Automated Optical Inspection

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***Abstract* — The purpose of this project is to utilize optical inspection to provide quality control for a thermochromic fabric production line. In this project, visible light will be used to detect defects by a machine learning process connected to a camera module. Upon training completion, the project will demonstrate an accuracy detection rate above 60%.**

***Index Terms* — Camera, laser, lens, machine learning, optical inspection, quality control, thermochromic, training.**

I. INTRODUCTION

Automated Optical Inspection units (AOIs) are complex, high precision camera systems meant for quality control (QC) purposes. AOIs check for catastrophic failures and quality defects on small parts such as PCBs, small hardware, and sensitive microelectronics by using machine learning. The AI will have a set of benchmarks (passing and failing photos) and check against that database in real time while a manufacturing line is producing a particular part. This leads to an unbiased analysis of a large magnitude of parts.

AOIs are expensive and require a large amount of batch data in order to have a sufficient library to determine the quality of a part. This issue is also compounded when the part being analyzed is unique to the manufacturing world. Down scaling premade AOI systems for smaller, unique parts becomes a barrier of entry.

The purpose of the system being developed in this paper is to develop a stable prototype of a small scale, cost effective AOI that will inspect the unique wires on a fabric that was developed by the ChroMorphous research team at CREOL. The goal is to create an Optical system that will capture images in real time in order to determine if the electrical system in place for the fabric passes their QC checks. Also included in this project is a laser counting system that will be capable of counting how many threads from the fabric have passed through the line for further manufacturing goals.

II. SYSTEM CONCEPT

Our system was divided into separate components to maximize the amount of progress on each component that can be made in parallel rather than in series relative to each component. This also allowed us to easily disperse responsibilities amongst ourselves. The separation of the Control System and Power Supply into separate PCBs was also done with the intention to mitigate electrical noise in the various systems.

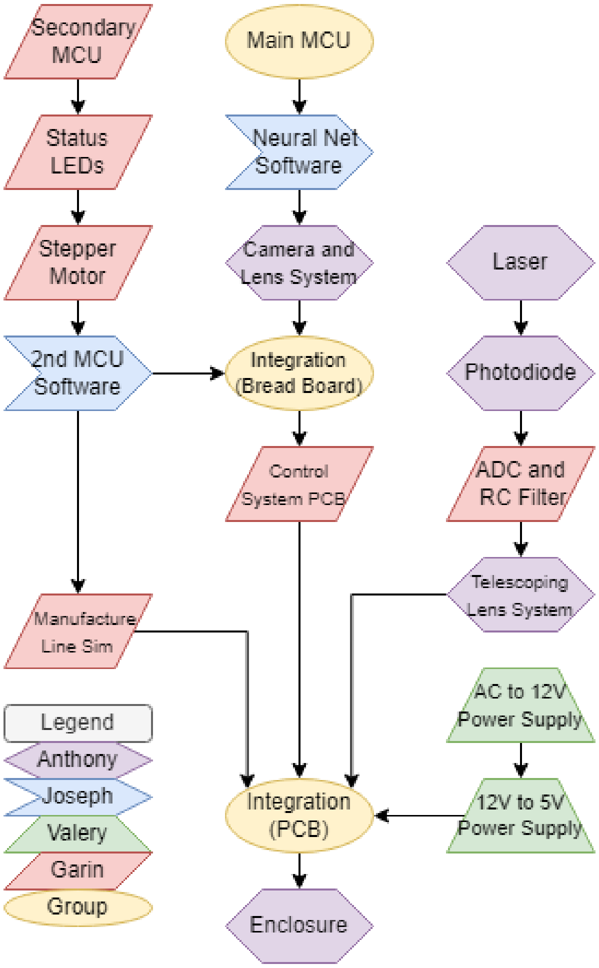

Fig 1. Schematic of the design process.

III. SYSTEM COMPONENTS

A. Main Microcontroller

The heart of our project is our Main Microcontroller (MCU) the NVIDIA Jetson Nano. This MCU was selected since, unlike most other MCUs, it features a dedicated GPU. This dedicated GPU is critical as we will be trying to match our image processing rate to the speed of the manufacturing line. At the start of the project, this speed was relayed to us as one foot of fabric per second, or 360 images per second (360 threads per foot of fabric, and one image per thread).

Given this large image processing requirement, the Jetson also provides the advantage of scalability. Since the Jetson Nano is based on a NVIDIA GPU, the software we write for this can be scaled into a more powerful NVIDIA GPU such as a Quadro 2000, if more image processing power than the Jetson can provide is needed.

Finally, the Jetson Nano development kit features plenty of connectivity. This connectivity includes two Mobile Industry Processor Interface Camera Serial Interface ports (MIPI CSI-2). One of these MIPI CSI-2 ports will be used to connect our Arducam to the Jetson Nano. For general connectivity, the Jetson has four USB 3.0 ports, HDMI output, DisplayPort, and a Gigabit Ethernet port. The Jetson also features a 40–pin header with General Purpose Input Output (GPIO) pins and UART communication functionality. This added functionality will allow us to offload our other computational requirements to our secondary MCU in order to utilize all the Jetson's processing power for image processing only.

B. Neural Net Programming

A vital part of the project involves off-loading the tedious and time-consuming task of quality control to a specialized application running on dedicated hardware. After exploring some initial options, a neural network became the ideal solution for the project. The progression and adaptability of neural networks make them superior for the job compared to other solutions.

To reduce design time, we utilized transfer learning to take advantage of a neural network for the project. Transfer learning utilizes a previously designed neural network and re-trains the network on a new dataset to shorten the time involved in creating one from the ground up. We settled on a model that offered good results in image detection without overtaxing the hardware. The model provided a good basis to continue developing the overall design.

C. Camera and Lens System

Our camera system centers around an Arducam HQ IR-CUT Camera, chosen for our proof of concept due to the native integration with our Nvidia Jetson. The IR cutoff mechanic was disconnected from the internal board, so that low light scenarios would not cause the filter to activate. This camera system is also accompanied with a stock 6mm CCTV lens and has an optical magnifier for imaging.

D. Secondary Microcontroller

Our secondary microcontroller is the Raspberry Pi Pico. As previously mentioned, this is meant to handle any computational requirements outside of image processing. These requirements include driving the PWM signals needed for our status LEDs, driving our A4988 stepper motor driver, and handling the analog-to-digital conversion (ADC) for reading data from the photodiode of the laser counter system. While many microcontrollers can handle these requirements, the Pico was specifically selected for its low cost and the team's familiarity with its operation.

E. Control System PCB

This is the printed circuit board (PCB) that will connect all our electrical systems together. This board will feature terminal blocks to connect to the power supply and stepper motor. The board will also hold the A4988 stepper motor driver, Raspberry Pi Pico, and their associated traces. There will also need to be a 5-pin jumper to connect this PCB to the NVIDIA Jetson Nano, a 2-pin jumper to connect the laser counter system to the Pico's ADC, and a 2-pin jumper for a variable 5V source to power each fabric thread.

F. Laser Counter System

Our laser counting system consists of 3 integral parts: a collimated Gaussian beam, a beam expander, and a photodiode receptor. The initial protocol for this system was to create a 50-micron laser spot size since the width of the wires on the fabric are 100 microns. Placing a photodiode behind the fabric creates a beam block that will let the system keep count of how many strands have passed through the system.

At the time of this writing, the laser counter works while reading a discernable voltage difference when the laser is shining on the diode and when the diode is on standby. The spot size is also within tolerance of what is expected. The accuracy of the counter is under question due to clumping of the fibers in our present sample, and the lack of a controlled translation system. We are confident though that when the counter is set up in a controlled system that the desired accuracy will be achieved.

G. Power Supplies

One of the major aspects for the implementation of this project is to come up with a power supply for the device. The purpose of this power supply is to provide electric energy to the other electrical components that will be comprised by the device. As one of the requirements, our device will need to be powered under an input voltage of 100 to 240 V AC. To achieve that we investigated all our constraints and the device requirement to implement the power supplies according to the needs.

IV. HARDWARE DETAILS

This section will provide the technical details associated with each system component outlined in section III.

A. Main Microcontroller

The NVIDIA Jetson Nano Developer Kit features a Quad-core ARM A57 CPU, which runs at 1.43GHz and supported by 4GB of 64-bit LPDDR4 RAM. More importantly, the Jetson features a 128 Core Maxwell GPU which will be handling our image processing. The Jetson Nano Module is connected to the Developer Kit Carrier Board via a 260-pin SODIMM connector. Through this Carrier Board for the Jetson Nano Module, we are able to gain the connectivity needed to utilize the Jetson for our project.

We are utilizing the HDMI Type A port, MIPI CSI-2 port, USB Micro B slot, USB 3.0 Type A slot, and occasionally the RJ45 Gigabit Ethernet slot. Through all this connectivity we can easily utilize the Jetson.

The 40-pin headers are used as our connection to the Control System PCB. We deliver 5V, GND, and UART via 5 out these 40 pins. Specifically, the UART of the Jetson reports the status of the inspection to the Pico and the Pico illuminates the corresponding status LED to visually represent the inspection results.

Regarding the power of the Jetson Nano, it can take a maximum of 25 watts. Specifically, it can take 5 volts at 2.5 amps from each pin 2 and 4. However, the Jetson Nano module itself can only utilize 10 watts.

B. Camera and Lens System

The Arducam HQ IR-CUT Camera is a 1.23 MP, 1/2.3 -in sensor camera with an IR cutoff and includes a 6 mm CCTV lens. The camera itself, as is, is not sustainable for telescopic imaging on its own as stated before. Therefore, a simple Keplerian magnifier was used. A 2-inch 150 mm NBK-7 lens was used as our front-end optic in order to focus at the 6 inches required. With the initial image of the fabric taken, a 1 inch 75 mm NBK-7 lens was then placed 75 mm behind our front-end optic. This resulting image was then gathered by our Arducam camera by slowly rotating the lens out of the sensor until the resulting image covered a majority of the sensor for magnification. Without pulling the lens forward away from the sensor, the image would be of the fabric, the 75 mm lens and of the resulting object space in the background.

The resulting image that is resolved by the camera is an image that is a quarter inch of fabric. This results in around 10 to 11 strands of wire that can be easily resolved by the AI to analyze, specifically in the Region of Interest (ROI) setting.

This optical system's hardware can be further increased with investment in more expensive optics and imaging sensor. The capabilities for the camera with the Jetson program running is around 22 fps max, with an average of 20 fps. This is the equivalent of reading and analyzing a half inch of fabric per second, or 2.5 feet of fabric per minute. Chromatic aberration can be observed depending on the ambient lighting of the room this is operating in. This chromatic aberration as of now has not produced issues in testing, so long as the system is trained with the aberration present. This aberration can be resolved with achromatic cement doublets, specifically for the 75 mm lens.

C. Secondary Microcontroller

The Raspberry Pi Pico utilizes the Raspberry Pi RP2040. This features Dual Cortex M0+ processor cores capable of 133MHz, 264kB of SRAM, 30 multifunction GPIO, and a 4 channel 12-bit analog-to-digital convertor (ADC) with an internal temperature sensor. The Pico itself has 2MB of flash memory, a Micro USB Type B port, and 40-pins for various purposes.

The 12-bit ADC found on the Pico will be utilized in Laser Counter System and was a relevant metric when selecting the secondary MCU thanks to its high resolution of 12-bits.

$$\text{ADC Voltage Resolution} = \frac{(V_H - V_L)}{2^n} \tag{1}$$

We can use (1) to find the minimum voltage that the ADC can detect, also known as ADC Voltage Resolution. Where V_H refers to our voltage high (3.3V), V_L refers to our voltage low (0V), and n refers to the number of bits (12-bit). We get the value of 0.8mV, meaning that the photodiode of the Laser Counter System would at minimum need to create a voltage difference of 0.8mV in order to be detected by the ADC without any signal amplification. Through testing, we found the photodiode to create approximately 0.2V of difference, which will give us a substantially different digital value without the need for any signal amplification.

While the resolution of the ADC is excellent, the voltage reference has an issue. The RP2040 chip does not feature an on-board reference. By default, the power supply of the chip is used as reference which comes from 3.3V SMPS which does not have great output accuracy.

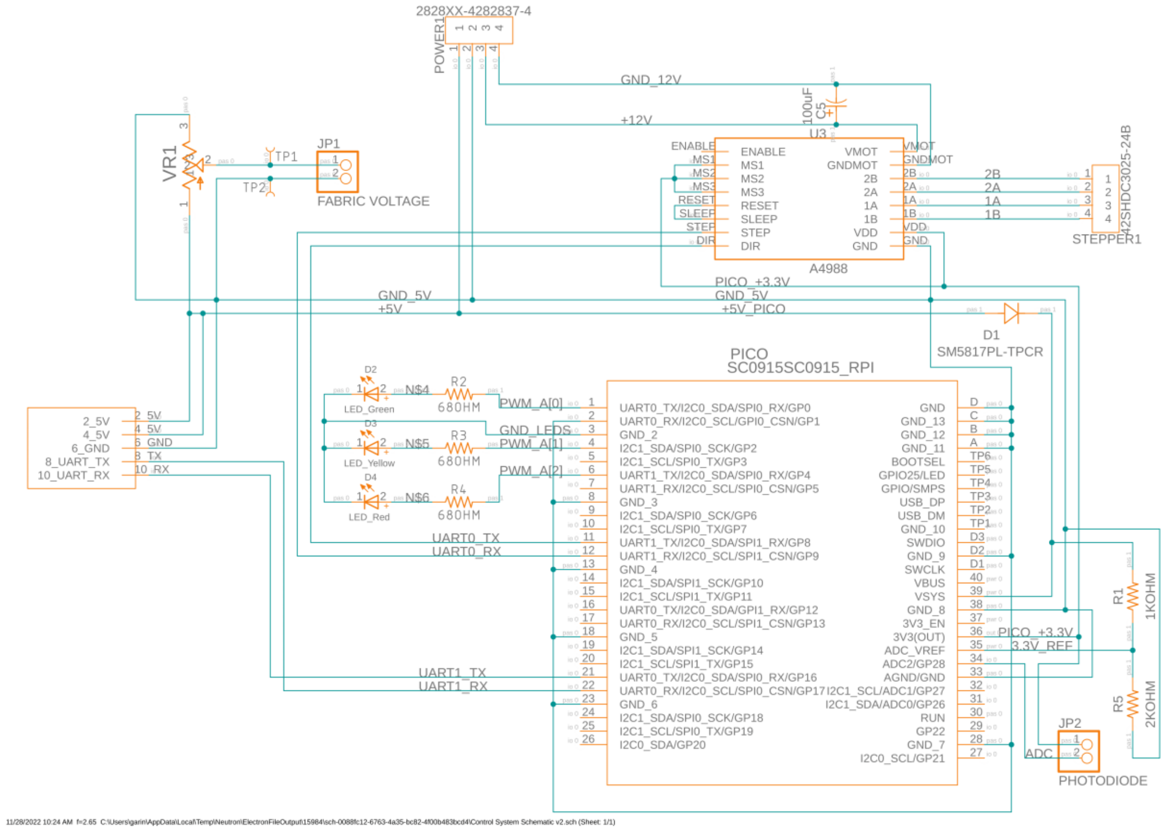

Fig 2. Control System PCB schematic drawing rev. 2

Since our project already requires a power supply, we will utilize our own power supply as the voltage refence. In order to do this the ADC_VREF pin on the Pico needs to be isolated. This is achieved by removing a 0603 SMT resistor known as R7 found on the Pico. With this resistor removed, we need to supply 3.3V to the ADC_VREF pin and the relevant ground to AGND. With these changes, we sought to ideally eliminate any potential inaccuracies from our ADC measurements.

Regarding power for the Pico, it requires 1.8V to 5.5V which can by supplied via the Micro USB Type B port or the via the VBUS and VSYS pins. When the Pico is only powered via the USB port, VBUS and VSYS can be shorted as the Schottky between them is not needed in this case. In the case that the USB port is not used, power can be connected directly to the VSYS pin. However, we intend to the Pico to run without the USB port, but we still wish to use the USB port to occasionally monitor the Pico during operation. Therefore, the solution used was to feed the Pico 5V from our power supply and protect it with an additional Schottky diode. This allows the Pico to receive power from VSYS when the USB is not connected, and when the USB is connected the two voltages will be OR'd and the higher of the two voltages will supplied. The two diodes will also prevent the two sources from back powering the other.

From the Pico's various GPIO pins, we will utilize UART functionality to communicate with the Jetson and three PWM channels to run our red, yellow, and green LED.

D. Control System PCB

The size of the board and locations of the mounting holes mimic that of the NVIDIA Jetson Nano exactly so it can be mounted below the Jetson.

Using a four-terminal block, the board receives +5V, 5V_GND, +12V, and 12V_GND. These are then dispersed accordingly, with 5V being provided to the two 5V pins on the 5-pin connecter that goes to the Jetson, 5V to the Pico through a Schottky diode to avoid back feeding power when USB is connected, and finally to a voltage divider for the ADC_VREF pin on the Pico. The 12V is no longer utilized and will be removed in a future revision.

As mentioned above, 5V is being supplied to a voltage divider. This voltage divider is made with a 1kΩ and 2kΩ resistors in order to divide 5V down to 3.3V. This is then fed to the Pico's ADC_VREF pin in order to provide a more stable voltage reference point to the analog-to-digital converter. During our testing, we observed a voltage variation in the photodiode from 0V to 0.3V while covered up. However, after removing a resistor known as R7 from the Pico we saw this variation shift to 0.1V to 0.3V. This R7 resistor is what isolated the ADC's voltage reference from the internal Pico power supply, therefore making the reference point our voltage divider and power supply and showed improvement. For context, when excited by the laser, the photodiode showed a value close to 0.6V consistently. In a future revision, we would implement a linear regulator (such as the MIC5232-3.3YD5-TR) in place of our voltage divider. This would give a significant improvement to the stability of our voltage reference point. In order to connect this photodiode, a two-pin jumper was added which supplied 3.3V from the Pico to reverse bias the photodiode. The anode side of the photodiode was then fed back through the other pin on this jumper and sent to pin ADC2 on the Pico to read the value.

In order to provide power to the fabric for testing, another two-pin jumper was added. This time the jumper has one pin for 5V_GND and the other pin is supplied voltage anywhere from 0V to 5V through a 10kΩ potentiometer. This potentiometer is fed 5V directly, and depending on the position of the potentiometer, power can be supplied directly to the fabric testing set up. This also featured test point 1 (TP1) and test point 2 (TP2) on the board in order to test the voltage value with a multimeter before utilizing it. However, we underestimate the current draw the fabric would have, so when this system was used the overcurrent protection of our bench power supply would kick in stopped the test.

To physically show the AOI system status, three LEDs were added to the PCB showing red, yellow, and green. These LEDs are connected to three pins on the Pico, each capable of outputting a PWM signal. Each LED was then put in series with a 68Ω resistor.

Finally, REV2 of this PCB still includes the A4988 stepper motor driver board. Since the systems this was intended to serve are no longer used, it will be removed along with the relevant 100µF capacitor and four terminal blocks in a future revision.

E. Laser Counter System

The laser being used is a donated semiconductor laser diode provided by a member of the ChroMorphous Fabric team. This 534 nm laser emits a spot size of around 1 mm. The laser is redirected by a mirror, simply to help conserve space and use the available volume of our device. The laser beam is then subjected to a Galilean beam expander, which is necessary due to the relationship of the following equations (3), (4) and (5).

$$2w_0 = \left(\frac{4\lambda}{\pi}\right)\left(\frac{F}{D}\right) \tag{3}$$

$$\mathrm{DOF} = \left(\frac{8\lambda}{\pi}\right)\left(\frac{F}{D}\right)^2 \tag{4}$$

$$\mathrm{MP} = -\frac{\text{Focal Length}_{\text{Objective Lens}}}{\text{Focal Length}_{\text{Image Lens}}} \tag{5}$$

To achieve the target goal of 50 µm at a focal distance of 150 mm, we would need the initial spot size of the laser to be 3 mm. This means the Galilean beam expander must 3x the emitted beam, which is achieved by stacking a 30 mm with a 100 mm negative lens. The distance between these lenses would be 70 mm, since the principal of this beam system is to expand the spot size

One of the greatest challenges to overcome with this laser is the high-power output and the surface refraction that comes from it. The system includes a shortwave bypass filter, with 50% transmission in our lasers wavelength, with an additional OD1 filter.

The laser is then read by our photodiode, an FD11A Si photodiode with 400 ns Rise Time. The stimulated voltage is driven to the Pico, where the process has been previously described in the Secondary Microcontroller section.

To support the photodiode, a simple low-pass RC filter with a 1500Hz cutoff frequency was made on perf-board. This RC filter was made using a 1kΩ resistor and a 0.1µF capacitor. This helped to eliminate noise that the system could encounter and is recommended by the photodiode manufacturer.

F. Power Supplies

As we follow our project requirements, there are two major components that need to be powered with different voltages that will bring us to design two types of power supplies: one will be the AC to DC converter and the other one the DC-to-DC converter. As we are making one single unit system the AC to DC converter will give power to the DC-to-DC converter. The reason for that is we need to energize the Control System PCB with a 5V DC supply at 5A while the stepper motor needs a 12V DC supply at 2A.

In the case of AC to DC converter, we used the LM5021 regulator from the TI WEBENCH design. It is a pulse width modulation (PWM) controller which made with lot of features such as high efficiency of implementation, single-ended flyback and forward power converters using mode control, also has low start up current by reducing the loss of power in the high voltage start up network. This power supply system can range from less than 100V to 240V AC or more and can deliver an output voltage of 12V at 4A. This power supply will be used to energize at the same time the stepper motor and the DC-to-DC converter.

The second power supply is using a DC-DC buck converter that can convert a 12V DC to 5V DC at 5A that the Jetson NANO requirement. This power supply will take its 12V input from one of the outputs of the AC-DC power supply that we mention above. The design of this converter comes from the Texas Instruments WEBENCH design for the implementation of this power supply. The TPS54561-Q1 is the regulator that we used for this power supply. This device has great features such as it is a step-down regulator with an integrated high-side MOSFET which means it can survive up to an input of 65V at 5A. Power is Good for output monitor Undervoltage and Overvoltage. When the voltage is dropping under 4.3V the device is locked out. Also, it has high efficiency at light loads with pulse-skipping eco-mode MOSFET [1].

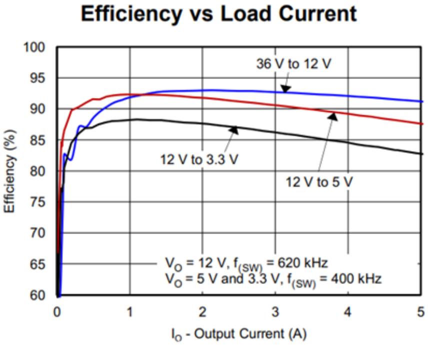

Fig 3. Graph of the efficiency versus the load current [1]

G. Manufacturing Line Simulator

In our other use scenario, the motor would have been used before fabric inspection began to make the adjustments then the motor would have gone unused for the duration of the program. The lag introduced from continuous use was so extreme that the Pico could not properly read the UART protocol coming from the Jetson and errors did not get reported immediately via the status LEDs. For this reason, this system is going unused to protect the main goals and objectives of the project overall.

V. SOFTWARE DETAILS

The main software design of the project involves many different components working in tandem. By dividing the components into manageable sections, the project software was realized along with the necessary framework required for intercomponent cooperation.

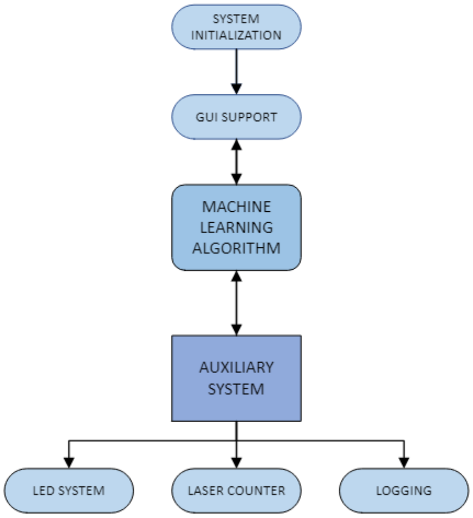

Fig 4. Block diagram of our software design process

A. Programming Language

The software language utilized for the project is Python. It is an interpreted programming language that has gained significant influence recently due to its versatility. This versatility benefited the project since it was used to code all the hardware in the design.

Of course, Python is very attractive due to its low cost and the ability to handle machine learning tasks that are necessary in the project. One of the main reasons to utilizes python is due to the availability of various libraries. In particular, the extensive support for machine learning libraries available in python allow for many different approaches to solve the challenge. The group will take advantage of Python's machine learning libraries to produce the project. Also, a graphic user interface for the project will also be developed using Python.

B. Training the Neural Network

Before utilizing the neural net, the algorithm utilized had to be trained on our new dataset. Training took place by capturing the dataset for each class the neural net would identify. Each class required between 60 – 110 images for training along with 20% of those images used for validation and testing. Afterward, the neural net would train for 35 iterations on the dataset before exporting to an open neural network format to use in the project.

C. Application usage

The general application uses many different python libraries to instantiate everything from the video stream to the serial communication and neural network. The main function loads the stream in a preview window before continuing to either one of two modes. In wide mode, the fabric is classified as a whole section while Region of Interest (ROI) mode classifies a few threads at a time. Each mode can be accessed by key switching from one to the other depending on and the situational requires. A serial port and logging function is included to monitor output and control the external Raspberry Pi Pico auxiliary software.

D. Auxiliary Software

In the Raspberry Pi Pico, some auxiliary functions have been offloaded to manage resources. These auxiliary functions include a LED status indicator and laser counter. For the LED system, the Raspberry Pi Pico will offer a visual indicator when image detection is in progress through a green/red pass/fail system. The laser counter function will count the threads during image detections and store/send the results to a local file. These support systems are python based and serve to assist the Jetson Nano in completing the project design.

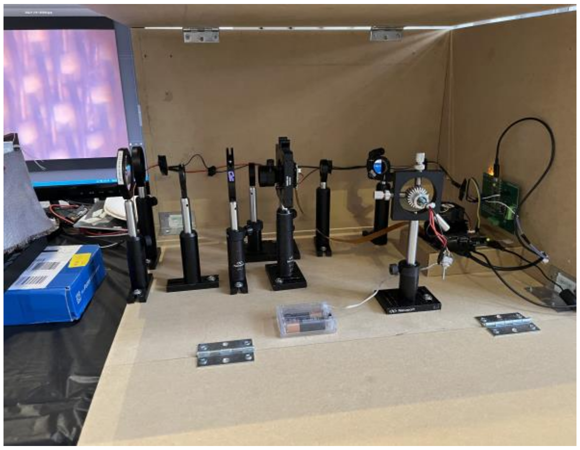

Figure 5: Overall Setup

VI. TESTING PROCEDURES

With the main system assembled, the following will cover the testing and validation associated with making our senior design perform. It will cover the initial phase of training on simple cases before advancing to more complex cases. Afterward, the team will discuss the results from multiple testing instances, in order to, determine the detection and error rate.

A. Initial Phase

Upon assembly of the hardware, the project needed to be validated to verify proper operation. Initially, the first training models deployed provided excellent feedback into the factors that would affect the overall results. Utilizing simple images for training, the team discovered how lighting, positioning and excess noise were accounting for classification errors. By adapting the optical portion of the design, we were able to minimize these errors and improve our training process.

With the physical portion of the project secured, we proceeded to finding an optimal neural network to match the process of classifying more complex cases. While some models yielded better results than others, they also came with additional overhead in training and resource utilization. Overall, we selected a residual network utilizing 18 deep layers that could handle over 11 million parameters. With our chosen model, we elected to capture images at a resolution of 800x600 which when multiplied by the RGB component equaled to 1.4 million features for the model to read. Our decisions allow for more efficient training along with maintaining lower overhead to help in coordinating the neural network’s ability in image classification.

B. Final Phase

Afterward, we began capturing the fabric dataset to mimic different manufacturing results. Some of the fabric threads were isolated and excited in specific patterns for passing and failing results. The model was trained for 50 epochs and the resulting neural network was used to gather the metrics for our engineering features.

C. Results

To quantify our results, we started by calculating the frame rates associated with the running model. The frame rates achieved while running the demonstration average about 22 fps or about 50 millisecond per frame read. When used to read a ¼ inch size of fabric, the rate of classification is approximately 5.5 in/sec. This estimation gives a general average of our current speed.

To demonstrate our detection rates, we aggregated multiple passes with the fabric in different controlled scenarios to build a confusion matrix. Depending on the observed outcome, the result could be classified as one of the following consequences true positive, true negative, false positive, or false negative. For each instance, the fabric is either excited or not excited and the result from the model are logged into the following matrix.

Table 1: Confusion matrix results

Total Population 100 = P + N	**Positive (PP)**	**Negative (PN)**
Positive (P)	True Positive (34)	False Negative (13)
Negative (N)	False Positive (19)	True Negative (35)

Given the results, we are able to derive the accuracy and misclassification rate for the neural network using the values and following equations.

$$\text{Accuracy} = TP + TN/P + N = 68\%$$
$$\text{Misclassification Rate} = 1 - \text{Accuracy} = 32\%$$

D. Operation

During operation, the system, when trained, will start in preview mode. Preview mode is to allow for corrections before classification mode commences. Two classification modes are available depending on the area of interest dictated by the setup. Wide mode classifies on a greater field of view while region of interest mode provides a more granular view. Each mode will provide a confidence score during operation. The score is the probability the model assigns to the current view. The more confident the neural network the higher the score. The score will dictate the class the model will assign, accordingly. A score can vary depending on environmental factors such as lighting and color so it is best to maintain a standard setup from initial dataset acquisition to operation. Exiting the program will stop all operations.

VII. CONCLUSION

After developing and constructing our design project, the group will share some insight into the results. From a software perspective, the programming language selected was the correct decision due to the flexibility it allowed in programming each hardware device. Also, some of the hardware was showing its limitation when in service. The Raspberry Pi Pico, especially, did not provide the necessary throughput to keep up with the system. Some edits had to be made for it to keep up with the design which inevitability disturbed other portions of the project.

Furthermore, during the initial training sessions many difficult lessons were learned about external circumstances affecting the results. Eventually, we realized that an isolated and properly lit imaged produced the best results. Later, when the enclosure was added, the team struggled with those conditions and many re-training sessions were lost due to the change. After minimizing external influences, the team was able to demonstrate a working project.

Overall, the experience in creating a project from the ground up with a group of individuals was very illuminating and demanding. The result we were able to achieve summarized our efforts. By adapting and utilizing our knowledge, we realized the true awareness that was bestowed upon us by our education.

THE ENGINEERS

Anthony Badillo is a 28-year-old PSE engineering student. He plans to continue working with the MOFD after graduation full time. His dream career is working in manufacturing and assembly of complex imaging systems, such as telescopes.

Joseph Sauceda is currently a senior at the University of Central Florida. He plans to graduate with his Bachelors of Science in Computer Engineering in December of 2022. He plans to attend the University of Central Florida for his graduate studies in the field of Machine Learning. He intends to continue working for Walt Disney World as an engineer after receiving his Bachelor’s Degree.

Valery Jean is a is currently a senior at the University of Central Florida and will be graduating with a Bachelor of Science in Electrical Engineering in December 2022. He is planning to remain in the Orlando area to pursue a career after graduation.

Garin Arabaci is a 25-year-old graduating Electrical Engineering student. Garin hopes to turn an internship with Siemens Energy in Orlando, FL into a career. Specializing in generator protection and controls. A dream career would be with SpaceX supporting their Falcon rockets.

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