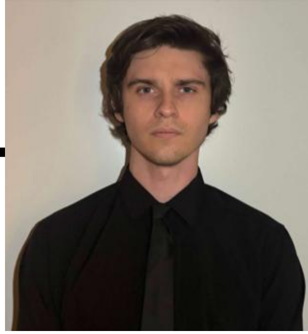
THE PROJECTILE TRACKING CHRONOGRAPH PROJECT

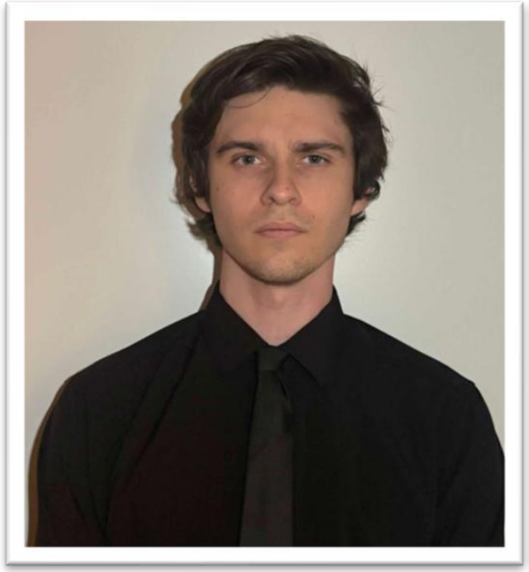
Group 5

Austin Stoetzer

PSE



OUR TEAM

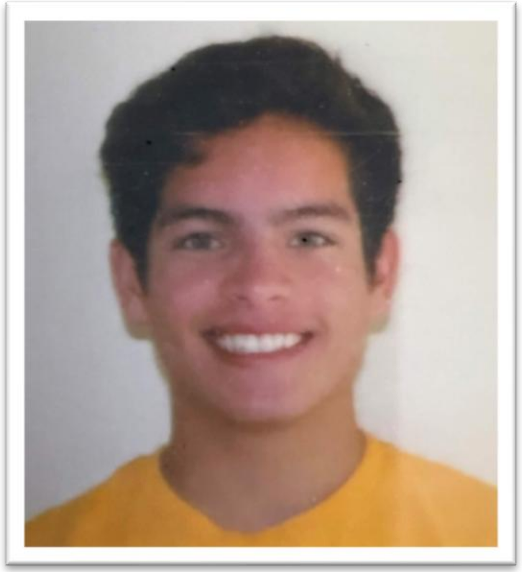


Austin Stoetzer

Optical Engineering

Blake Rainwater

Optical Engineering



Matthew Aranibar

Electrical Engineering

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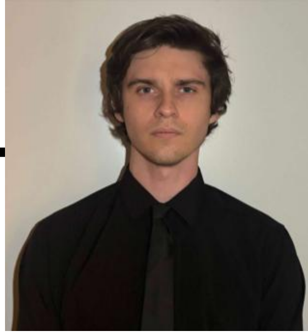
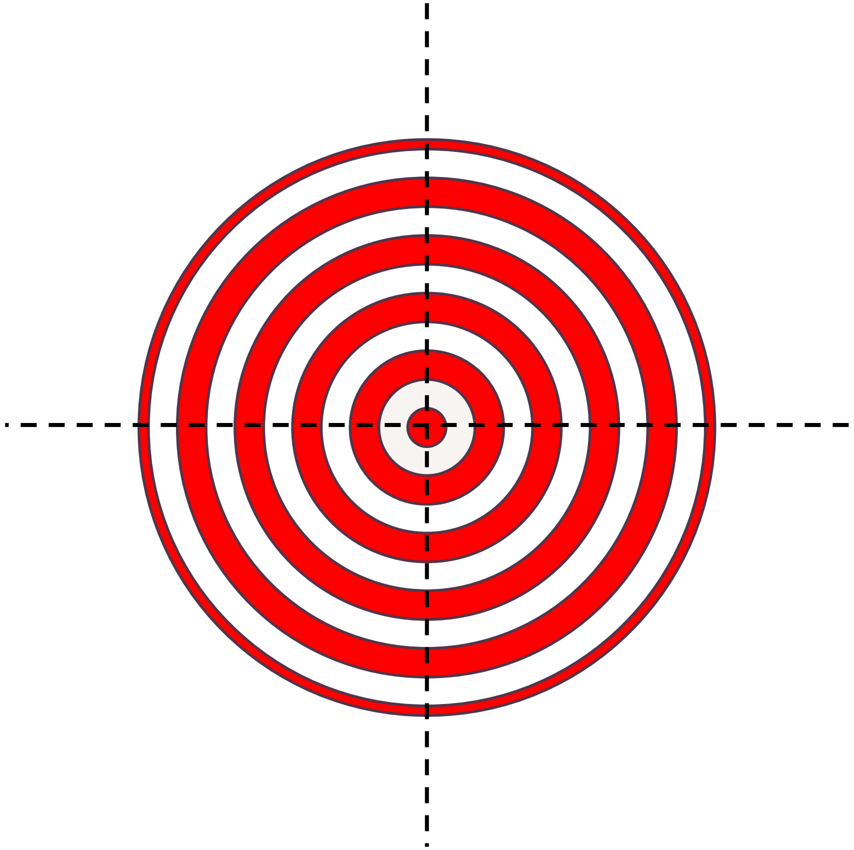
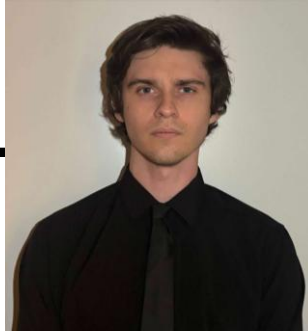


MOTIVATION AND BACKGROUND

We wanted to build a system that not only measures speed but also provides meaningful trajectory and spatial information without relying on high-cost radar technology. In this system, we aim to develop an easy-to-use and portable ballistic measurement tool. To do this, we will incorporate optical sensing, precise timing, and embedded computational techniques to provide accurate projectile information.





GOALS

Basic Goals:

- Detect a projectile.
- Accurately measure the projectile's velocity from a minimum of 5 m/s
- Ensure reliability in variable ambient lighting
- Provide velocity results within 10 seconds of detection, in an intuitive and presentable manner

Advanced Goals:

- Measure and extrapolate trajectory information
- Display processed data on an integrated screen
- Construct and visualize a two-dimensional representation of the projectile's trajectory

Stretch Goals:

- Predict target impact at 10 m for a 1 m diameter target
- Support a maximum projectile velocity of 100 m/s
- Integrate sensors to improve ballistic calculations and display more information

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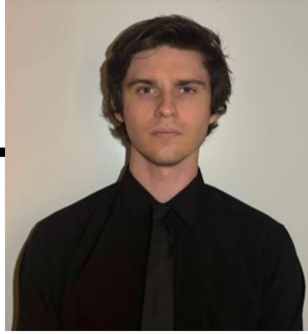

OBJECTIVES

Basic Objectives:

- Implement an optical detection system that does not require precise alignment by the user
- Capture projectile event data using optical sensors, cameras, or laser-based detection methods
- Use an MCU to coordinate sensing, timing, and computational tasks

Advanced Objectives:

- Develop an intuitive calibration procedure using known references
- Synchronize detection with strobe lighting and image capture
- Implement image processing and mathematical analysis to extract trajectory information

Stretch Objectives:

- Integrate magnetometer to determine the heading of the projectile
- Integrate accelerometer to determine the vertical orientation of PTC device and infer projectile's elevation angle
- Combine sensor data to improve accuracy of trajectory estimation

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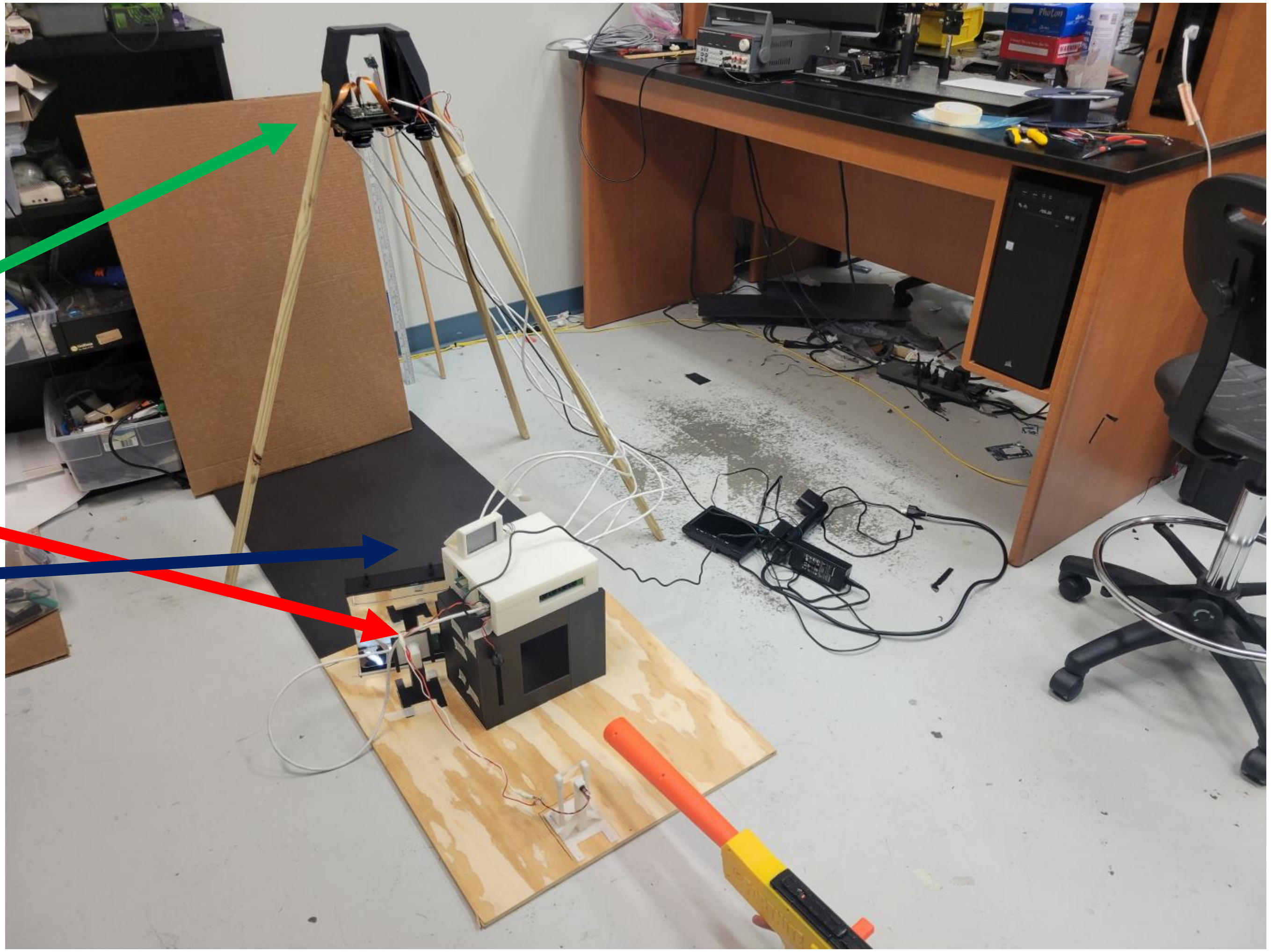
WHAT DOES THE PTC LOOK LIKE?

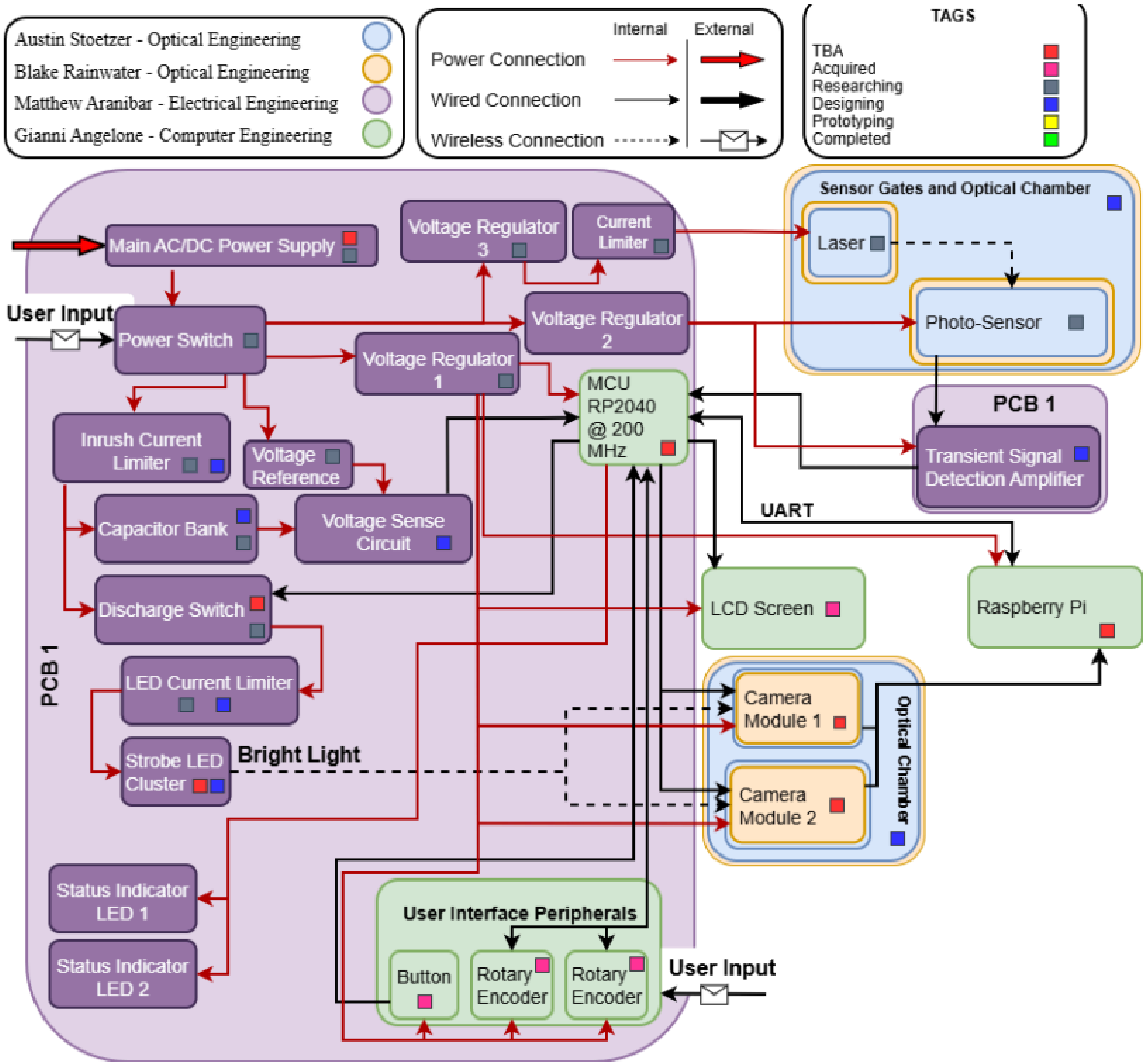
- The PTC consists of two primary components:
  - The Strobe Imaging Subsystem
  - The Sensor Gate Subsystem
- A UI screen will display information to the user



ENGINEERING SPECIFICATIONS

Parameter	Specification
Speed Measurement Error	< 20%
System Response Time	< 5 s
Detectable Projectile Size	15mm to 50mm
Detectable speeds	10 m/s to 50 m/s
Angular Resolution Error	< 0.2 radian
Power Requirements	< 300 W
Sensing area	> 10 cm x 10 cm
Size	< 3m x 3m x 3m
Ambient Light Tolerance	> 20 lumens per square foot

HARDWARE DESIGN – BLOCK DIAGRAM



- Multiple Subsystems
- Multiple Data Connections
- Controlling Circuitry centralized on a motherboard

Matthew Aranibar
EE

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EE

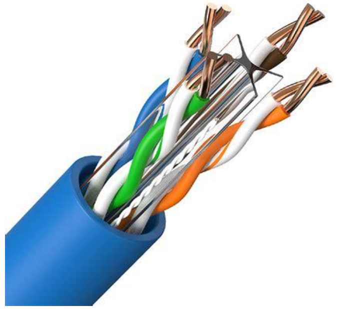
HARDWARE DESIGN – DESIGN PHILOSOPHY

Emphasis On:

- Modular Design
- Durability
- Easy Diagnosis

Achieved With:

- Detachable/Replaceable Modules
- Status Indicator LEDs
- Fault-Handling System



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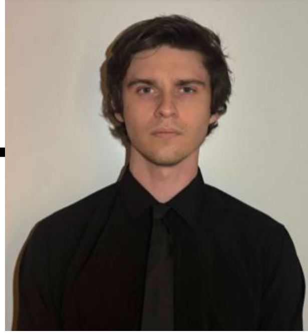

SENSOR GATE SUBSYSTEM TECHNOLOGY CHOICE - LASER DIODE

- A laser diode was chosen over an LED
- We chose visible red (650 nm) due to its fair responsivity on silicon photodiodes
- The Adafruit 1057 line laser was chosen to produce the laser sheet

[Adafruit 1057]

[VLM-650-23 LPO]

Characteristic	Adafruit 1057	VLM-650-23 LPO	VLM-650-27 LPT-10
Wavelength (nm)	650	640-650	645-655
Optical Output Power (mW)	5	1	2
Operating Voltage (V)	2.8-5.2	3-6	2.6-6
Operating Current (mA)	< 25	< 50	< 35
Fan Angle (degrees)	120	50	90
Cost	$8.95	$79.40	$75.16

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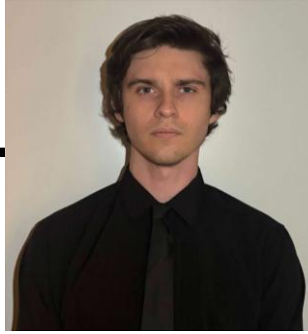
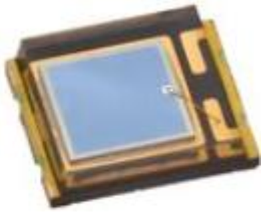


SENSOR GATE SUBSYSTEM TECHNOLOGY CHOICE - PHOTODIODE

- Contains a large sensing area
- Decent responsivity at 650 nm
- Offers moderate junction capacitance and low dark current
- Includes surface-mount packaging for PCB integration

[PDB-C142]



[PDB-C171SM]

Characteristic	PDB-C142	PDB-C171SM	PDB-C152SM
Peak Wavelength (nm)	650-660	940	900
Responsivity @ 650 nm (A/W)	0.53	0.4	0.33
Active Area (mm^2)	4.12	7.5	1.66
Dark Current (nA)	5-30	2-30	2-10
Short Circuit Current (µA)	100-150	50	8-10
Cost	$3.32	$4.49	$1.96

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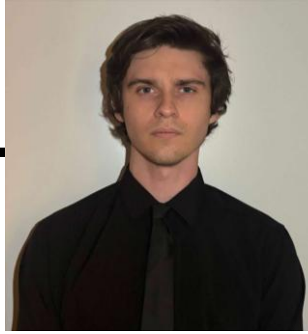

LIGHT GATE SUBSYSTEM TECHNOLOGY CHOICE - REFLECTORS

Characteristic	Glass Mirror	Acrylic Mirror	Aluminum Foil Tape
Reflectivity	~90-95%	~85-90%	~86%
Reflection Type	Specular	Specular	Mostly Specular
Surface Quality	Uniform	Uniform	Variable
Thickness	~ 2 mm	~ 2 mm	~ 15-16 µm
Cost	$27.94 (for 4)	$6.00 (for 2)	$6.99

- A combination of flat glass mirrors and parabolic mirrors made of acrylic were chosen to create and focus the laser sheets

[Plymor Glass Mirror]

[Acrylic Mirror]

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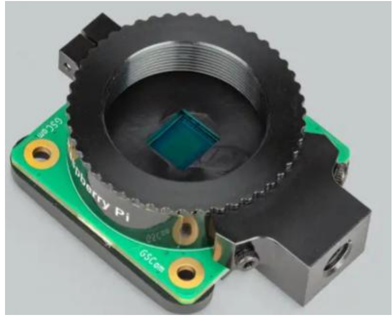
IMAGING CHAMBER SUBSYSTEM TECHNOLOGY CHOICE – CAMERA SELECTION

- Global shutter was chosen to avoid issues with rolling shutter artifacts
- The Raspberry Pi Global Shutter camera was chosen for its price, quality, and compatibility/ease of use
- The low price of the color camera was more important than the benefits in resolution and sensitivity of a monochrome camera

Name	Price	Resolution	Shutter	Trigger	Color
Raspberry Pi Global Shutter	$50	1456x1088	Global	Yes	Color
Raspberry Pi HQ Camera	$55	4056x3040	Rolling	Yes	Color
Raspberry Pi Camera Module 2	$15	3280x2464	Rolling	No	Color
E-CAM21_CURB	$90	1600x1300	Global	Yes	Monochrome
ArduCam OV9281	$42	1280x800	Global	No	Monochrome



[Raspberry Pi Global Shutter]

[Raspberry Pi HQ Camera]

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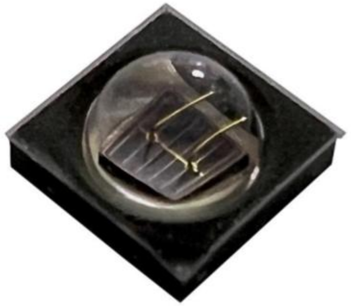
IMAGING CHAMBER SUBSYSTEM TECHNOLOGY CHOICE – STROBE LED SELECTION

- White LEDs were cheap and high power, but with the drawback of needing chromatic aberration compensation
- IR LEDs were chosen to allow monochromatic imaging and ambient light filtering



[AC3535A-YRR-1000MA]

[AC3535L-YRR-1000MA]

Name	Price	Radiant Intensity	Viewing Angle	mW/$
AC3535A-YRR-1000MA	$1	550 mW/sr	90°	1012
AC3535B-YRR1000-mA-H1	$1	900 mW/sr	60°	758
AG3535C-YRR-1000mA-H1	$1.1	430 mW/sr	120°	1228
AC3535L-YRR-1000MA	$1	175 mW/sr	150°	1012

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CPE

SOFTWARE COMPARISON AND SELECTION

Characteristic	OpenCV	MATLAB Toolbox	Scikit-image
Real-time Performance	Excellent	Moderate	Operate
Embedded (RPi 5) Compatibility	Excellent	Poor	Good
Cost	Free	High (license required)	Free
Integration with Python	Seamless	Limited	Excellent
Speed	High	Moderate	Moderate
Suitability for PTC	High	Low	Moderate

Image Processing Library:
OpenCV

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SOFTWARE COMPARISON AND SELECTION

Characteristic	Layered + Event-Driven	Model-View-Controller	Pure Event Driven
Modularity	Excellent	High	Moderate
Support for Hardware Triggered Operation	Excellent	Moderate	Excellent
Ease of Integration with UI	High	Excellent	Moderate
Maintainability	High	High	Moderate
Suitability for Embedded Real-Time Processing	High	Moderate	High
Suitability for PTC Project	High	Moderate	Moderate

Architecture: Layered, event-driven

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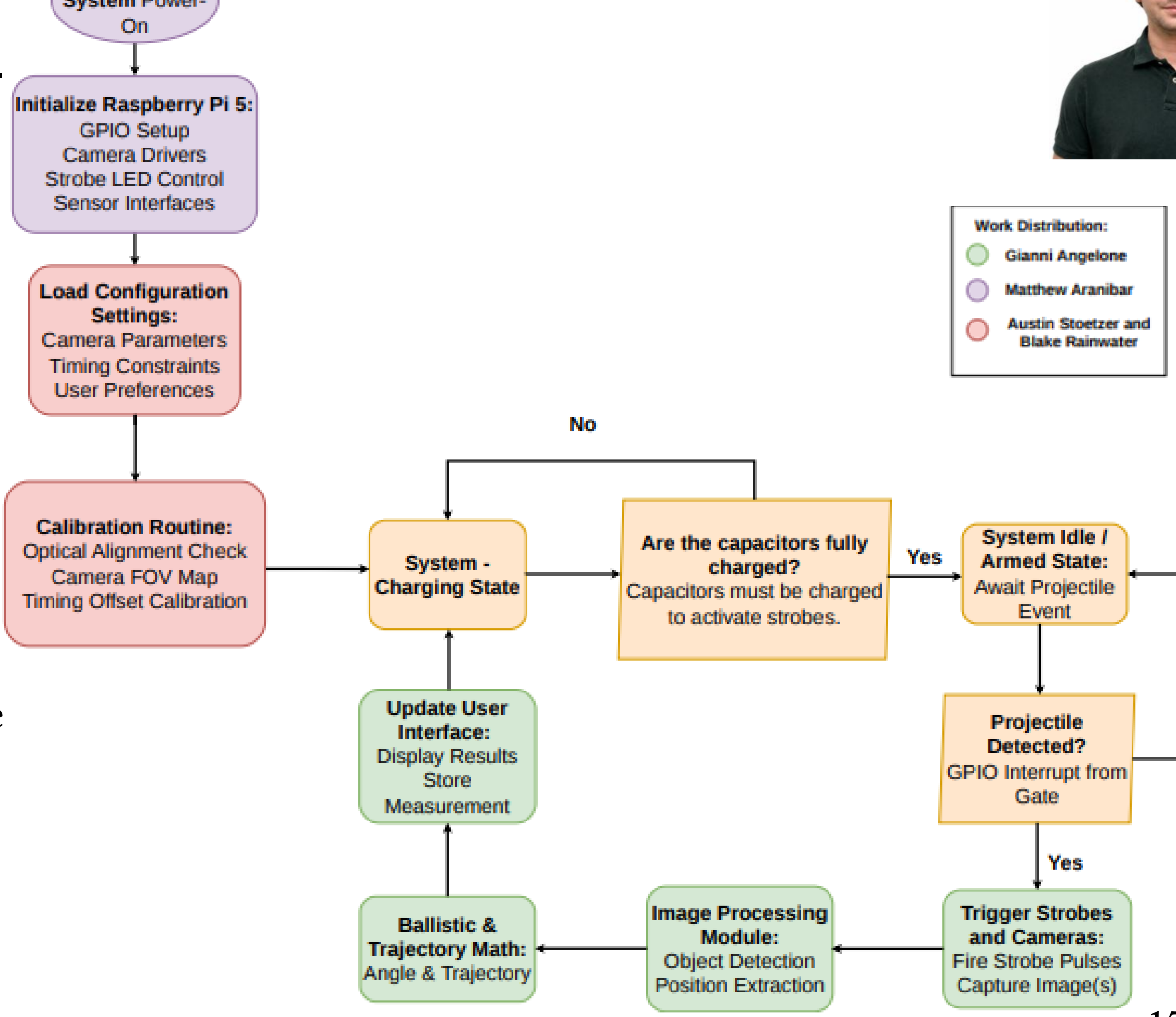
Projectile Tracking Chronograph - Software

SOFTWARE DESIGN – OVERVIEW

- MCU handles timing-critical control
- Raspberry Pi 5 handles image processing
- Laser gate provides projectile velocity
- Camera subsystem provides spatial data
- Results shown through integrated interface



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SOFTWARE DESIGN - EXECUTION FLOW

Initialize: Initialize hardware and load settings

Wait in: Wait in idle state

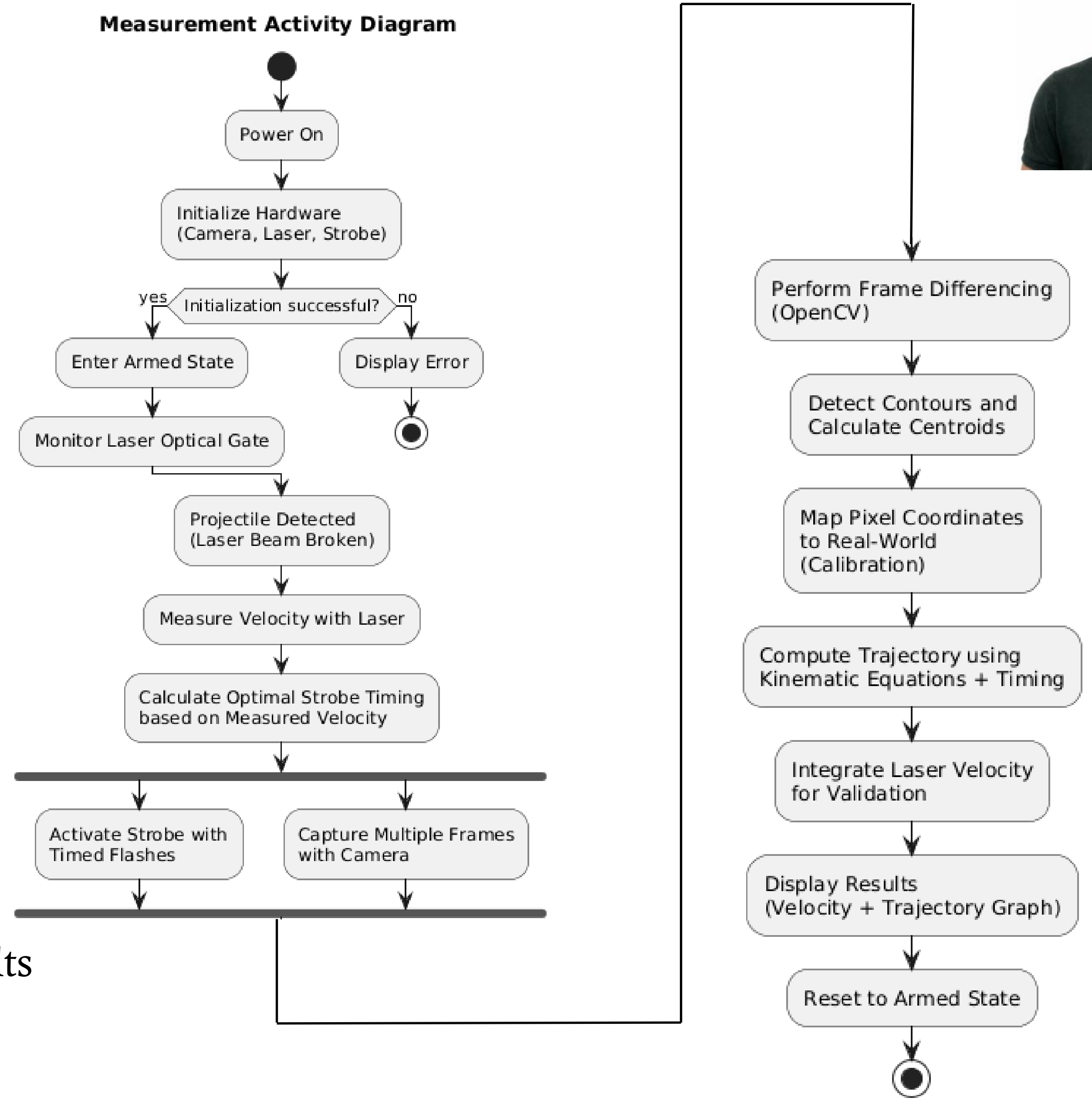
Detect: Detect projectile with gate

Measure: Measure velocity

Trigger: Trigger strobes and capture images

Process: Process images and extract position

Compute: Compute trajectory and display results



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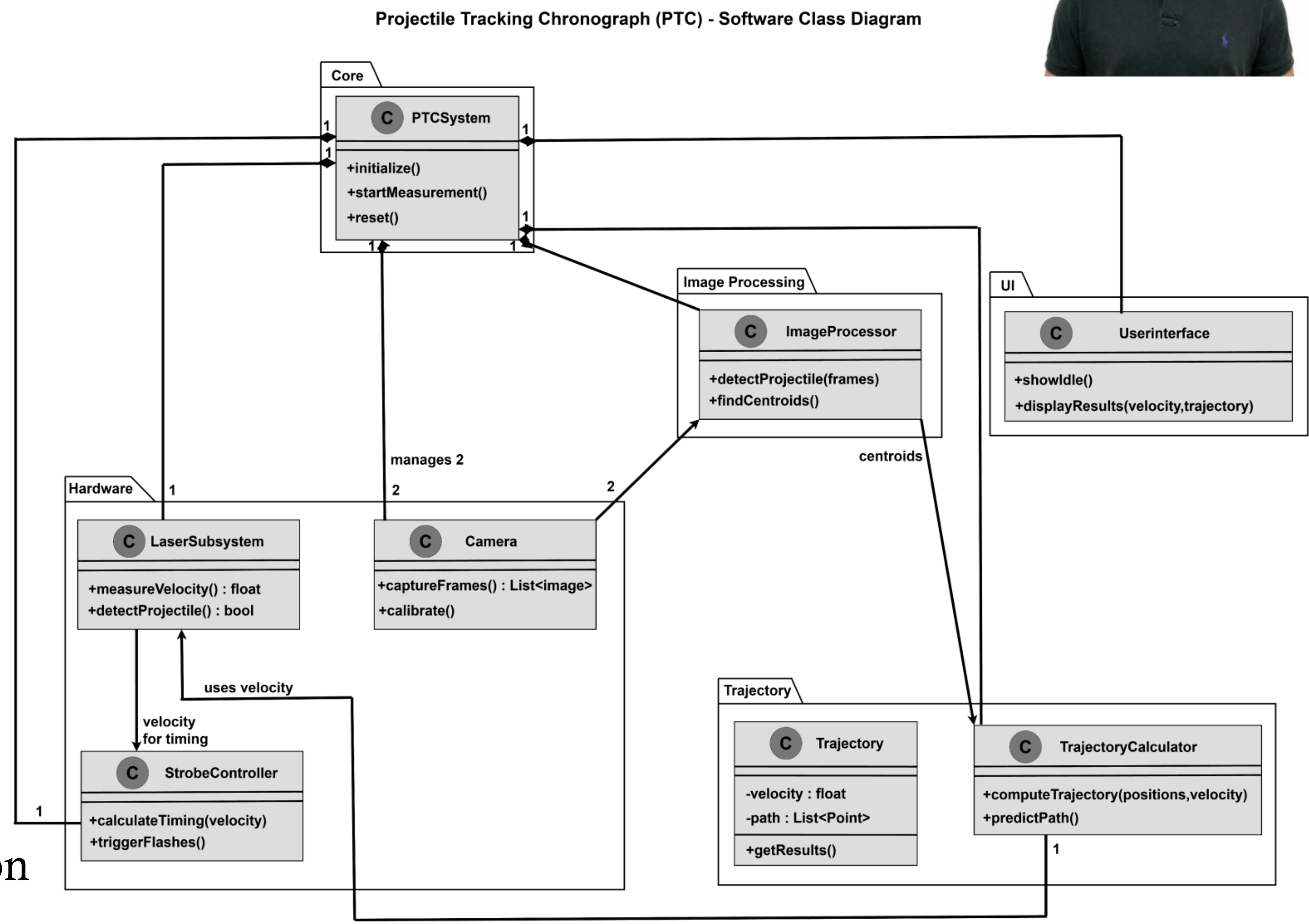
SOFTWARE DESIGN – ARCHITECTURE

- Layered, event-driven organization
- Modular processing stages
- Separate hardware control and UI logic
- Simple user-friendly display
- Numerical results + trajectory visualization



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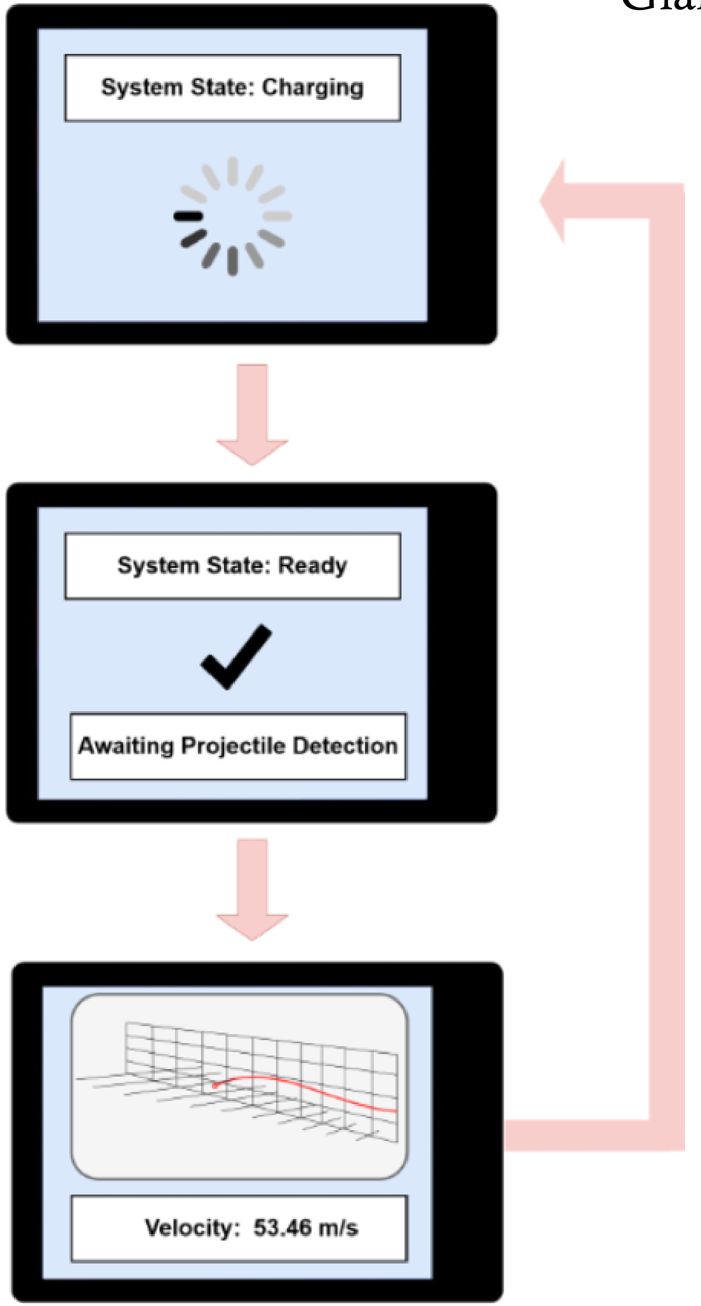
SOFTWARE DESIGN – USER INTERFACE

- Displays projectile velocity
- Displays trajectory-related results
- Designed for quick and simple reading
- Intended for standalone system use



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HARDWARE COMPARISON AND SELECTION – MCU

- Chose ESP32-S3-WROOM for accessibility and solderability
- High clock speed of up to 240 MHz ensures accurate timing and speed calculations
- Many pins capable of Analog-to-Digital Conversion and communication protocols like I2C, SPI, UART

Name	Price	Dev Board Cost	Max Clock Speed	GPIO Pins	Package Type
ESP32-S3-WROOM-1	$6.32	$15	240 MHz	36	Custom
Arduino UNO	$5.36	$24.33	48 MHz	20	Gull Wing
Raspberry Pi Pico 2	$1	$5	150 MHz	30	QFN
MSP430	$1.13	$10.99	16 MHz	16	DIP

ESP32-S3-WROOM-1

RA4M1 (Uno)

MSP430G2553

RP2350

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HARDWARE COMPARISON AND SELECTION – SWITCHING REGULATOR

- The LM2576, while more expensive, comes in a package that is easier to solder
- Low switching frequency prevents issues with layout and grounding
- Capable of handling input voltage of 24 V, supplying at least 1 A

Name	Price	Max Vin (V)	Max Current (A)	Adjustable	Efficiency	Switching Frequency
LM2576S	$6.32	40	3.0	Yes	75%	52 kHz
AP5100	$0.60	24	1.2	Yes	87%	1.4 MHz
LM2594M-3.3-EV	$1.27	45	1.5	No	75%	150 kHz
LM2575-3.3WT	$1.72	40	1.0	No	80%	52 kHz

LM2576S

AP5100WG-7

LM2594M

LM2575

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HARDWARE COMPARISON AND SELECTION – LINEAR REGULATOR

- The LM2576, while more expensive, comes in a package that is easier to solder
- Low switching frequency prevents issues with layout and grounding
- Capable of handling input voltage of 24 V, supplying at least 1 A

Name	Price	Max Vin	Max Current	Adjustable	Dropout Voltage
LD1086DTTRY	$1.81	30 V	1.5 A	Yes	1.5 V
AZ1117-ADJ	$0.21	15 V	1 A	Yes	1.3 V
LT3080	$6.23	36 V	1.1 A	Yes	1.6 V
LT1086	$6.61	25 V	1.5 A	Yes	1.5 V

LD1086

AZ1117

LT3080

LT1086

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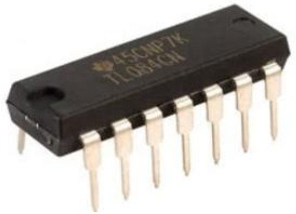
HARDWARE COMPARISON AND SELECTION – OPERATIONAL AMPLIFIER

- MCP6489 is quad package
- Low noise comparable to OPA2727
- Price comparable to TL084
- Near double GBW of TL084
- Operates at a maximum of 5.5 V

MCP6489

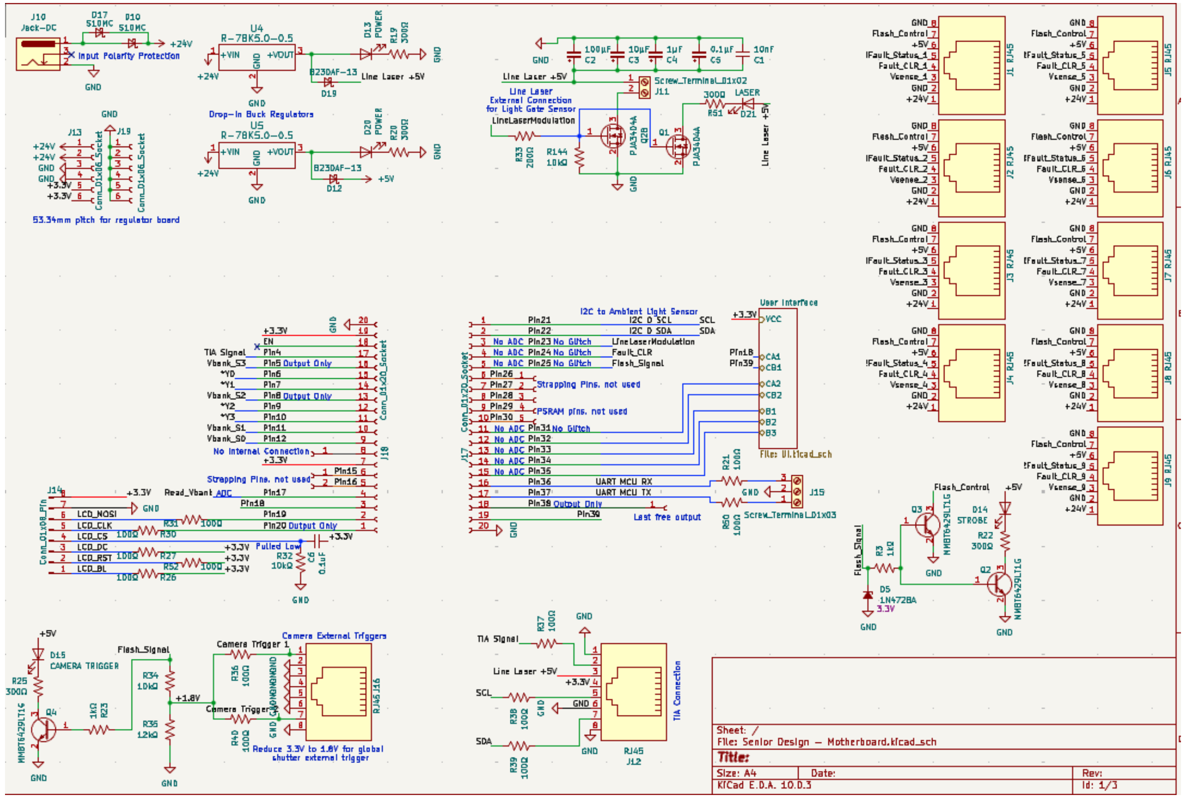


TL084

OPA2727

Name	Cost	Input Noise Voltage Density (nV/(Hz)^-1)	Slew Rate (V/us)	GBW
MCP6489	$0.48	16	20	10 MHz
TL084	$0.35	37	20	5.2 MHz
OPA2727	$3.64	10	30	20 MHz

HARDWARE DESIGN – MOTHERBOARD AND PERIPHERALS



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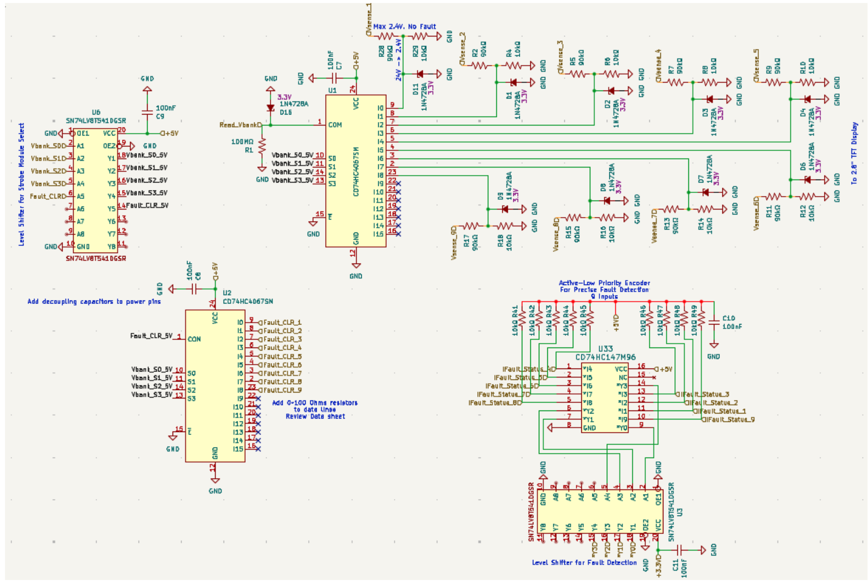
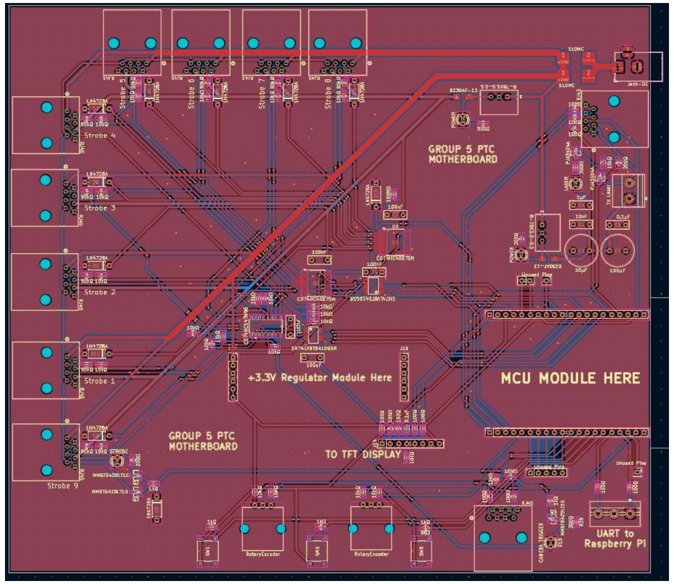
- Built to facilitate signal communication between modules, supply power, and indicate statuses
- RJ45 ports and Cat6 wire are used for connections to other modules





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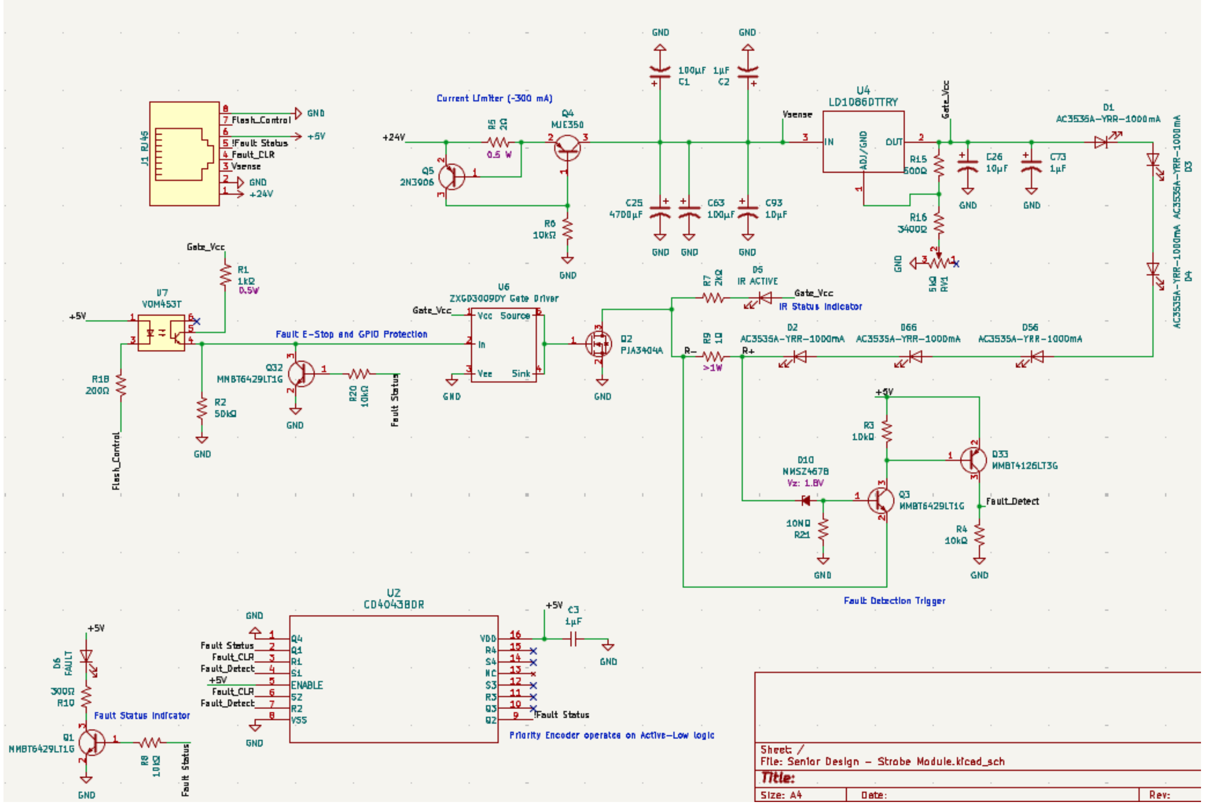
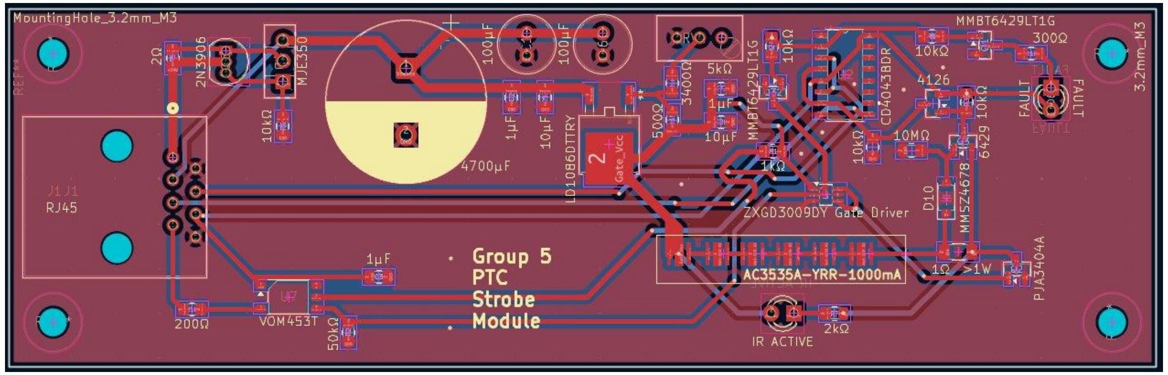
HARDWARE DESIGN – STROBE





- 9 independent, detachable strobe modules
- Status LEDs for Fault condition and IR on
- Built to handle short pulses of large current
- Fault Detection & Handling, Status Latch
- High Voltage Isolated From MCU

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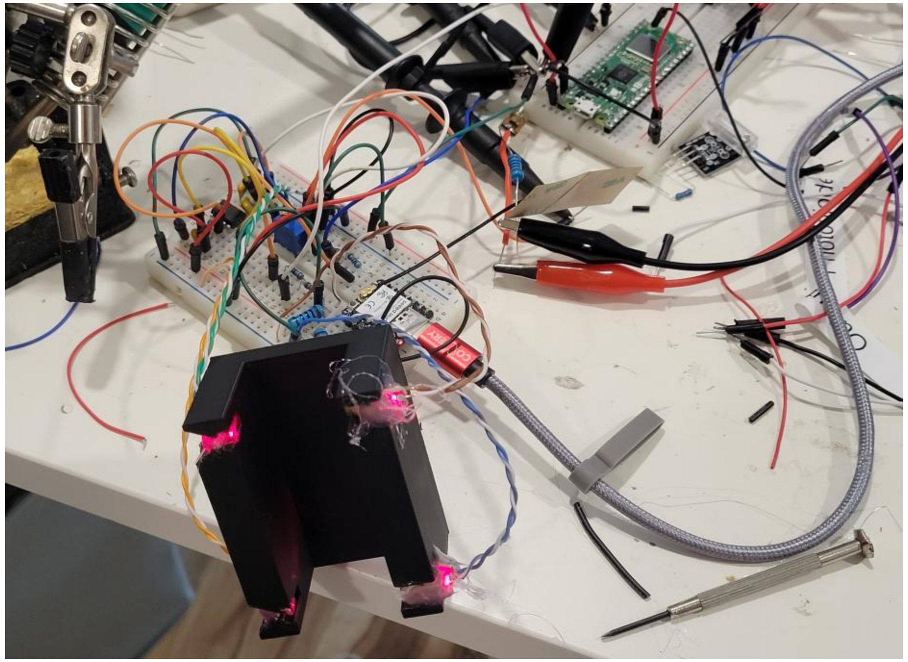
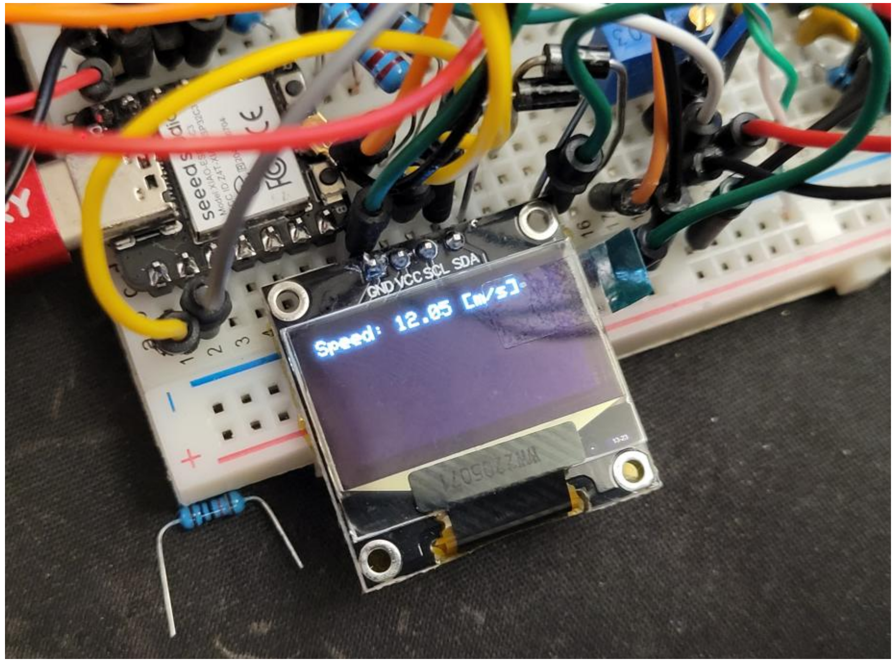
PROTOTYPING AND TESTING – PROOF OF CONCEPT

- A laser gate prototype was created to test the speed detection and demonstrated in the middle of SD 1





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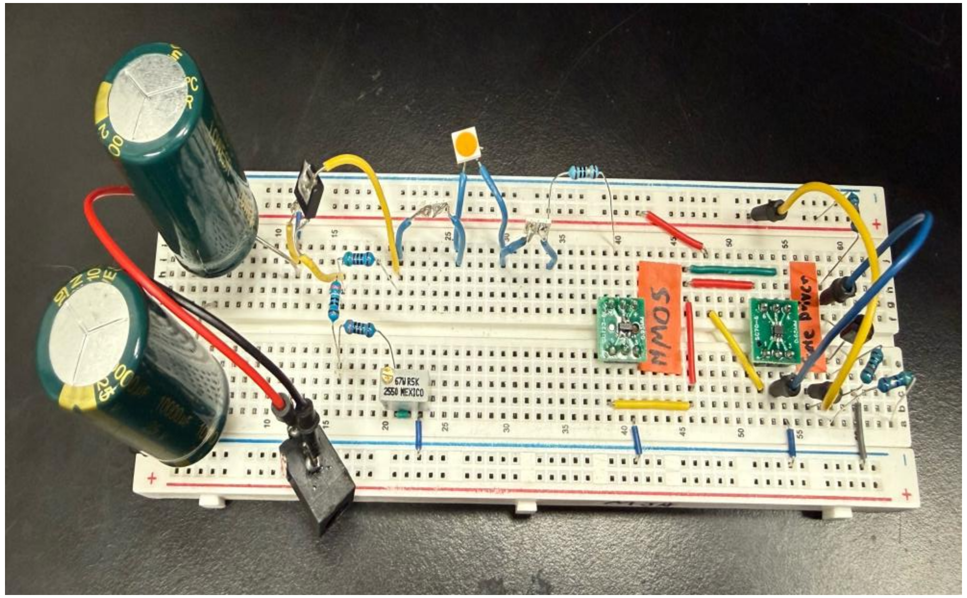
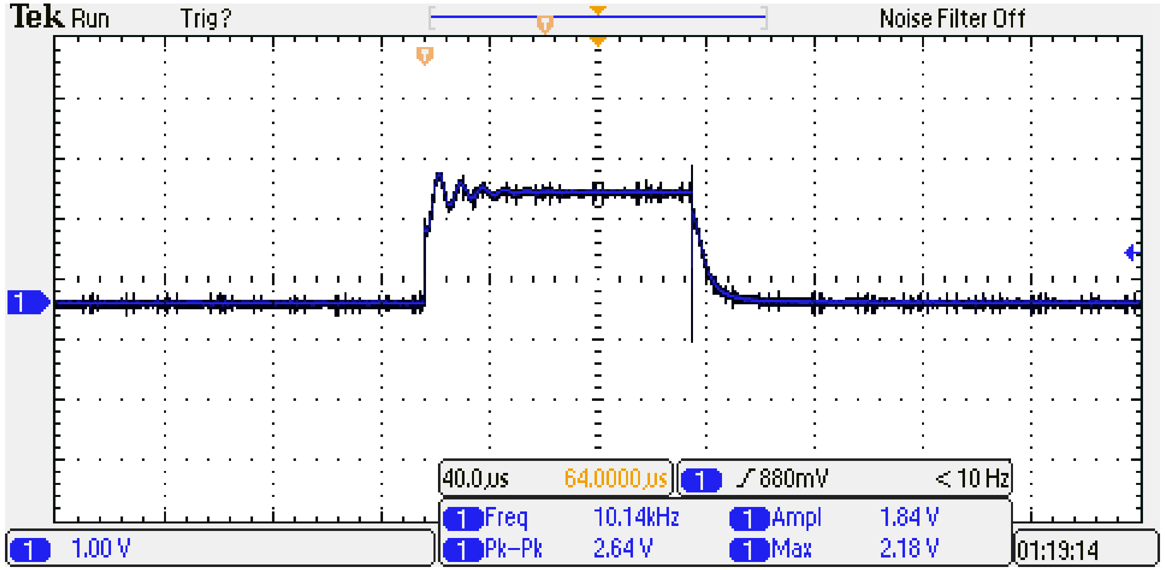
PROTOTYPING AND TESTING - STROBE



Strobe module prototype assembled with MOSFET and Gate Driver, adjustable LDO regulator, bright white LEDs, and large capacitors. Triggering is driven by a function generator.



Voltage output taken from load resistor in series with strobe LEDs. With minimal ringing, indicates a stable voltage and current throughput controlled by adjustable LDO.

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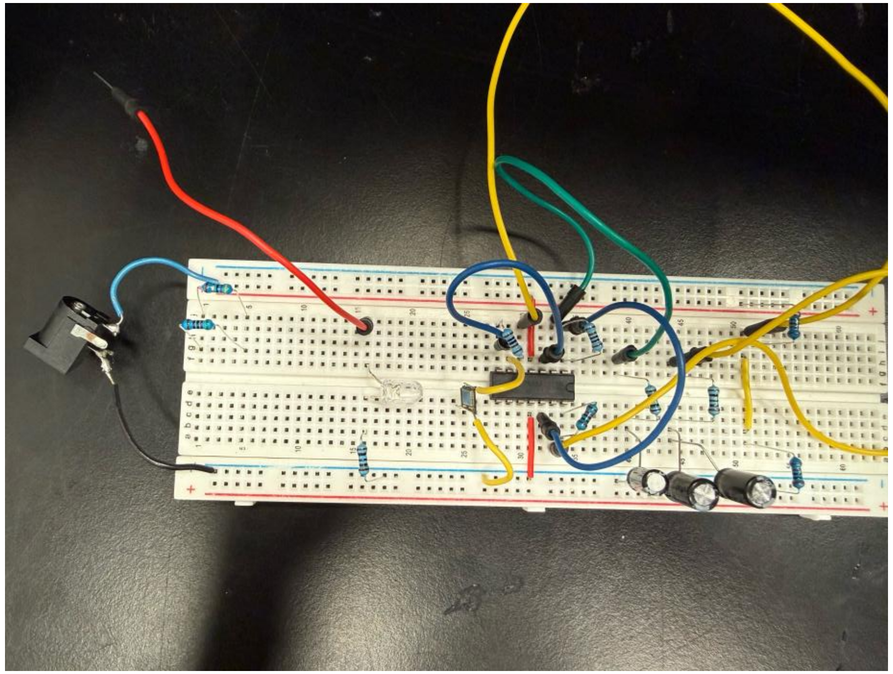
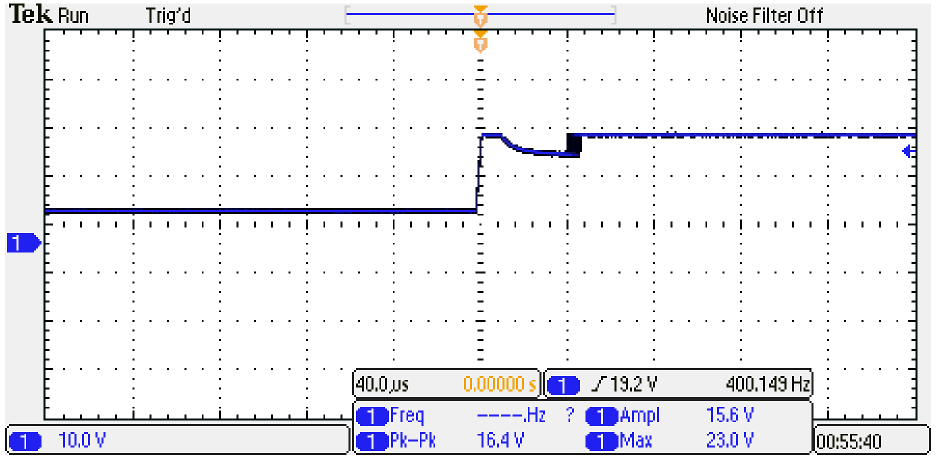
PROTOTYPING AND TESTING - TIA

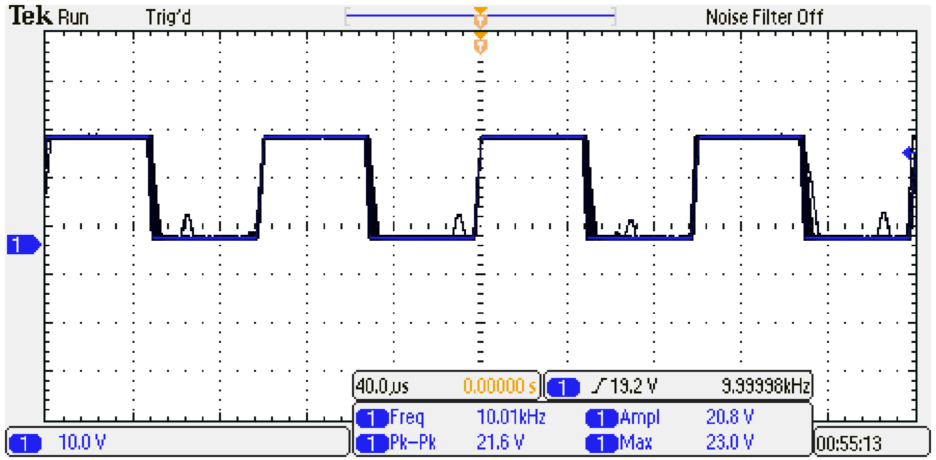


TIA prototype built on breadboard using a TL084 quad op-amp with 2 gain stages and tested using an external LED driven by a function generator.

Signal when LED is blocked:



Signal when LED remains un -blocked:



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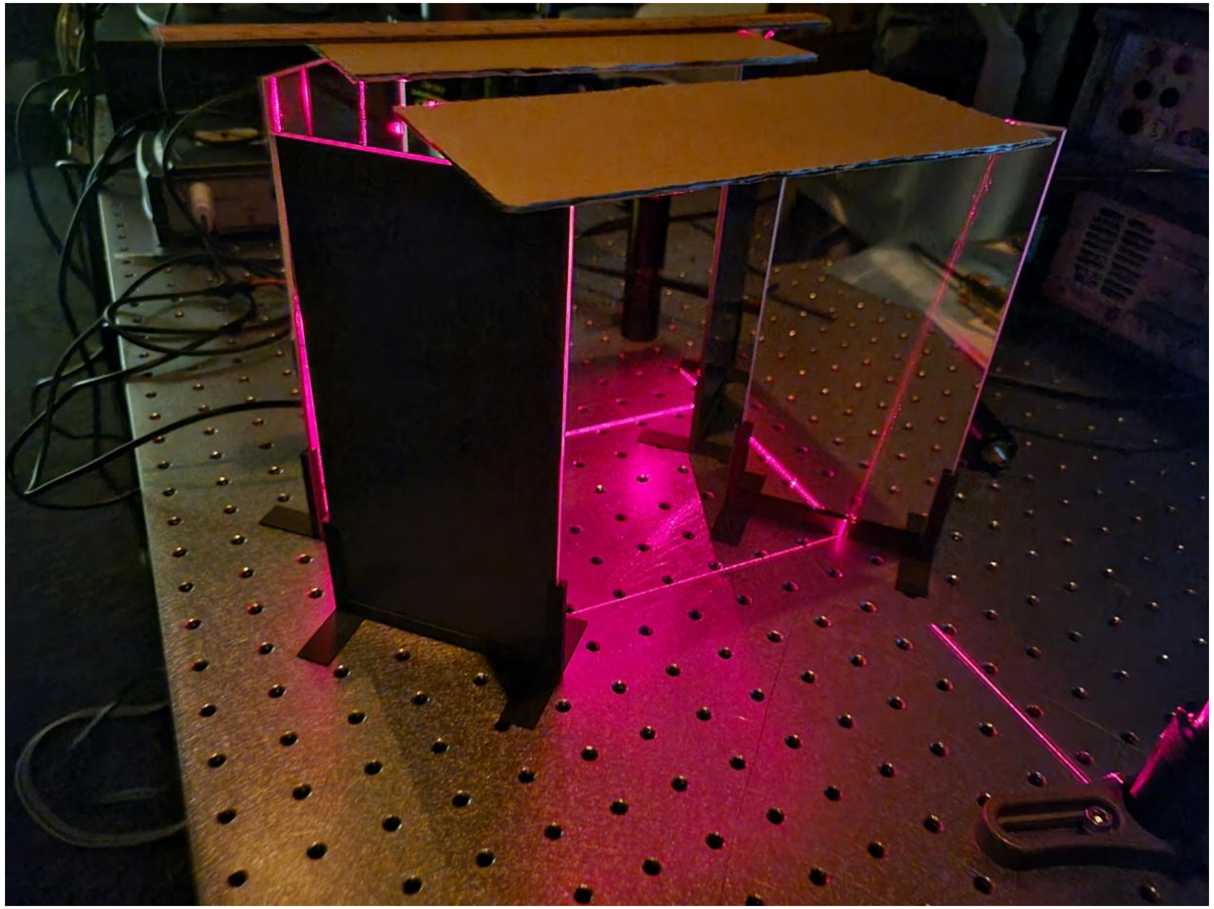
PROTOTYPING AND TESTING – INITIAL SENSOR GATE

- We tested the received signal on our photodiode using our TIA board, line laser, and chosen mirrors
- The detected change in signal (no collimation or focusing of the beam) was ~ 400-500 mV, and for our project we need to detect a change of around 1.7 V



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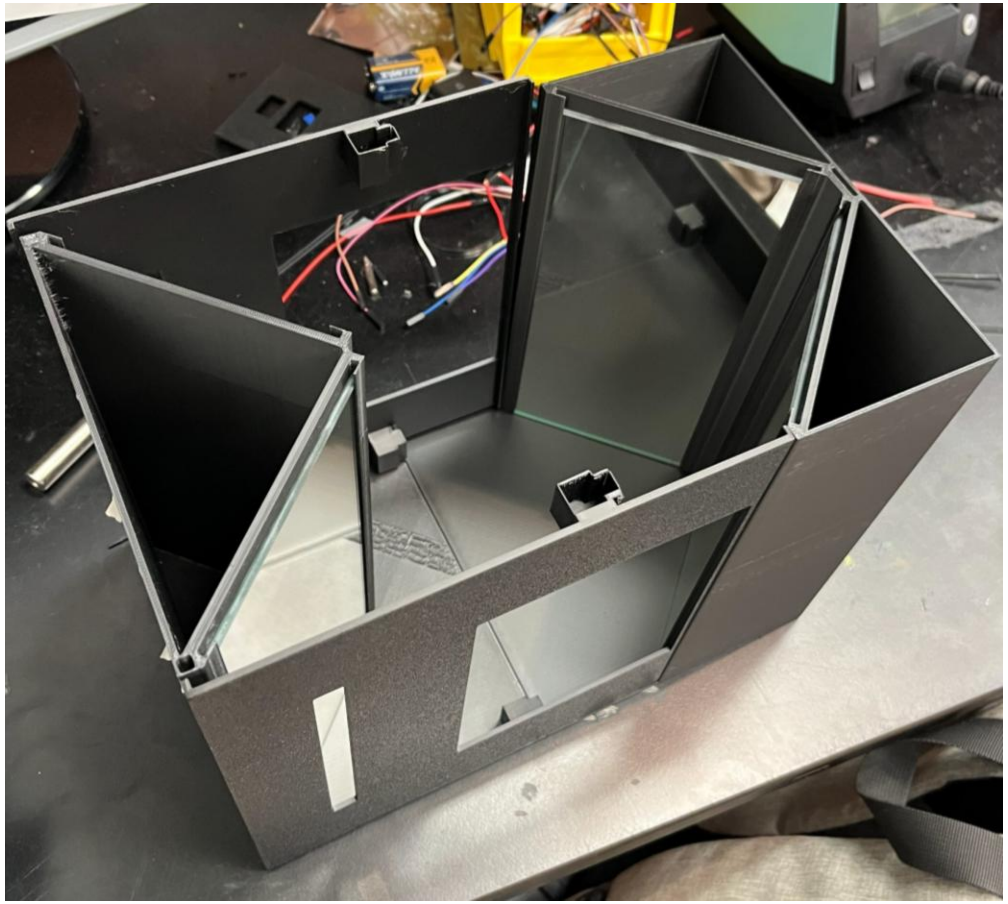
PROTOTYPING AND TESTING – REFLECTOR ENCLOSURE DESIGN (VOICEOVER NEEDED)

- This is a top-down view of the cavity design for the creation of the laser sheets that the object will pass through
- There is an entry and exit slot for the laser beam and the projectile, with 4 mirrors bouncing the laser across the sensing region



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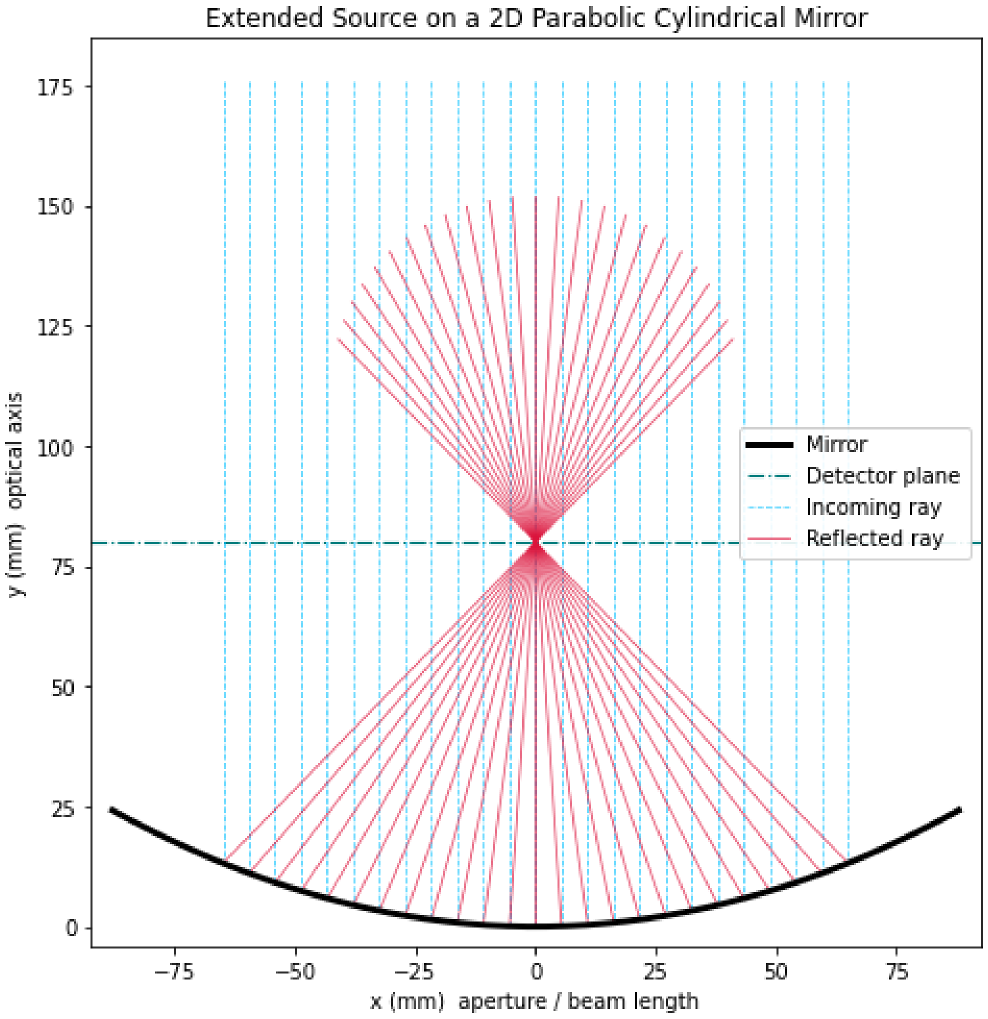
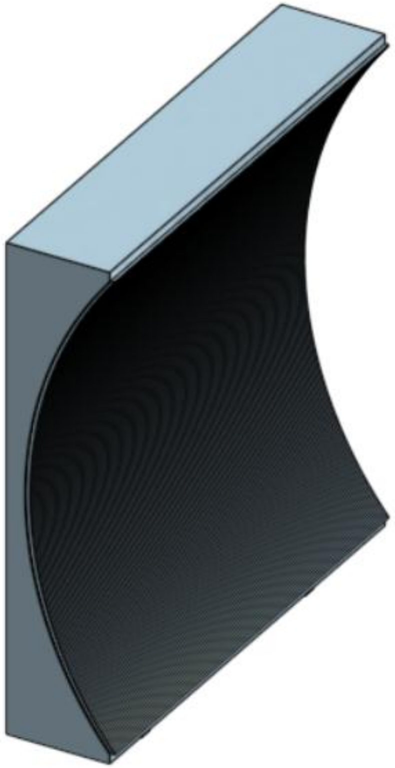
PROTOTYPING AND TESTING – PARABOLIC MIRROR THEORY (VOICEOVER NEEDED)

- A parabolic mirror is designed to take the incoming sheet of light and focus it down to a point
- Using the geometry of the output beam dictated by the exit slit of the sensor box, a mirror mold was designed





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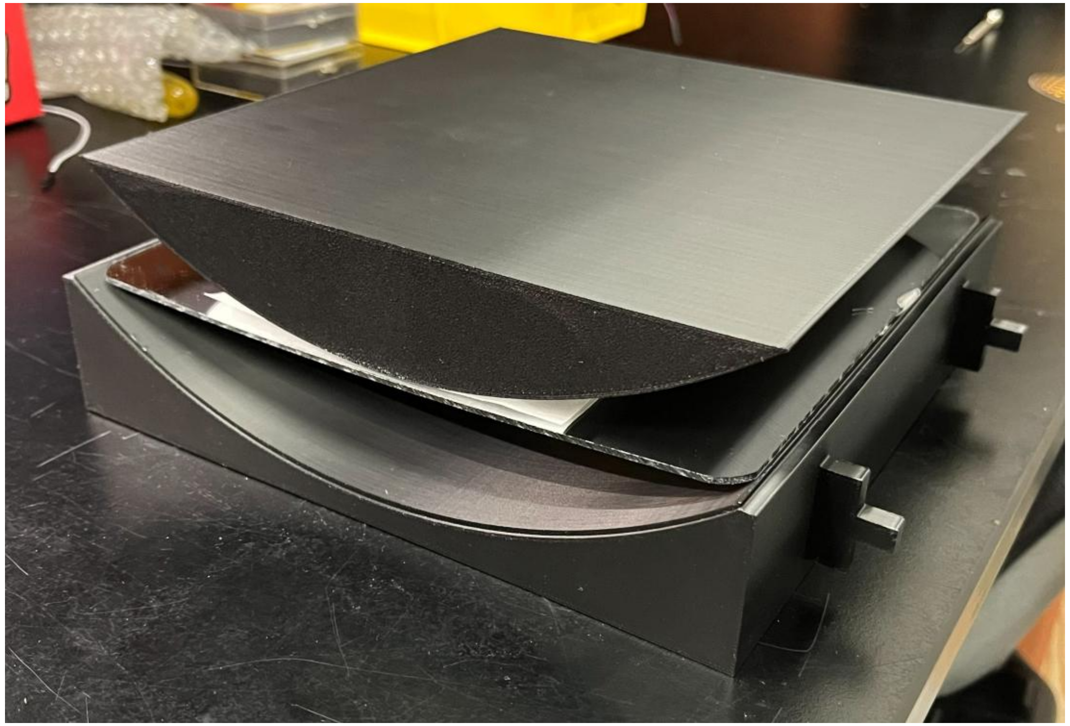
PROTOTYPING AND TESTING – PARABOLIC MIRROR MOUNT (VOICEOVER NEEDED)

- Concave and convex pieces were 3D printed to form the mount for the parabolic mirror
- The acrylic mirror was thermoformed and then pressed into shape using the molds



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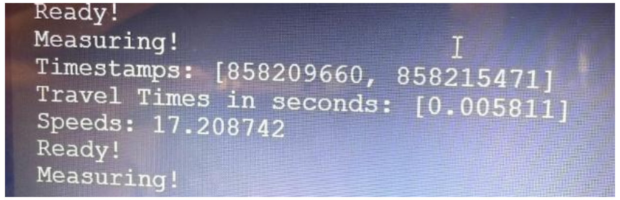
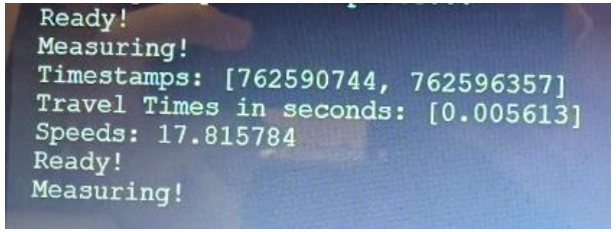
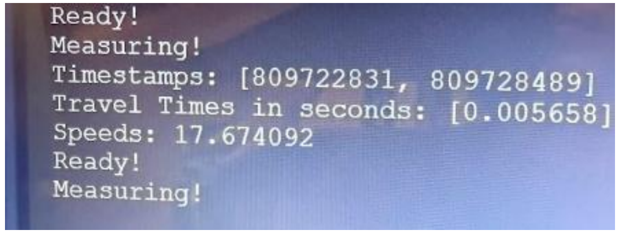
PROTOTYPING AND TESTING – FULL SENSOR GATE TRIALS (VOICEOVER NEEDED)

- The full sensor gate subsystem was aligned and tested
- Multiple projectiles were fired through the sensing region, with varying speeds corresponding to the different projectiles being captured accurately







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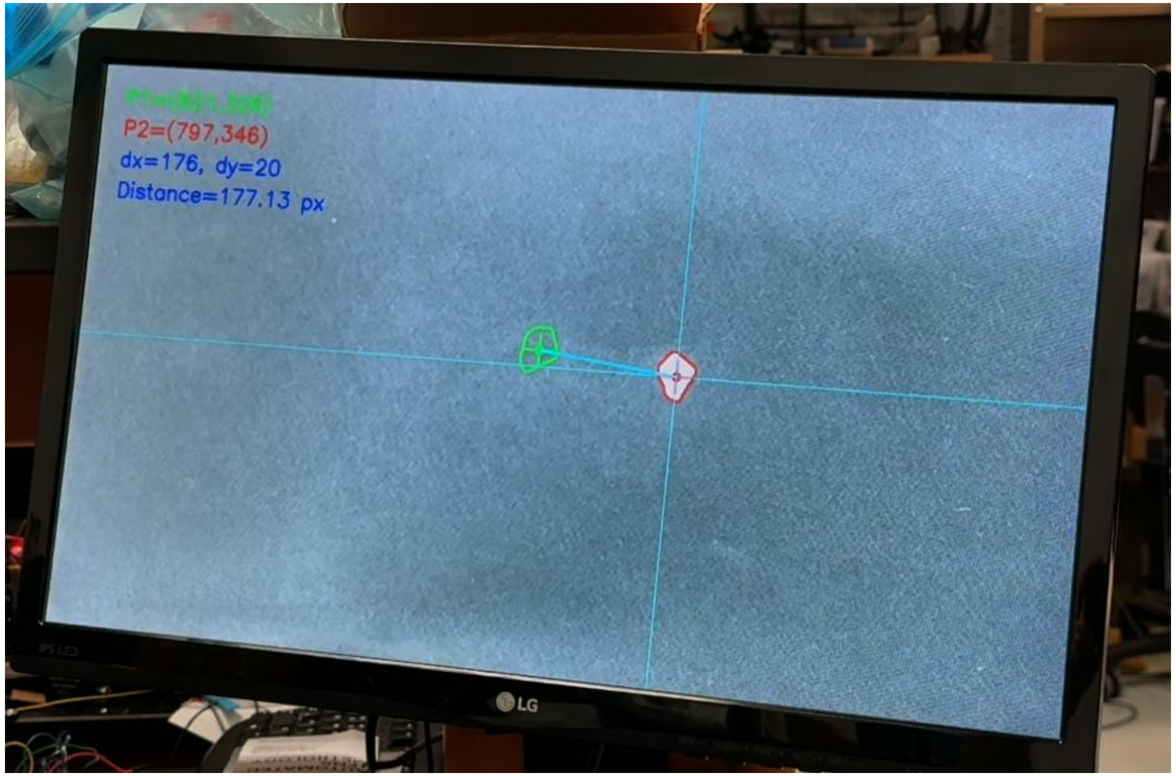
CPE

PROTOTYPING AND TESTING - SOFTWARE



- Raspberry Pi 5 tested with Python + OpenCV Library
- Blank and object images captured successfully
- Object Detected and position extracted
- Output displayed on local screen
- Confirms feasibility of software pipeline

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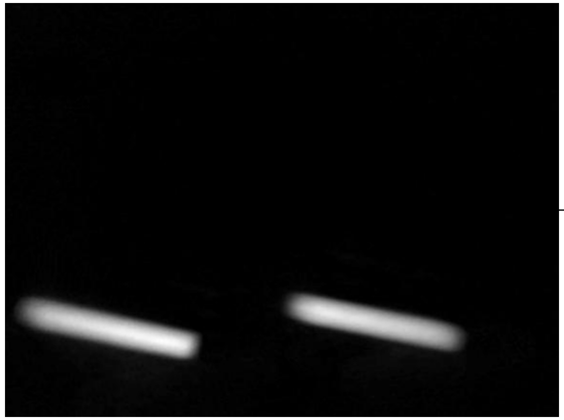
CPE

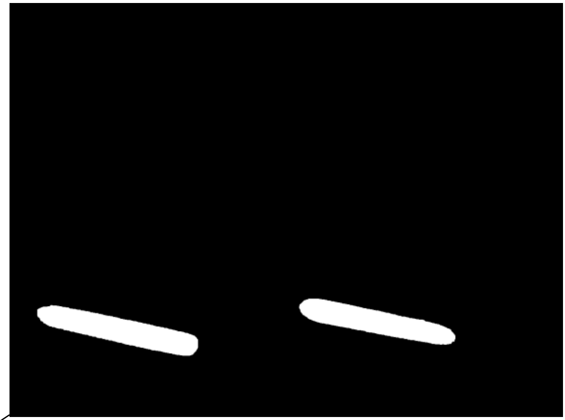
PROTOTYPING AND TESTING – PROJECTILE CENTROID DETECTION

Blank Scene

Raw Long Exposure Image
(2 Separate Strobe Flashes)

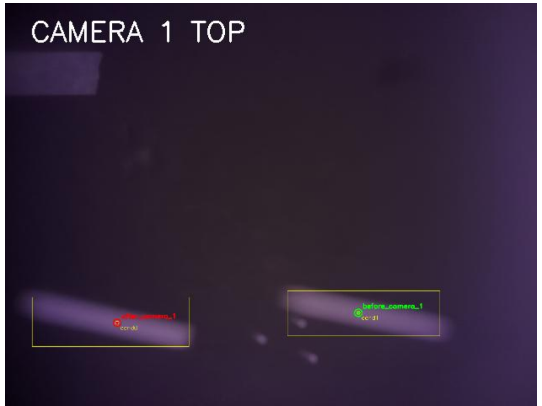


Normalized Image



Threshold Image

Final Centroid Output



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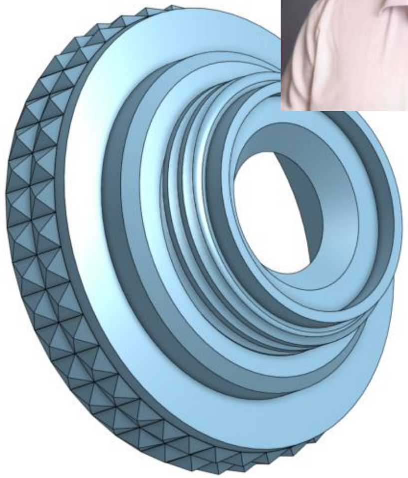
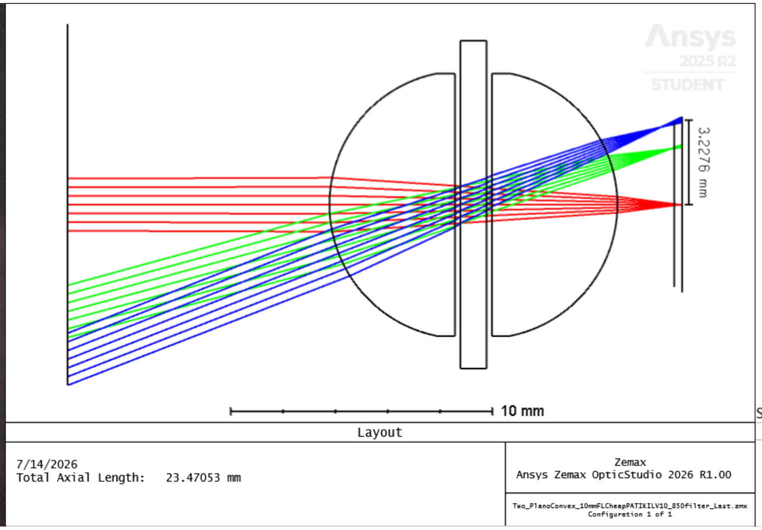
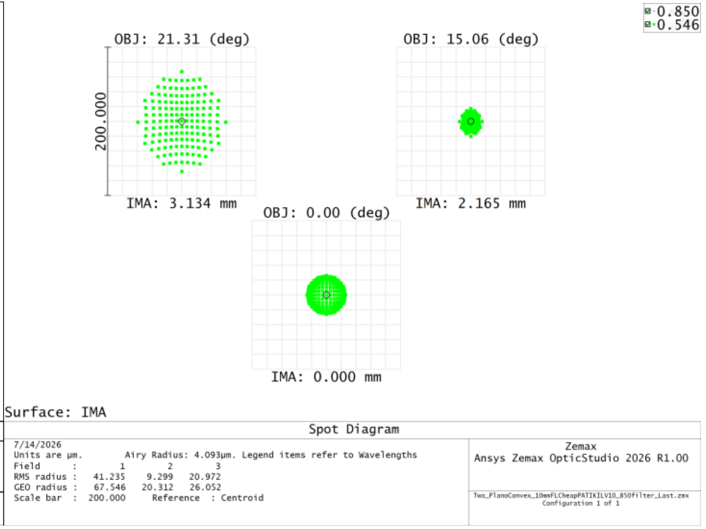
PROTOTYPING AND TESTING – IMAGING LENS ASSEMBLY

- Images from the custom lens assembly, the Zemax layout ray trace diagram, spot diagram, and part of the lens mount







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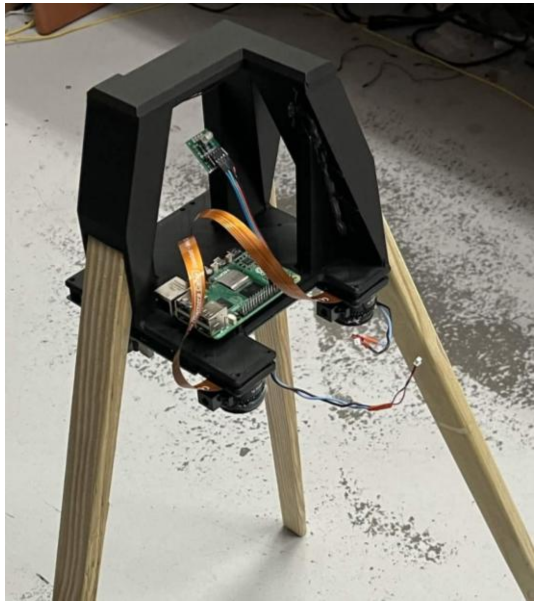
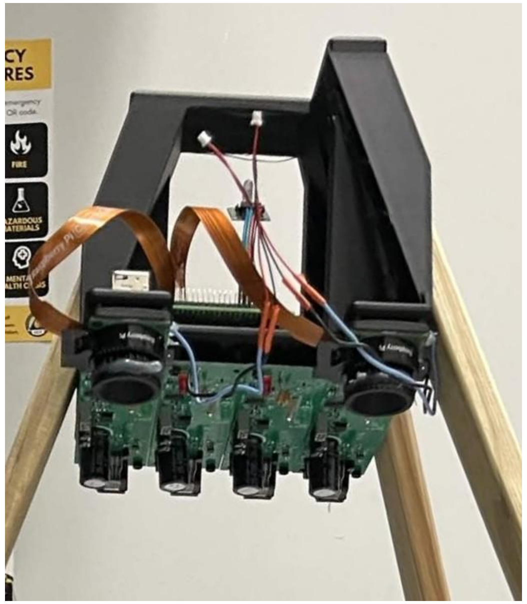
PROTOTYPING AND TESTING – CAMERA AND STROBE MOUNT

- 3D printed mount for the cameras, strobes, and raspberry pi





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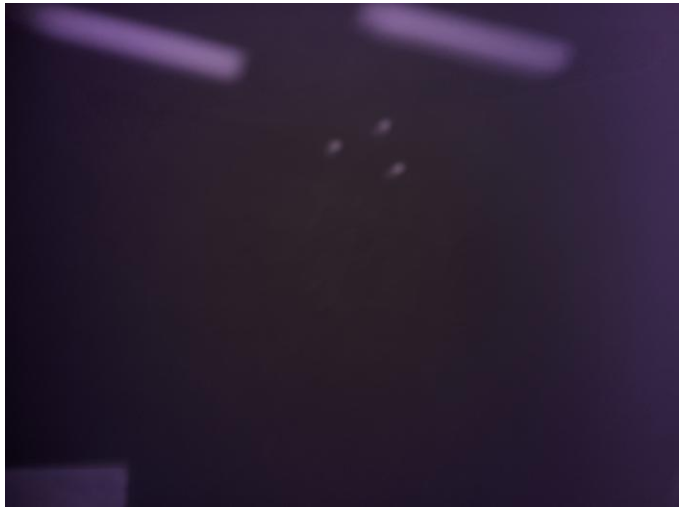
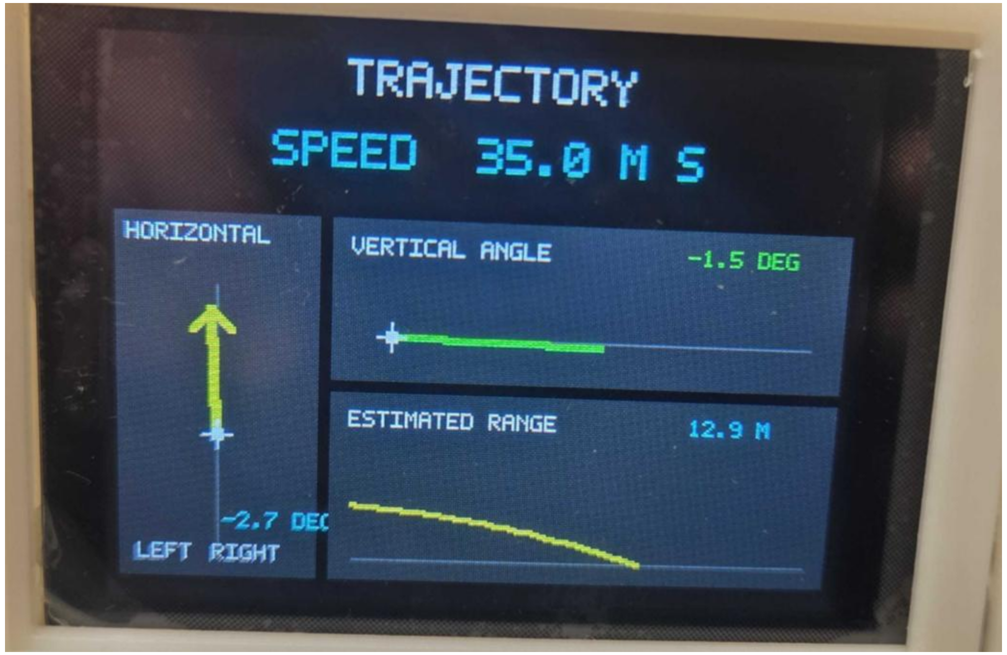
PROTOTYPING AND TESTING – FULL SYSTEM TEST

Camera 1

Camera 2





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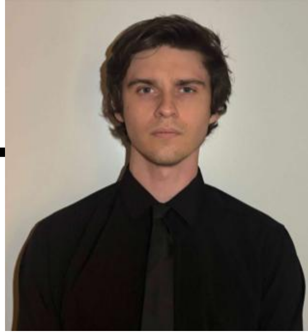

ADMINISTRATIVE CONTENT – BUDGET

Device	Part#	Quantity	Cost (BOM)	Cost (Budget)
Laser Diode	Adafruit 1057	2x	$17.90	$50.00
Photodetector	PDB-C171SM	2x	$8.98	$50.00
IR LED	AC3535A-YRR-1000 mA	60x	$60.00	$100.00
Flat Glass Mirrors	Plymor	4x	$27.94	$75.00
Cameras	Global Shutter	2x	$111.98	$200.00
Imaging Lenses	PATIKIL 10mm OD 10mm FL Lenses (5)	1x	$5.69	$100.00
850 nm Bandpass filters	Quanmin 850nm IR Narrow Bandpass Filter (2)	1x	$17.99	$50.00
Raspberry Pi 5	SC1642	1x	$65.00	$100.00
RJ45 Connectors	MTJ-881X1	22x	$8.16	$25.00
MCU	ESP32-S3-WROOOM-1-N8R8	1x	$6.32	$25.00
Level Shifter	SN74LV8T541DGSR	2x	$1.10	$5.00
Analog Multiplexer	CD74HC4067SM	2x	$1.26	$5.00
Plano-Convex Cylindrical Lens	28X12mm K9 Optical Glass	1x	$14.51	$50.00
PCBs	N/A	1x	$89.31	$100.00
PCB Stencils	N/A	1x	$122.70	$100.00

Device	Part#	Quantity	Cost (BOM)	Cost (Budget)
Priority Encoder	CD74HC147M96	1x	$0.48	$5.00
Switching Regulator	LM2576S	1x	$1.59	$5.00
LDO Linear Regulator	AZ1117	2x	$0.42	$5.00
Rail-to-Rail Op-Amp	MCP6489	1x	$0.48	$5.00
Ambient Light Sensor	LTR-329ALS-01	1x	$0.57	$5.00
Optocoupler	VOM453T	10x	$9.72	$20.00
SR Latch	CD4043BDR	10x	$5.26	$15.00
Gate Driver	ZXGD3009DY	10x	$1.68	$5.00
LDO Linear Regulator	LD1086DTTRY	10x	$13.31	$20.00
Switching Regulator	R-78K5.0-0.5	2x	$5.70	$10.00
LCD Display	Waveshare General 2.4inch LCD Display Module	1x	$11.99	$20.00
3D Print Filament	PLA	3x	$61.00	$50.00
Wooden Base Mount	Plywood	1x	$23.46	$25.00
Wood Glue	Gorilla Original Wood Glue	1x	$3.98	$5.00
Imaging Mount Tripod Legs	1”x2”x8’ Wood	3x	$9.24	$20.00
		Sub Total Estimate	$713.02	$1290.00 Goal: < $1000.00

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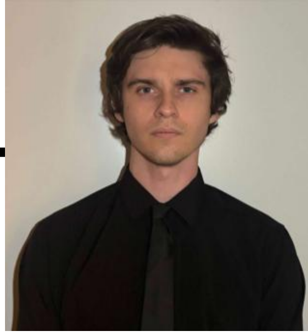

WORK DISTRIBUTION

Task	Primary	Secondary
Sensor Gate Subsystem	Austin Stoetzer	Matthew Aranibar
Imaging Chamber Subsystem	Blake Rainwater	Austin Stoetzer
Strobe Subsystem	Blake Rainwater	Matthew Aranibar
MCU and Embedded Control	Matthew Aranibar	Gianni Angelone
Motherboard / PCB Design	Matthew Aranibar	Blake Rainwater
Software and UI	Gianni Angelone	Blake Rainwater
Trajectory Visualization	Gianni Angelone	Blake Rainwater
Website and Project Materials	Gianni Angelone	Austin Stoetzer
Administrative Documentation	Austin Stoetzer	Matthew Aranibar
System Integration	Austin Stoetzer	Blake Rainwater

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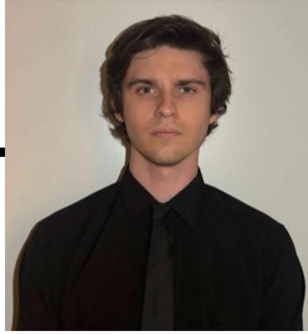

PROGRESS AND PLAN FOR COMPLETION