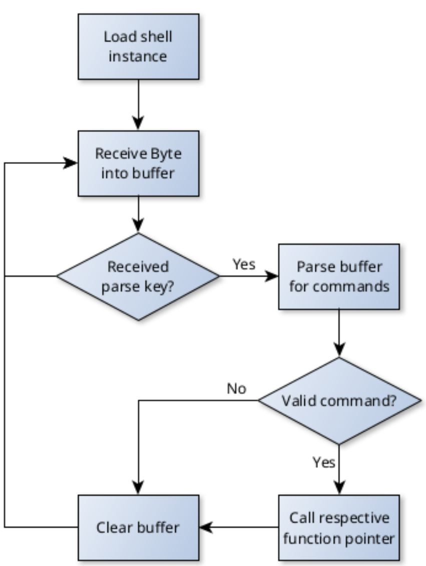

Figure ##; Main shell function control loop

The interchangeable shell instance contains a list of acceptable commands, function pointers for the commands, and optional responses for different events (such as user input prompt, valid command, invalid command, receive ACK, and parse ACK). All commands and responses can either be strings of characters or sequences of bytes. For example, an acceptable command in a shell interface can either be "set_pwm_delay" or 0xF4A2. Because each command has its own pointer to a function in the firmware code, commands can have extremely customizable effects. If desired, two commands from different shell instances can even point to the same function. A command can recursively call the main shell function with new shell instances, allowing for the creation of a menu system. Below is an example of this, where usr_cli_sub_menu() is a command function of the shell usr_cli:

```
main() {
  shell_inst usr_cli;
  shell_inst sub_menu;

  usr_cli_init(&usr_cli);          // populate instance
  sub_menu_init(&sub_menu);  // populate instance

  shell(&usr_ci);
}

int usr_cli_sub_menu()
{
  printString("Entering into sub menu shell!\r\n");
  clearBuffer();
  shell(&sub_menu);
  return 0;
}
```

Figure ##; Example of shell instances and command functions

Because most subsystems of the D-MILE can be controlled using GPIO from the MCU, the controllers are essentially collections of functions to coordinate GPIO timing and signals. Each controller will have its own instance stored in global memory containing controller-specific parameters. This structure is so that both functions within the controller and command functions within shell instances have access to read and modify parameters. Doing this allows for a highly configurable system, where things like motor speed and laser pulse width can be modified between print jobs by the shell controller

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B. Document Processing

Documents are stored within the D-MILE system as simple bitmaps, with each bit representing a pixel. For example, a '1' represents a black pixel, and a '0' represents a blank pixel. Because documents are printed in this rasterized fashion, preparing any rasterized file format to be printed with the D-MILE system is as simple as converting the image to black and white and then writing to a bitmap file pixel-by-pixel. This simplicity was by design to increase legibility across a wide range of documents, as using a vector-based print process would result in either legible text or legible images, but not both.

Using the publicly available computer vision library OpenCV, loaded images are stored using matrices by default. After converting images to black and white, the image's bitmap is constructed as previously described. The bitmap data along with print parameters such as size, resolution, and speed are sent to the D-MILE system using a backend serial interface over USB. The MCU is then responsible for storing the file on the dedicated SD card, and for starting the print process.

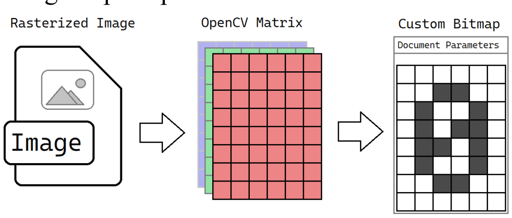

Figure ##; Document processing

Bibliography

Ethan Teodosio will graduate and receive his Bachelor's of Science in Photonic Science and Engineering in May 2023. Currently working at CREOL UCF, he plans on seeking a position in industry, particularly in biophotonics or fiber optic communications.

Sean McCormack will graduate and receive his Bachelor's of Science in Photonic Science and Engineering in May 2023. He currently works, as an intern, at Everix Optical Filters. He currently plans to continue working as an optical engineer for Everix once he graduates.

Franklin Ivey will graduate and receive his Bachelor's of Science in Computer Engineering in May 2023. He hopes to pursue a career in FPGA design.

Ifran Tello will graduate in May 2023 and receive a Bachelors of Science in Electrical Engineering. He currently has an internship at Advanced Charging Technologies and hopes to stay in the company or in the power electronics industry.

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