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Fire Detection and Monitoring for Emergency Situations

FLAMES – Group 6 Final Presentation

Motivation and Background

- NFPA Fire Loss Report (2021): ~896,500 false alarms annually from detection systems
- Ionization smoke detectors are only reliable for about 10 years due to sensor degradation
- Mismanagement of dust and metal chips accounts for nearly 30% of machine shop fires
- Dust and chips accumulate and are easily ignited by stray sparks.
- Accumulated metal chips, dust, and oil-based coolants increase flammability
- Unattended machine operation means fires can grow undetected without immediate intervention

- Impact Fire Services, “Special Hazard Fire Suppression Systems: A Guide for All Business Environments,” *Impact Fire Resources*. [Online]. Available: https://resources.impactfireservices.com/special-hazard-fire-suppression-systems-a-guide-for-all-business-environments.
- Firetrace International, “CNC Fire Risks and Fire Protection Solutions,” *Firetrace Blog*. [Online]. Available: https://www.firetrace.com/fire-protection-blog/cnc-fire.

Goals

Basic Goals:

- Compact enclosed FPGA-based system for detecting fire hazards and stochastic optical emissions (400–800 nm) in confined spaces (labs, CNC machines)
- Implement custom lens system for focusing light from source onto optoelectronic sensor for further signal processing

Advanced Goals:

- 180° rotating system with dynamic lux thresholding to locate emission sources
- Low-power mode for stepper motor to reduce energy use during idle periods
- Environmental baseline for accurate detection of optical intensity sources (e.g., flame)

Stretch Goals:

- Log trigger events to an external database via FPGA-to-PC communication.
- Incorporate machine learning into pattern matching off trained data for another layer of detection results.
- Integrate a filter wheel (UV, IR, specific wavelengths) to distinguish fire types (chemical, electrical)

Objectives

Basic Objectives:

- Audible Buzzer and Visual LED fire Alerts
- Pre-aligned, user–friendly 3D printed enclosure for all optics/ electronics
- FPGA-based spectral/temporal analysis using V(t); includes adaptive filtering, frequency-domain methods, real-time monitoring
- User-triggered baseline calibration (start button); resettable for consistent detection across environments

Advanced Objectives:

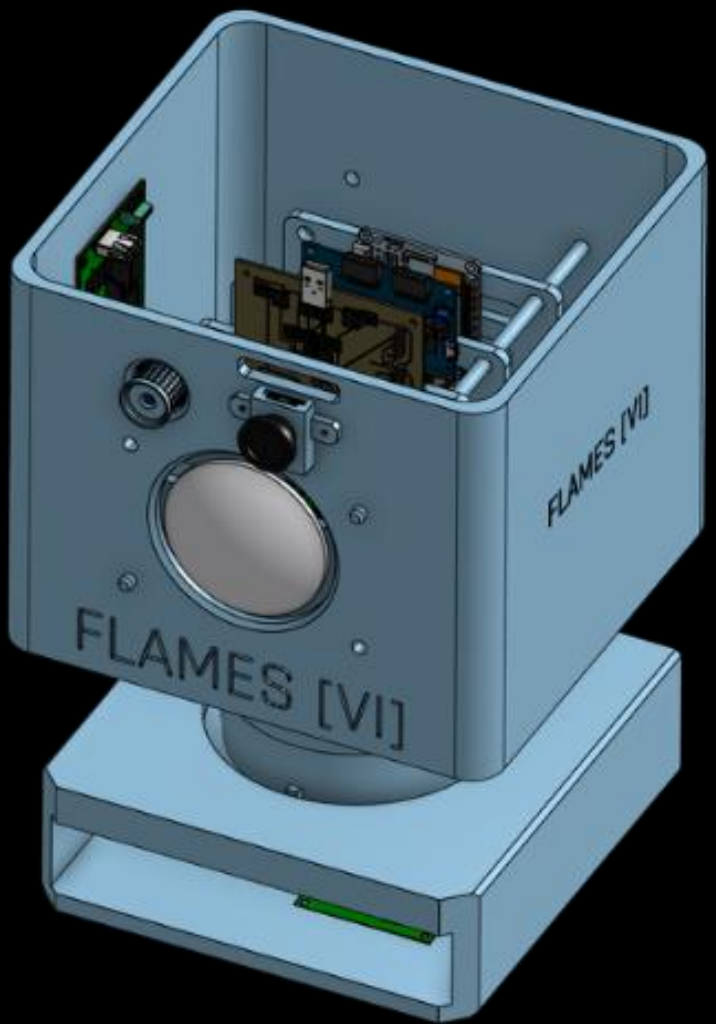
- ESP32 GPIO control for motor position, speed, direction
- Broadband Si photodiode + TIA + ADC for stochastic emission detection
- Parallel FPGA processing for real-time intensity analysis and alerts
- High-speed SPI between ESP32, Raspberry Pi 5, and Artix-7 for fast data/control

Stretch Objectives:

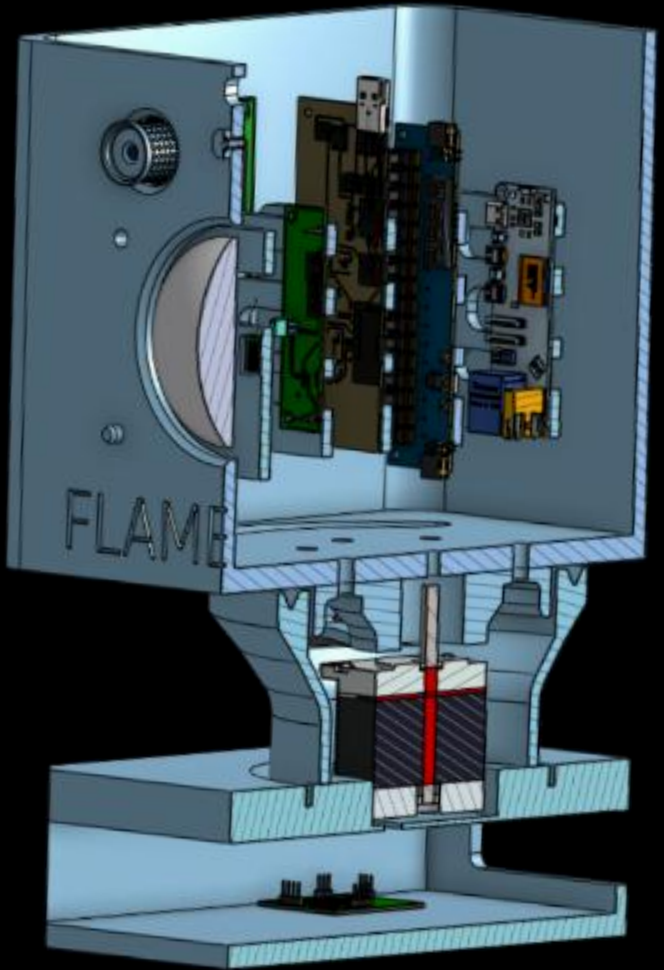
- Log FPGA-triggered events with timestamps to external database
- ML-based fire classification using FFT pattern recognition and adaptive learning
- Rotating filter wheel to modulate photocurrent, enabling fire type characterization via wavelength filtering (e.g., electrical vs. chemical)

Product Conceptualization

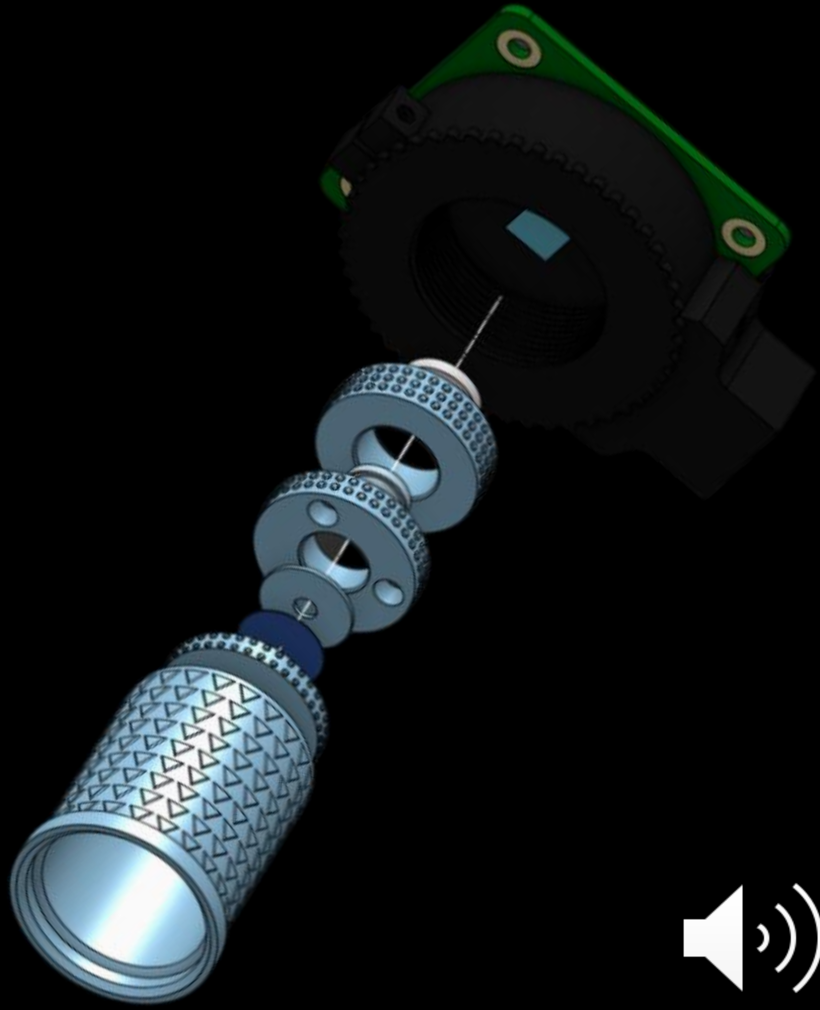
Full Assembly



Cross Section W, PCB Housing



Custom Imaging System



Final Product Design

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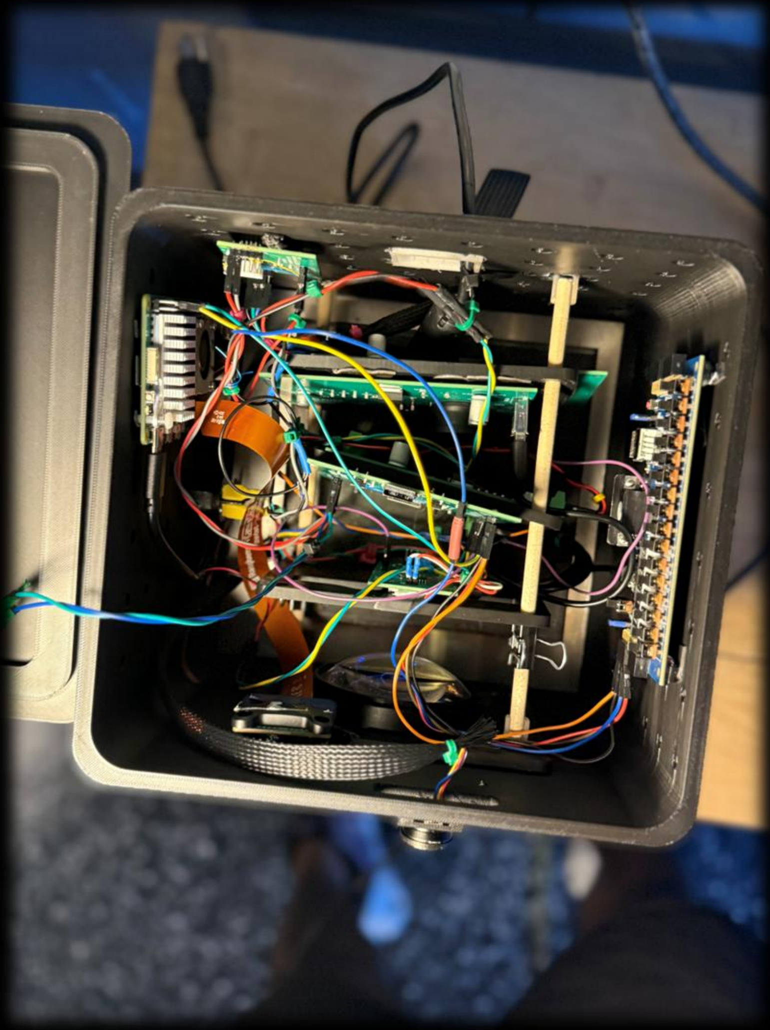

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Table of Engineering Specifications

Composite System	
Motor Stop and Hold Precision	+/- 10 degrees of optical source center
Scanning Area Coverage	180 Degrees
Response Time from Identification of Source to Alert Finish	At Most 15 sec
Detection Accuracy	At Least 90%
Max Power Consumption	At Most 44 W
Weight	4.5 kg – 6.8 kg
Size	Less than 0.186 m^2

Table of Engineering Specifications

Optical Lens Systems System	
Custom Imaging System (Camera Design) FOV	At Least 66 Degree Horizontal
Photodiode Lens System Spot Size	0.5 mm – 10 mm (Function of Optical Source distance)
Dual Photodiode (Lux Sensor) Spot Size	0.5 mm – 2 mm (Function of Optical Source distance)
Lens / Photodiode System Track length	Less than 0.2 m
Imaging Area (Camera System)	1/2.9 Optical Format – 6.33 mm Diagonal
Optoelectronics Focusing → Detection Working Distance	0 – 1 Meter Radially

Table of Engineering Specifications

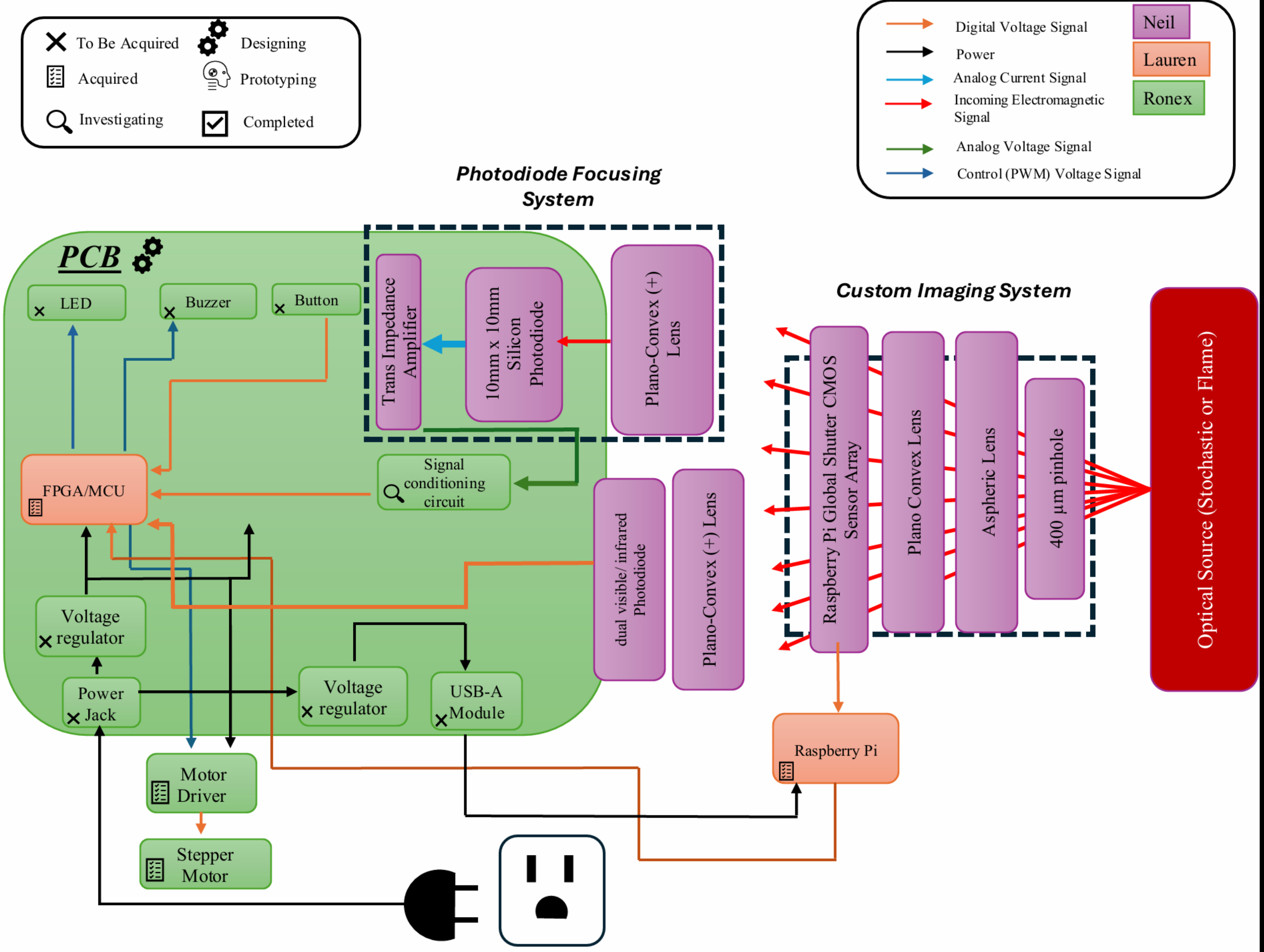
2nd order Butterworth Response:

$$\frac{1}{2\pi R_F(C_F + C_{STRAY})} = \sqrt{\frac{GBW}{4\pi R_F C_{TOT}}} \qquad (1)$$

Bandwidth:

$$f_{-3dB} = \sqrt{\frac{GBW}{2\pi R_F C_{TOT}}}\,\text{Hz} \qquad (2)$$

Optoelectronic System	
Transimpedance Amplifier Bandwidth	1.56 MHz
Transimpedance Amplifier Gain	15 kOhm
Op-Amp Gain-Bandwidth Product	90 MHz
Feedback Capacitance	0.1621 pF
Total Input Capacitance	379.1 pF
TIA Output Voltage Range	0 – 3.3 V



Hardware Block Diagram

Hardware Selection: Motor

- Offers precise speed control
- Cheaper alternative for larger motor selections that offer higher torque
- Disadvantages include high power consumption and heat dissipation even at idle positioning

Feature	Stepper	Servo Motor	DC motors
Speed Adjustability	Typically, 1000-1500RPM, can reach up to 3000RPM	3000-5000+RPM	1000-5000RPM but can reach higher speeds
Torque Range	Small: 0.05-0.2 Nm Medium: 0.2-0.5 Nm Large: 0.9-3 Nm	Small: 0.1-0.4 Nm Mid-range: 0.5-2 Nm High Torque: 3-50+	Small brushed: 0.01-0.05 Nm Medium: 0.2-1 Nm High-power: 2-10+ Nm Brushless: 0.3-5+ Nm
Energy Efficiency	High Power Consumption	Low Power Consumption	Moderate Power Consumption
Heat Generation	Higher	Lower	Higher
Cost	Small: \$10-\$20 Medium: \$15-\$30 Large: \$25-\$60	Small: \$5-\$20, Mid-range: \$20-\$100 High Torque: \$100+	Small brushed: \$2-\$10 Medium: \$15-\$40 High-power: \$50-\$200+ Brushless: \$30-\$150

Hardware Selection: Motor

- Offers wide torque range 0.44-40 Nm
- Lower power consumption than other Nema selections while maintaining strong performance
- Cost-effective solution for lighter load applications

Feature	Nema 17	Nema 23	Nema 24	Nema 34
Frame Size	42 x 42 mm	57 x 57 mm	60 x 60 mm	86 x 86 mm
Holding Torque	0.14-29.3 Nm	0.44-40 Nm	0.44-40 Nm	2-157 Nm
Step angle (degrees)	0.9/1.8	0.9/1.8	0.9/1.8	1.8
Revolution (steps)	400/200	400/200	400/200	200
Weight (kg)	0.37-0.44	0.8-1.75	0.84-1.83	3.05-4.5
Power Efficiency	High	Moderate	Low	Low
Typical Cost Range	$15-$30	$25-$60	$40-$80	$80-$200+

Hardware Selection: Motor Model

- Adequate holding torque
- Manageable Current Draw
- Lighter Nema 23 model which offers a balance between ease of integration for mechanical structure and performance
- Low cost

Feature	Nema 23HS21-0446S	Nema 23HS22-1006S	Nema 23H218D30U
Step Angle (degrees)	1.8	1.8	1.8
Holding Torque	0.6 Nm	0.9 Nm	1.66 Nm
Rated Current/phase	0.44 A	1 A	3 A
Voltage	11.88 V	7.4 V	2.82 V
Weight	0.69	0.7 kg	1.08 kg
Cost	$15.65	$10.59	$54.95

Hardware Selection: Motor Driver

- Offers up to 2.2A per phase (under heavy loads)
- A wide range of operating voltages
- Up to 32 microsteps
- Easy integration with MCU through Step/Dir
- Lower resolution
- Lower cost

Feature	EASON TB6600	Pololu Tic T500	Pololu DRV8825	Leadshine DM542	GeckoDrive G203V
Max Current	4 A	2.5 A	2.2 A	4.2 A	7 A
Voltage Range	9V - 42V	4.5V - 35V	8.2V - 45V	18V – 50V	18V-80V
Power Efficiency	Moderate	High	High	Very High	Very High
Micro steps	1/32	1/8	1/32	1/16	1/10
Control Interface	Step/Dir	Step/Dir, USB, TTL Serial, I2C	Step/Dir	Step/Dir	Step/Dir
Resolution with Nema23	0.05625°	0.225°	0.05625°	0.1125°	0.18°
Cost	$10.89	$29.85	$12.95	$46.23	$155

Hardware Selection: LED

- Delivers 600 mcd (millicandela) at 20 mA
- High brightness ensures visibility especially within a dark room
- Low cost

LED Model	Forward Voltage (V)	Current Drawn (mA)	Brightness (mcd) at 20mA	Cost
Wurth Elektronik 151051RS11000	2.1	20	30	$0.15
Kingbright L-934SRD	1.8	20	600	$0.34
Osram LS L296	1.8	20	28-112	$0.30
Everlight 204-10SURD	2.0	20	80	$0.33

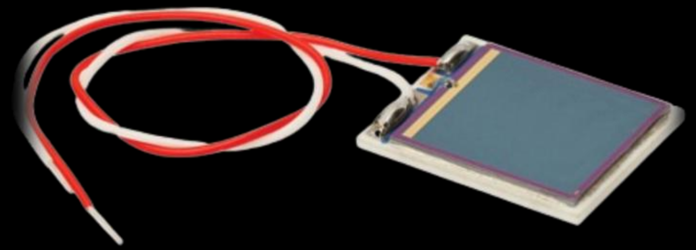
Hardware Selection: Buzzer

- Wide Operating Voltage range
- High sound output ensuring alerts are noticed by the user
- Active Buzzer
- 2.8 kHz resonating frequency

Features	Murata PKM13EPYH4000-A0	TDK PS1240P02CT	CUI Audio CPT-1495C	Mallory Sonalert PS-12	Kingstate KPEG158
Sound Output	78dB	70dB	84dB	85-100dB	70-85dB
Operating Voltage	Max 15V	Max 30V	Max 30V	5-15V	1-20V
Resonating Frequency	4kHz	2kHz	4.25kHz	2.8kHz	4kHz
Type	Passive	Passive	Passive	Active	Passive
Cost	$0.25	$0.6	$3.97	$3.44	$3.04

Hardware Selection: OE Device Semiconductor Substrate

- Covers visible and near-IR range (350–1100 nm)
- **Si suited for detecting visible/NIR emissions**
- InGaAs $\mathcal{R}$ < 800 nm = negligible suited for $\lambda = 800$ nm -1500 nm
- **Si commercially available** with large active areas



Specification	Silicon	InGaAs
Wavelengths Covered	350 nm -1100 nm	900 nm – 1700 nm
Responsivity @ Peak Wavelength	0.6 A/W	0.9 A/W
Peak Wavelength	850 nm 950 nm	1550nm
Large Active Area Available	Yes, larger than $1mm^2$	No, Common size is $1mm^2$
Spectrum	Visible – NIR limited	IR
Common Application Use	Optical sensing, visible light detection	Fiber optic communication

Hardware Selection: Si Photodiode

- FDS1010 active Area 100 mm^2
- FDS1010 – $65.46
- FDS10X10 – $134.73
- Prioritize The Following
  - Faster Diode Rise Time
  - Large Active Area
  - Low Diode Capacitance

Specification	FDS10X10	FDS1010
Circuit Bandwidth	4188.28 KHz	4244.12KHz
Rise Time	83.57 ns	82.7 ns
Output Photocurrent (Simulated)	4.2 mA	4.8 mA
Signal to Noise Ratio (SNR dB) (Simulated)	101.61 dB	104.72 dB
Active Area	100 mm^2	100 mm^2
Responsivity @ 700 nm	0.42 A/W	0.48 A/W

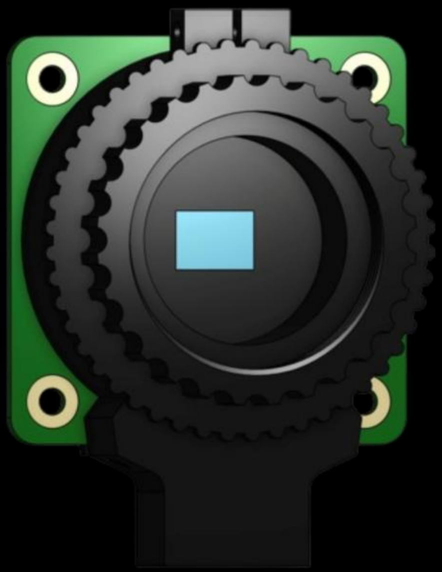
Hardware Selection: Optical Trigger

- Detects light from **0.000118 to 88,000 lux**
- **Outputs Lux Values I^2c**
- Separates **visible and infrared components**, enabling more accurate light profiling
- **Automatic Gain & Integration Control**
- Used to **detect sharp changes in light intensity** → triggers motor to stop

Specification: TSL2591	Value
Dynamic Range	600M:1
Spectral Responsivity Wavelength Range	300nm – 1100 nm
Peak Wavelength sensitivity	850nm
Max Irradiance Responsivity channel 0 (Visible and Infrared)	$264.1 \frac{Counts}{\frac{\mu W}{cm^2}}$
Max Irradiance Responsivity channel 1 (Infrared only)	$34.9 \frac{Counts}{\frac{\mu W}{cm^2}}$

Hardware Selection: Camera Sensor

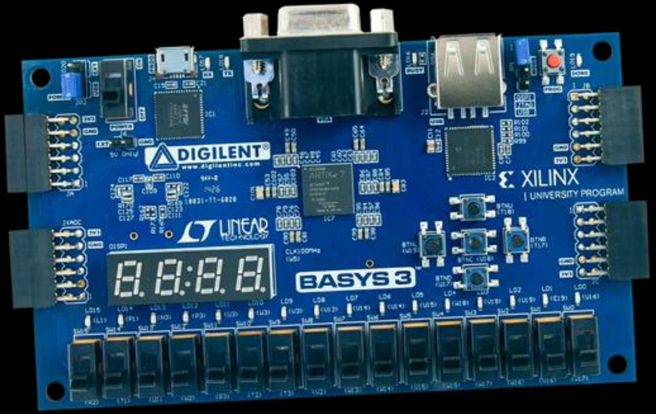
- Global shutter reads all pixels **simultaneously**
- Rolling shutter reads line-by-line
- Global shutter: **3.45 µm pixels** captures more light → improved low-light performance
- Larger Pixel Size better depth of field control



Specification	Raspberry Pi AI	Raspberry Pi Global Shutter
Sensor Type	Rolling Shutter	Global Shutter
Resolution	4056 x 3040 pixels	1456 x 1088 pixels
Imaging Area	7.857 mm (Diagonal) 6.8287 mm (Horizontal) 4.712mm (Vertical)	6.3 mm (Diagonal)
Low light sensitivity	No, Smaller Pixels $1.55\mu m^2$	Yes, larger Pixels $15.5\mu m^2$
Vertical FOV @ 4.74 mm	66 +/- 3 degrees	Lens dependent
Horz. FOV @ 4.74 mm	52.3 +/- 3 degrees	Lens dependent
Exposure time	112	15.5
Price	$70	$50
AI Compatibility	Yes	No
Still Resolution	12.3 Megapixels	1.58 Megapixe
Sensor	Sony IMX500 (AI)	Sony IMX296

Hardware Selection: FPGA Dev. Board

- BASYS 3 Board
- Prioritized for FLAMES due to:
  - Familiarity with FPGA
  - Ease of use
  - Well-documented



Feature	BASYS 3	DE10-Lite	NEXYS A7	PYNQ-Z2
FPGA Chip	Xilinx Artix-7 (XC7A35T)	Intel MAX 10 (10M50DAF484C6GES)	Xilinx Artix-7 (XC7A100T)	Xilinx Zynq-7000 (Z-7020, ARM + FPGA)
Logic Resources	33,280 LUTs, 1800 Kb Block RAM	50K LEs, 1.6 Mb RAM	101,440 LUTs, 4.8 Mb Block RAM	53,200 LUTs, 630 Kb Block RAM
I/O Availability	16 switches, 5 buttons, 16 LEDs, 7-seg	10 switches, 10 LEDs	Similar to Basys but more Pmod and audio I/O	HDMI, audio, Pmod, LEDs
Ease of Use	Beginner-friendly, well-documented	Moderate – some Quartus learning curve	Moderate – more complex, but well-supported	Intermediate – PYNQ OS setup, Python-based
Development Tools	Vivado (free WebPACK license)	Intel Quartus Prime (free)	Vivado (same as Basys)	Vivado + PYNQ/Python + Jupyter
Connectivity	USB UART, Pmod x4	GPIO, ADC, Pmod	More Pmod, audio codec, Ethernet	HDMI, Ethernet, USB
Power & Size	USB powered, compact	USB powered, slightly larger	USB or external powered, larger board	Larger, multiple regulators, higher power draw
Cost	~$150	~$80–$100	~$200+	~$120–$150

Hardware Selection: Microcontroller

- ESP32 (Highly Versatile)
- Prioritized for FLAMES due to:
  - Ease of development
  - Abundant GPIO pins
  - Sufficient processing power

- Raspberry Pi 5
- Prioritized for FLAMES due to:
  - Camera compatibility
  - Greater processing power

Feature	ESP32	Raspberry Pi	Arduino	STM32
Processing Power	Dual-core 32-bit LX6 (240 MHz)	Broadcom ARM CPU (varies by model, typically 1 GHz+)	8-bit AVR (16 MHz)	ARM Cortex-M series (varies, up to 400 MHz+)
Wireless Connectivity	Wi-Fi & Bluetooth 4.2 (BLE)	Requires external module	Requires external module	Requires external module
GPIO Pins	34 GPIOs	26-40 GPIOs (varies by model)	14 digital I/O (Arduino Uno)	Varies by model, often 40+
Power Consumption	Moderate (higher than Arduino, lower than Pi)	High (1.4 - 3.7W)	Low (ideal for battery-powered applications)	Low to moderate
Ease of Development	Easy to use, supports Arduino IDE & MicroPython	Requires full OS, complex setup	Very beginner-friendly	More complex, requires HAL or direct register programming
Boot Time	Instant	Slow (requires full OS boot)	Instant	Instant
Cost	~$6-$8	~$35+	~$3-$6 (Uno)	~$3-$20+ (varies by series)

Power Distribution Table

Component	Power Consumption	Operating Voltage
Buzzer	25 mW	5V rated
Basys 3 Artix 7 FPGA Board	5W	5V
Microcontroller (ESP32)	231mW	3.3V
Raspberry pi 5	3-5W (idle), 7-10W (moderate load), 20-25W (heavy load)	5V
Motor Driver (DRV8825)	12.3-67.5W	8.2V - 45V

Hardware Selection: Voltage Regulator

- LM2679 ADJ offers a balance of flexibility fixed voltage outputs, higher rated current, and higher efficiency

Feature	LM2576	LMR51430	LM2596	LM2679
Max Output Current	3A	3A	3A	5A
Efficiency	75%-88%	82%-92%	73%-90%	82%-92%
Switching Frequency	42-63 kHz	500 - 1100kHz	110 kHz	260 kHz
Input Voltage Options	4V-40V	4V-36V	4.5V-40V	8V-40V
Output Voltage Options	Fixed: 3.3V, 5V, 12V Adjustable: 1.23V-37V	Adjustable between -1.5% and 2.5% of set output value	Fixed: 3.3V, 5V, 12V Adjustable: 1.23V-37V	Fixed: 3.3V, 5V, 12V Adjustable: 1.2V-37V
Cost	$1.75	$1.29	$3.58	$ 3.93

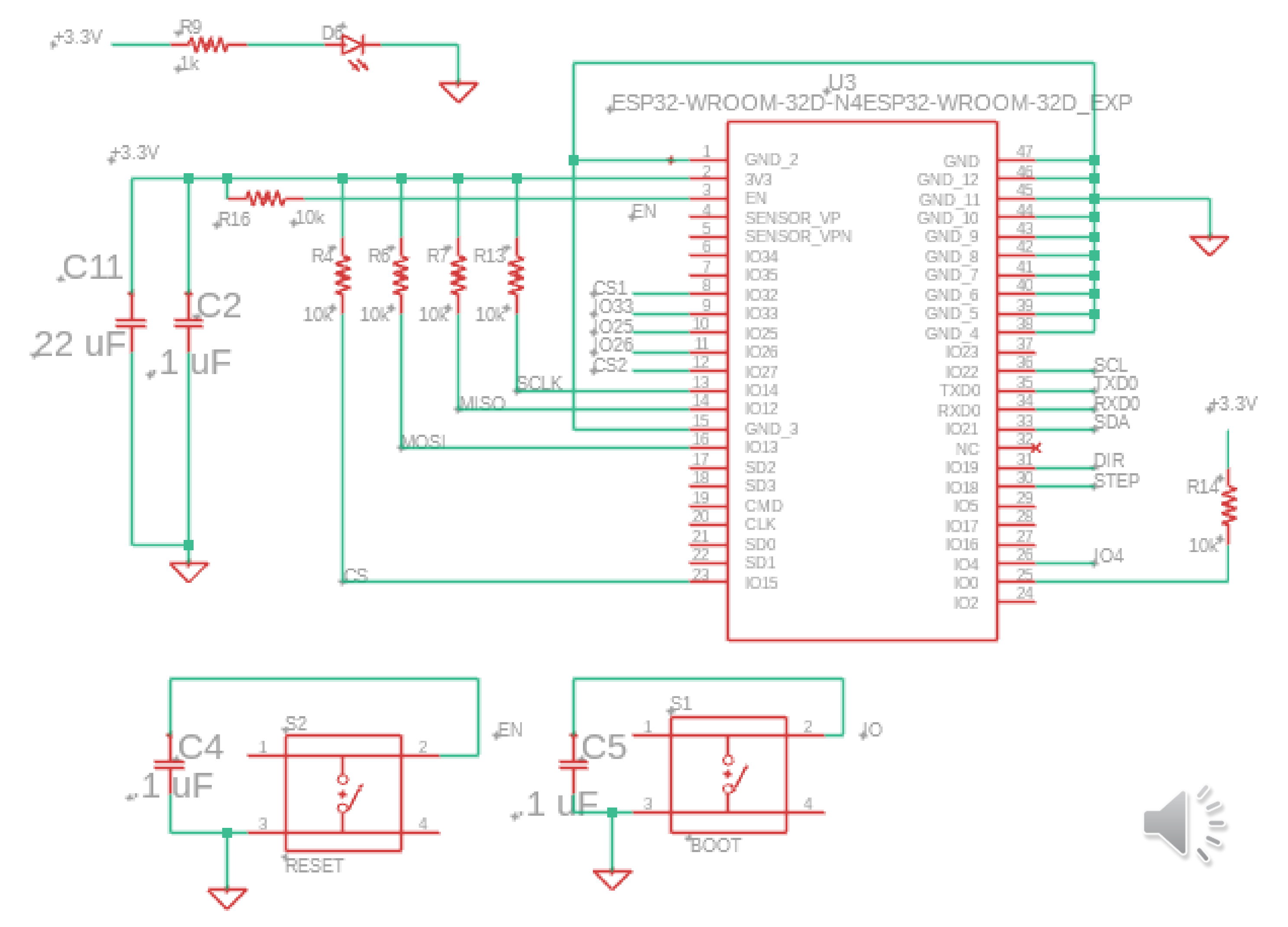
Hardware Selection: Power Supply

- Steps down 110V to 12V
- Supplies up to 10A
- Converts Analog Voltage to Digital
- Cheaper alternative

Model	Output Voltage	Output Current	Power Rating	Plug Size (mm)	Cost
LeTaoXing Power Supply Adapter	12V	8A	96W	5.5x2.5	$14.90
Mean Well GST90A12 -P1m	12V	6.67A	80W	5.5x2.1/ 5.5x2.5	$30.30
ALITOVE Power Supply	12V	10A	120W	5.5x2.5	$21.88
MTYTOT	12V	10A	120W	5.5x2.5	$29.89
LXLQZXW	12V	10A	120W	5.5x2.5/ 5.5x2.1	$17.99

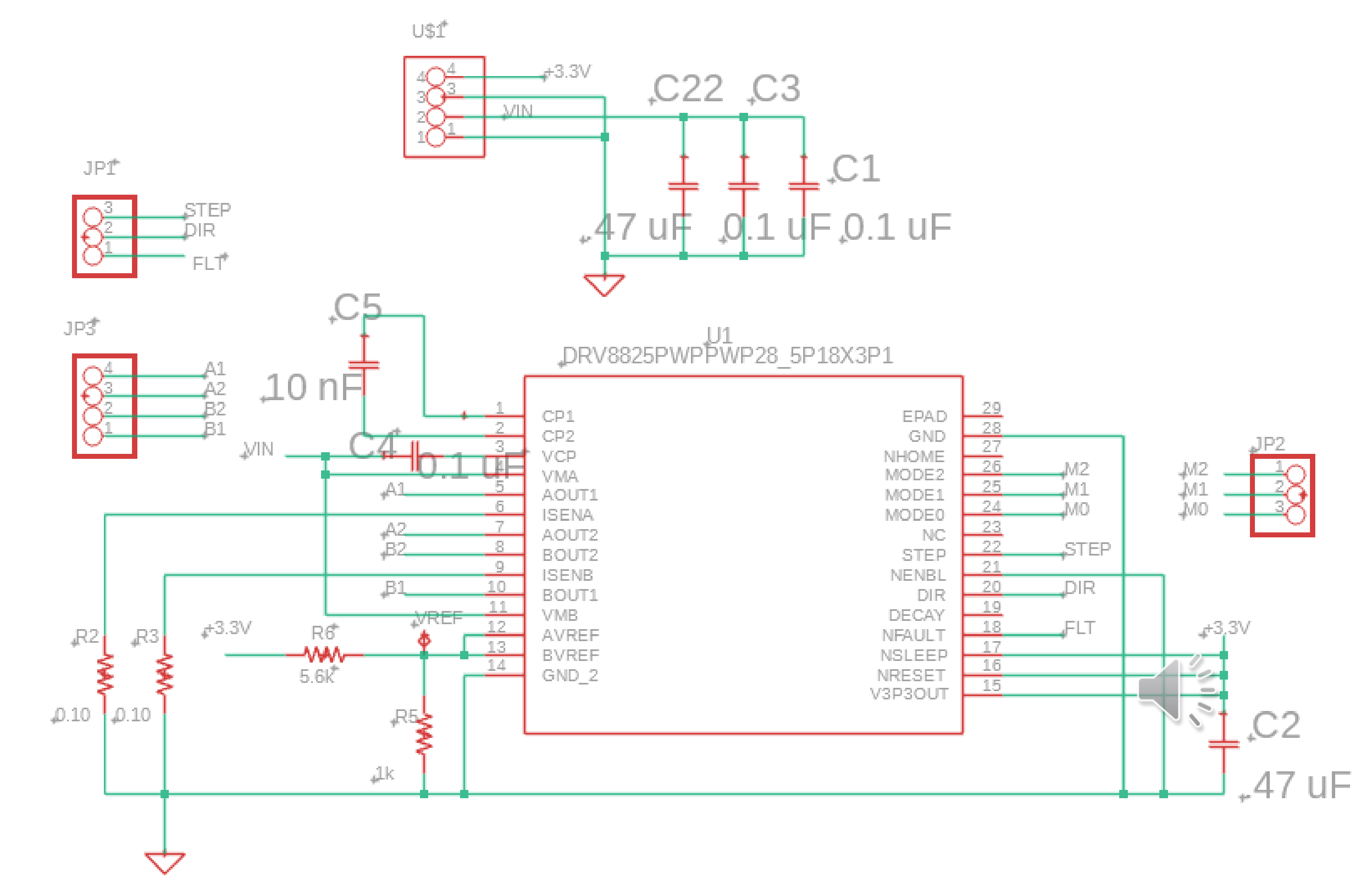
Hardware Schematic: ESP32-WROOM-32D

- Responsible for visible/audio alert once fire is detected
- Reads digital values via internal ADC
- Reads lux values via I2C from TSL 2591
- Controls motor driver via step/dir
- Communicates via SPI with FPGA amongst the confirmation of fire so that alert is indicated



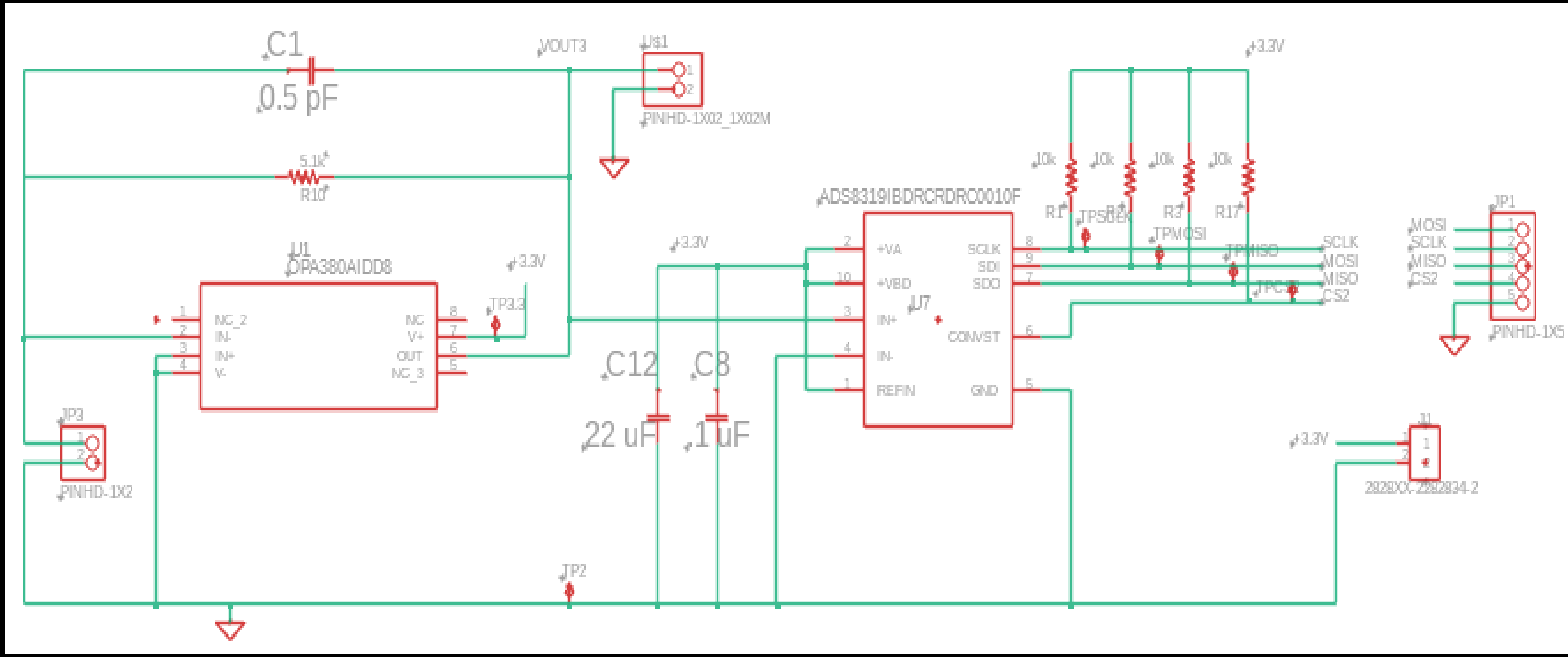
Hardware Schematic: Motor Driver

- Receives step and direction pulses from MCU
- Responsible for driving the motor and enables it to rotate through micro steps.



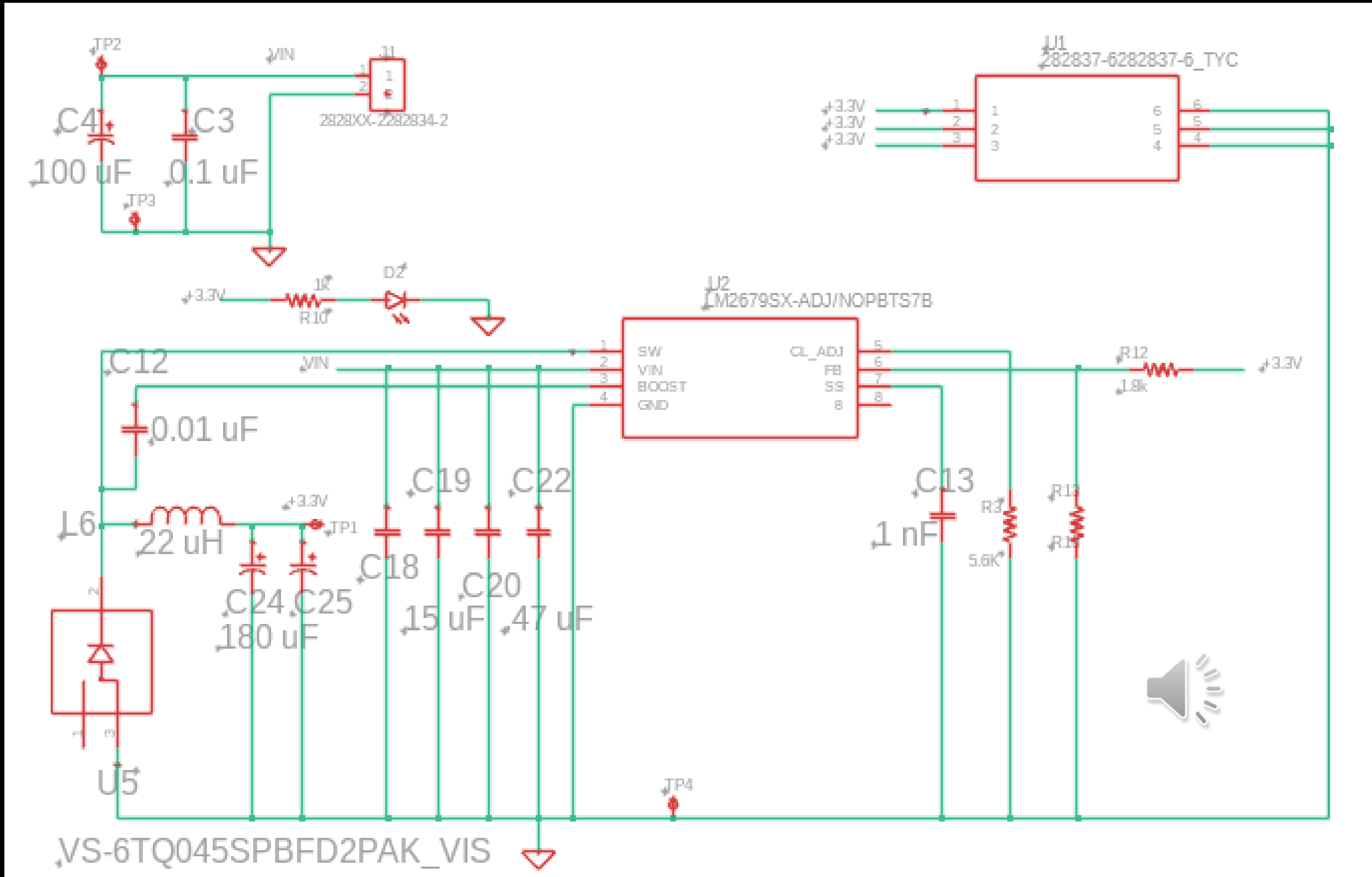
Hardware Diagram: Transimpedance Amplifier

- Converts photocurrent (µA) from FDS1010 Photodiode to voltage
- Voltage then converted to digital values through ADC for further processing by the MCU



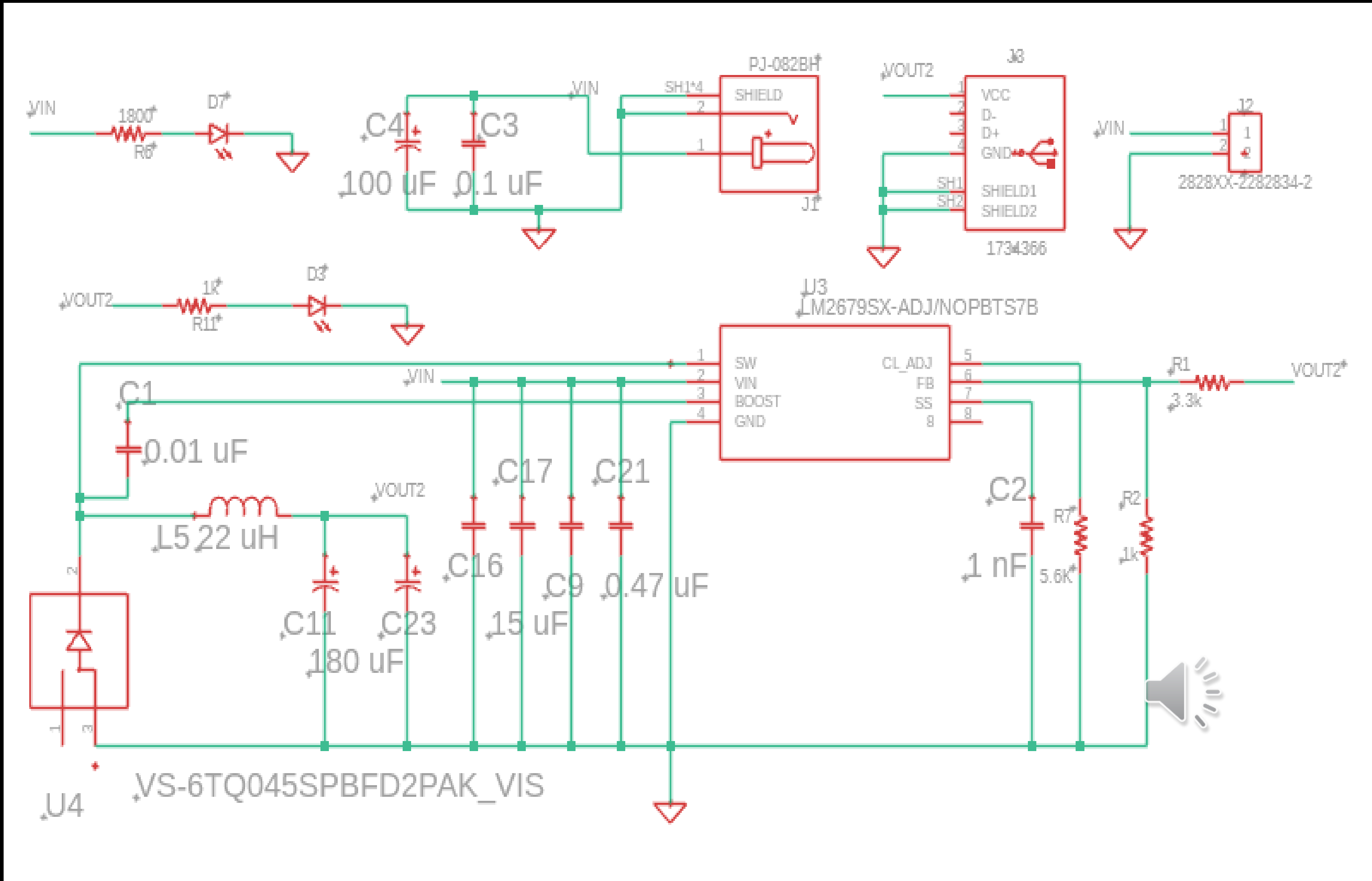
Hardware Diagram: 3.3V Regulator

- Responsible for powering MCU, ADC, OPA380, and operating RST and SLP pins of motor driver



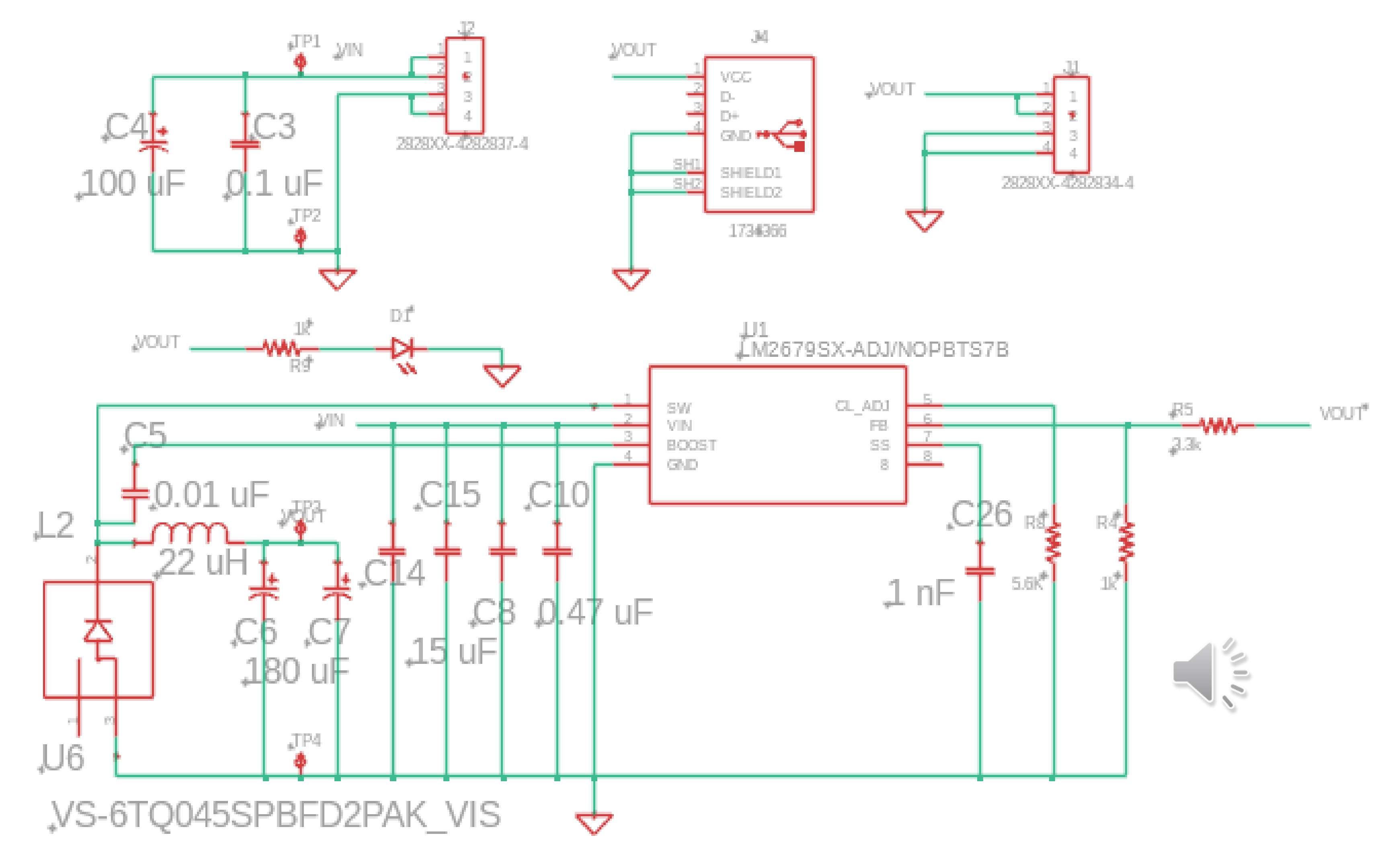
Hardware Diagram: 5V Rasp. pi 5 Regulator

- Will be utilized to establish a connection with 12V adapter from outlet
- Responsible of distributing power to all other regulator boards
- Supply power to Raspberry pi 5 Dev. Board



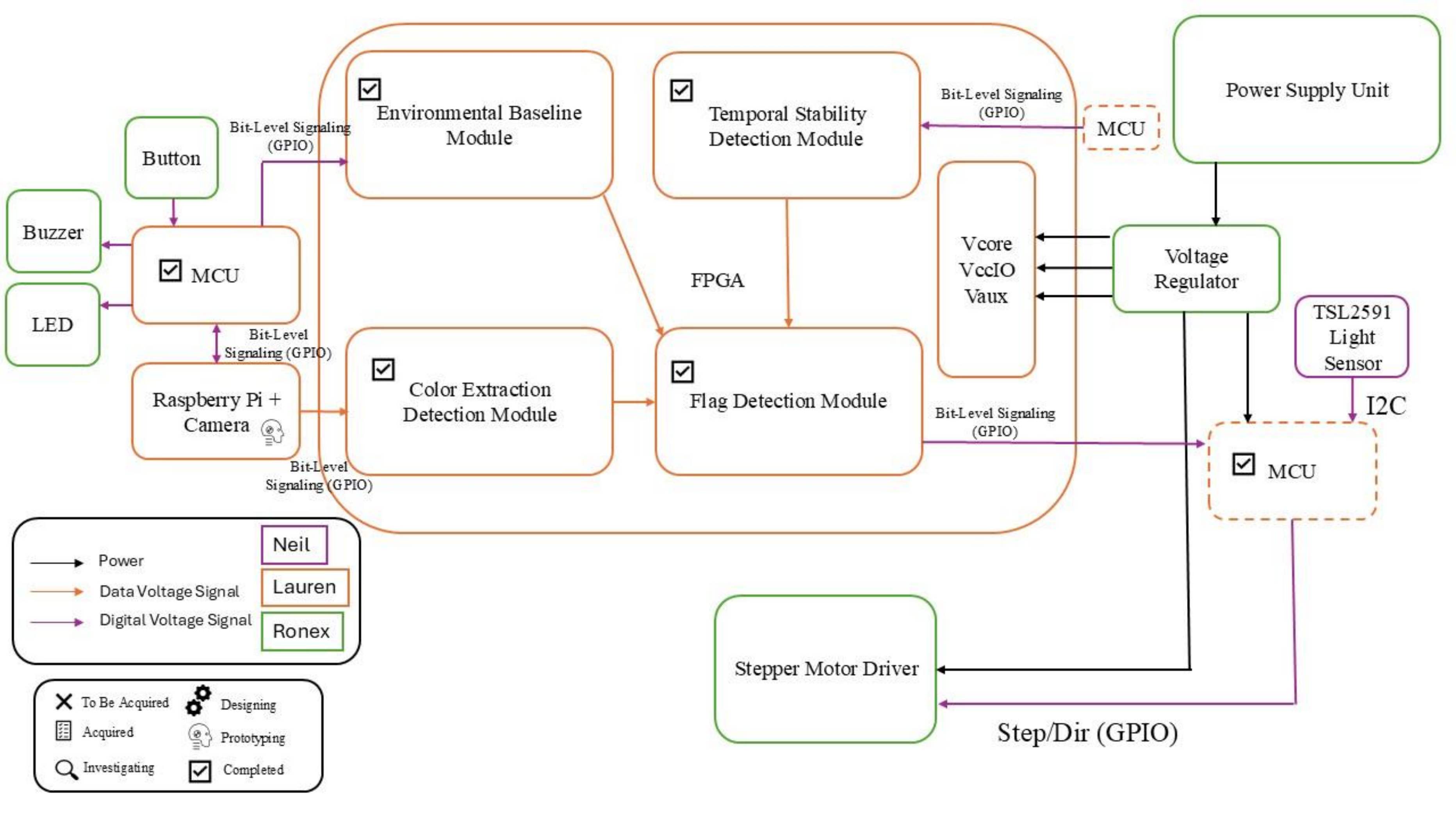
Hardware Diagram: 5V FPGA Regulator

- Responsible for power Basys 3 FPGA dev. Board
- Supply 5V to buzzer

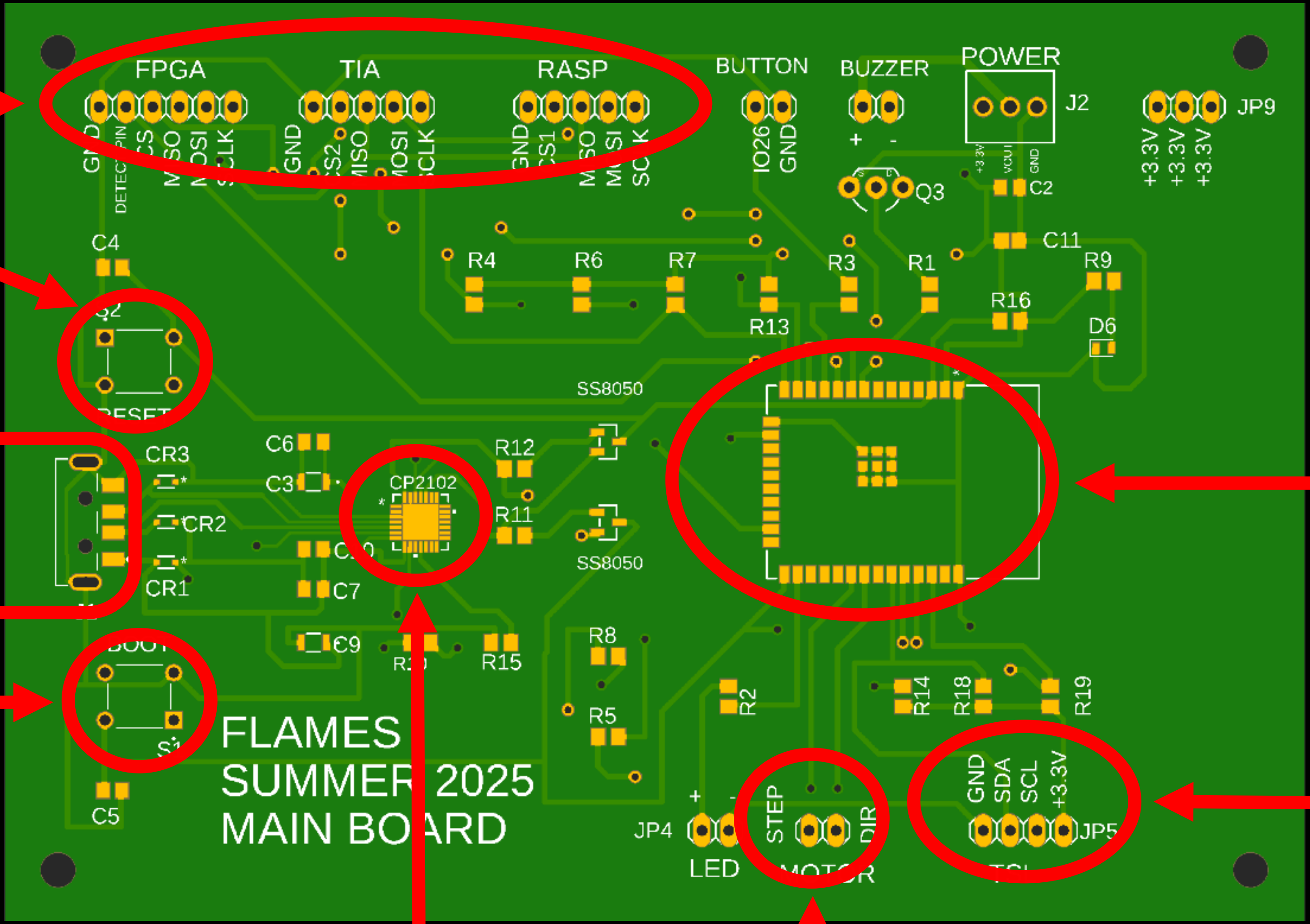


Hardware Diagram: BASYS 3 Dev. Board

- Each layer of analysis, as well as the final detection layer, is composed of four conceptual modules.
  - Combined all into one module.
- Connected to Raspberry Pi, MCU, and its voltage regulator.



Significant PCB Design: Main

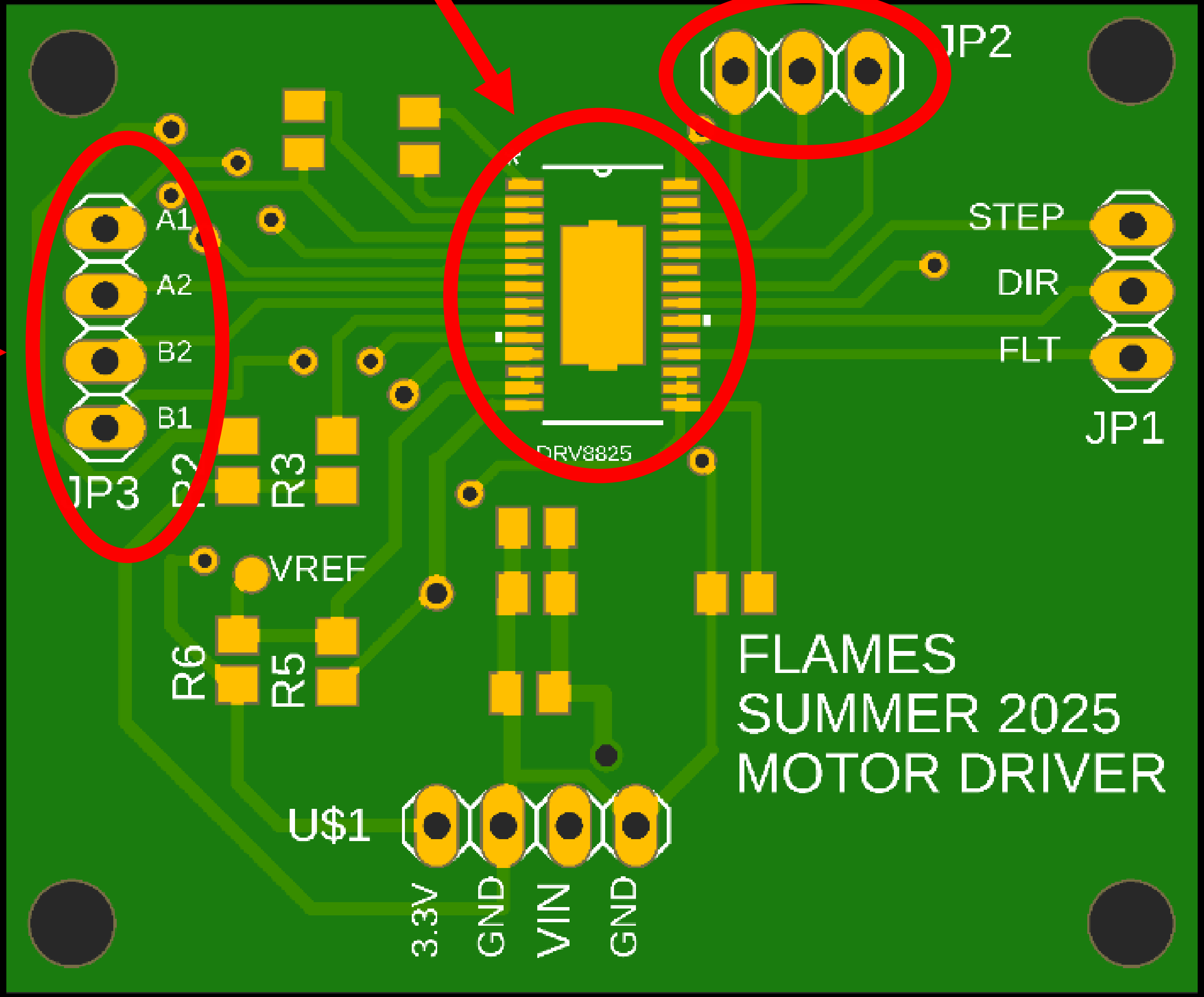


Significant PCB Design: Motor Driver

Micro-step Configuration

DRV8825 Motor Driver

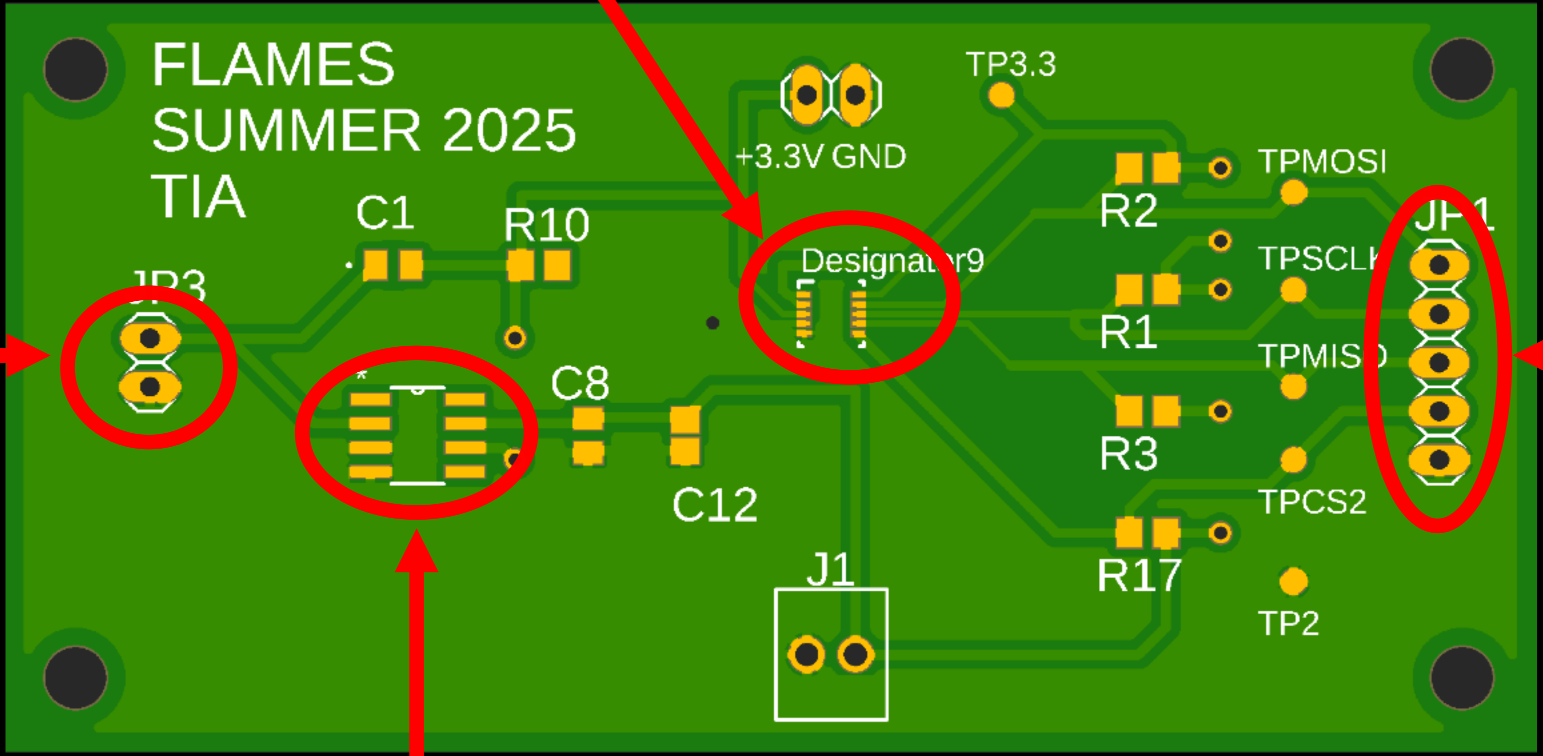
Nema 23 Connection



Significant PCB Design: TIA

ADS8319 ADC

FDS1010 Photodiode Header Pins

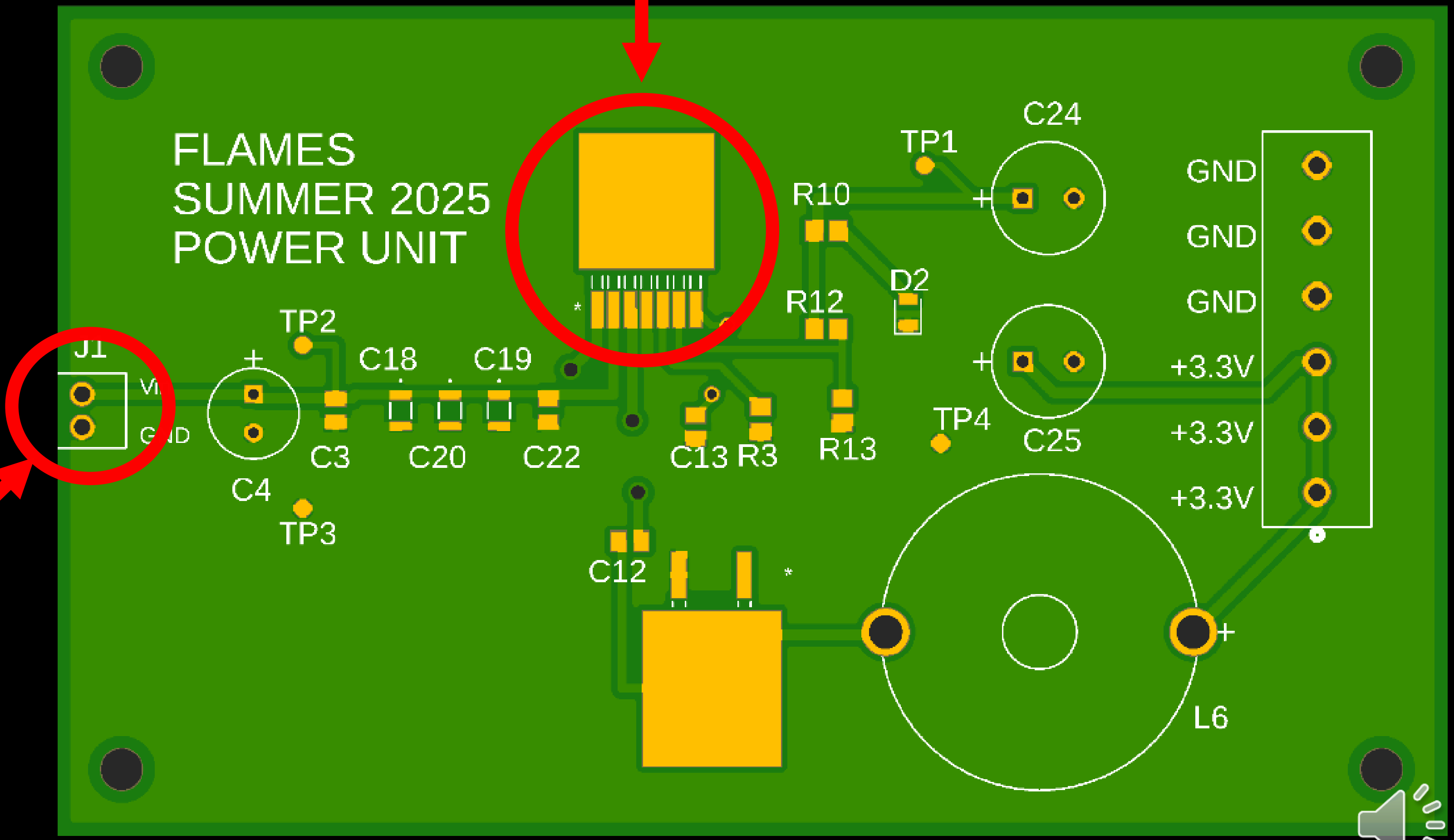


SPI

OPA 380 Operational Amplifier

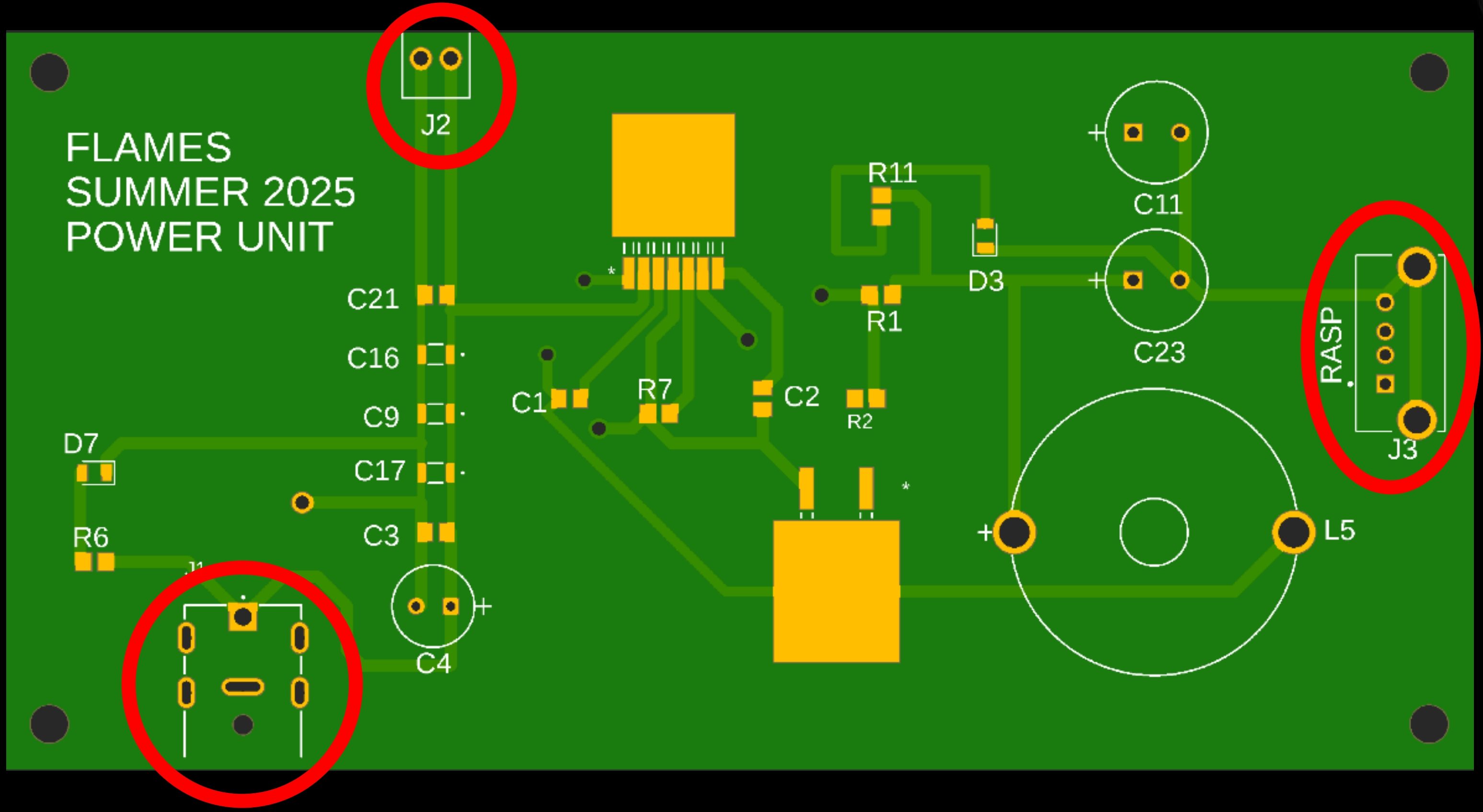
Significant PCB Design: 3.3V Regulator

LM2679 Voltage Regulator



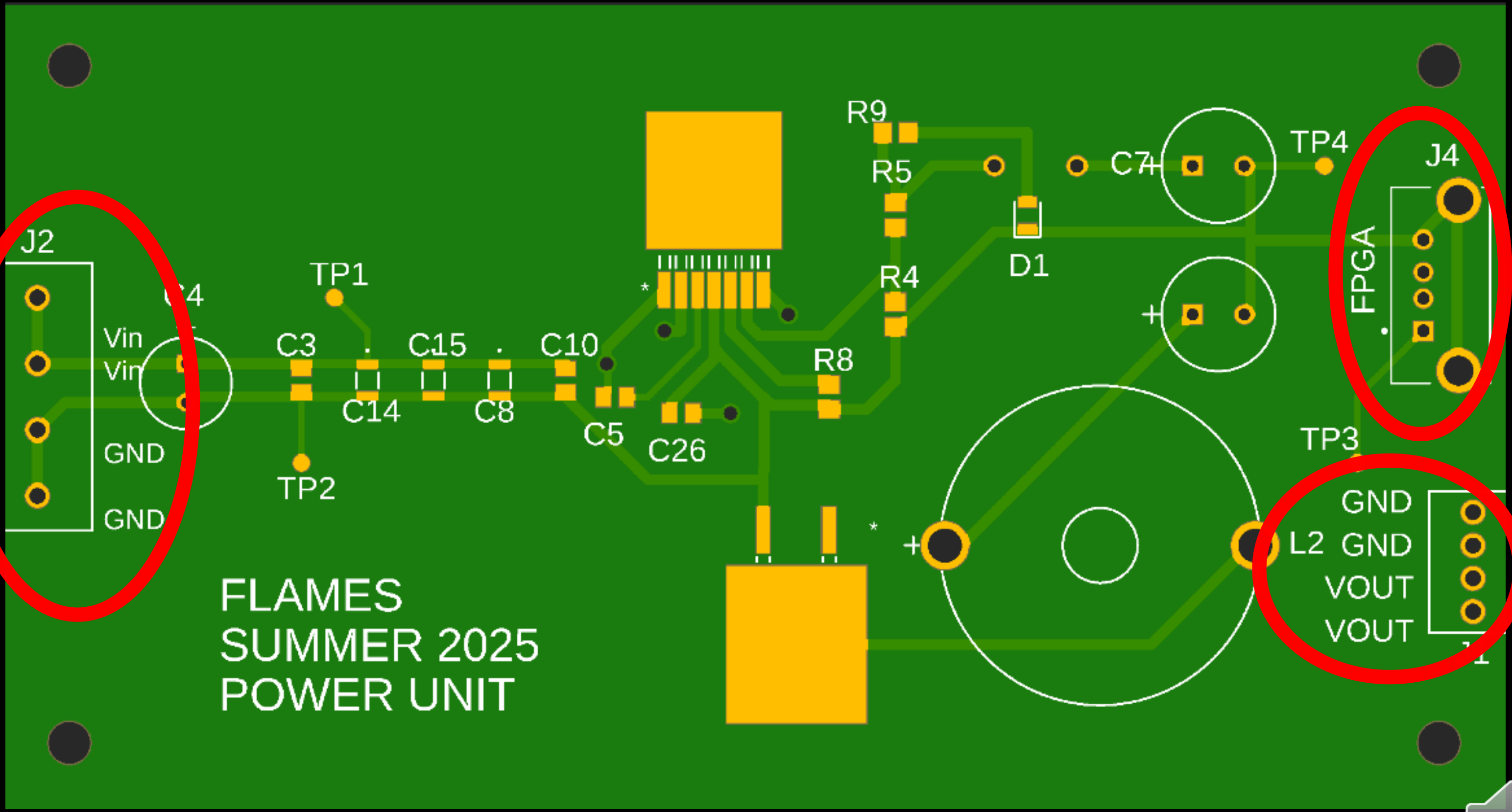
12V Input

Significant PCB Design: 5V Raspberry Pi 5 Regulator



Significant PCB Design: 5V Basys 3 Dev. Regulator

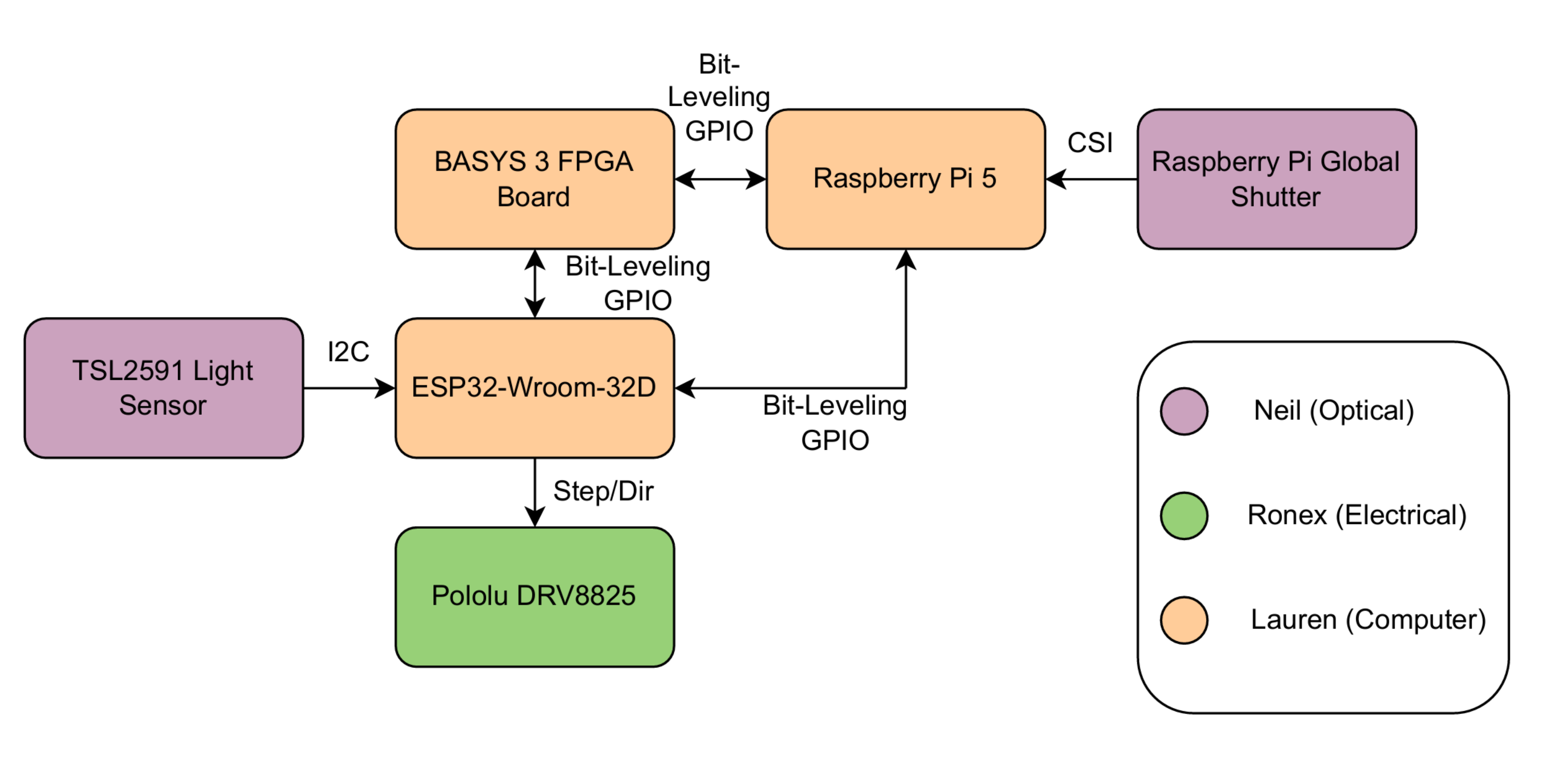
12V Output



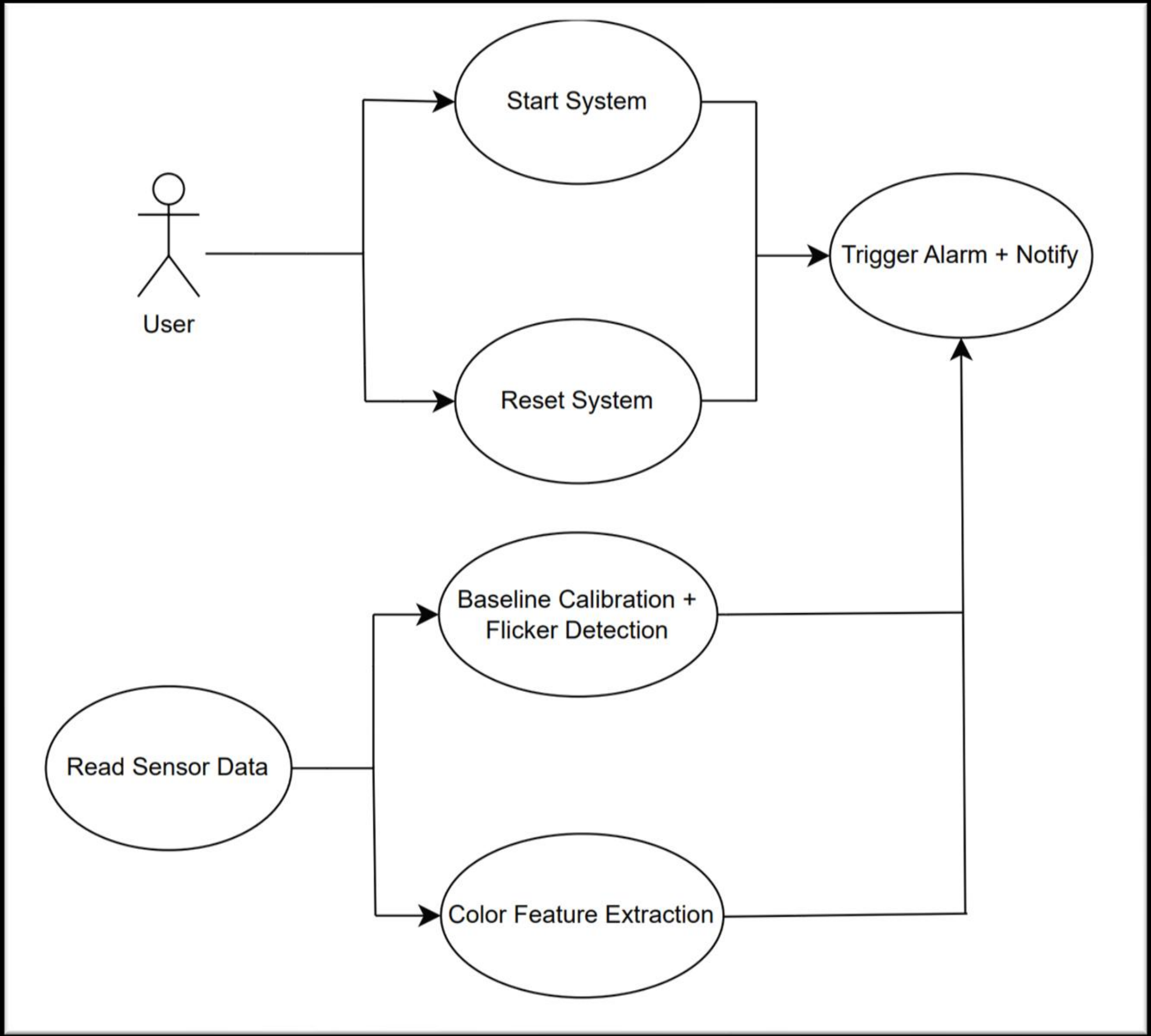
USBA 5V Output

5V Output

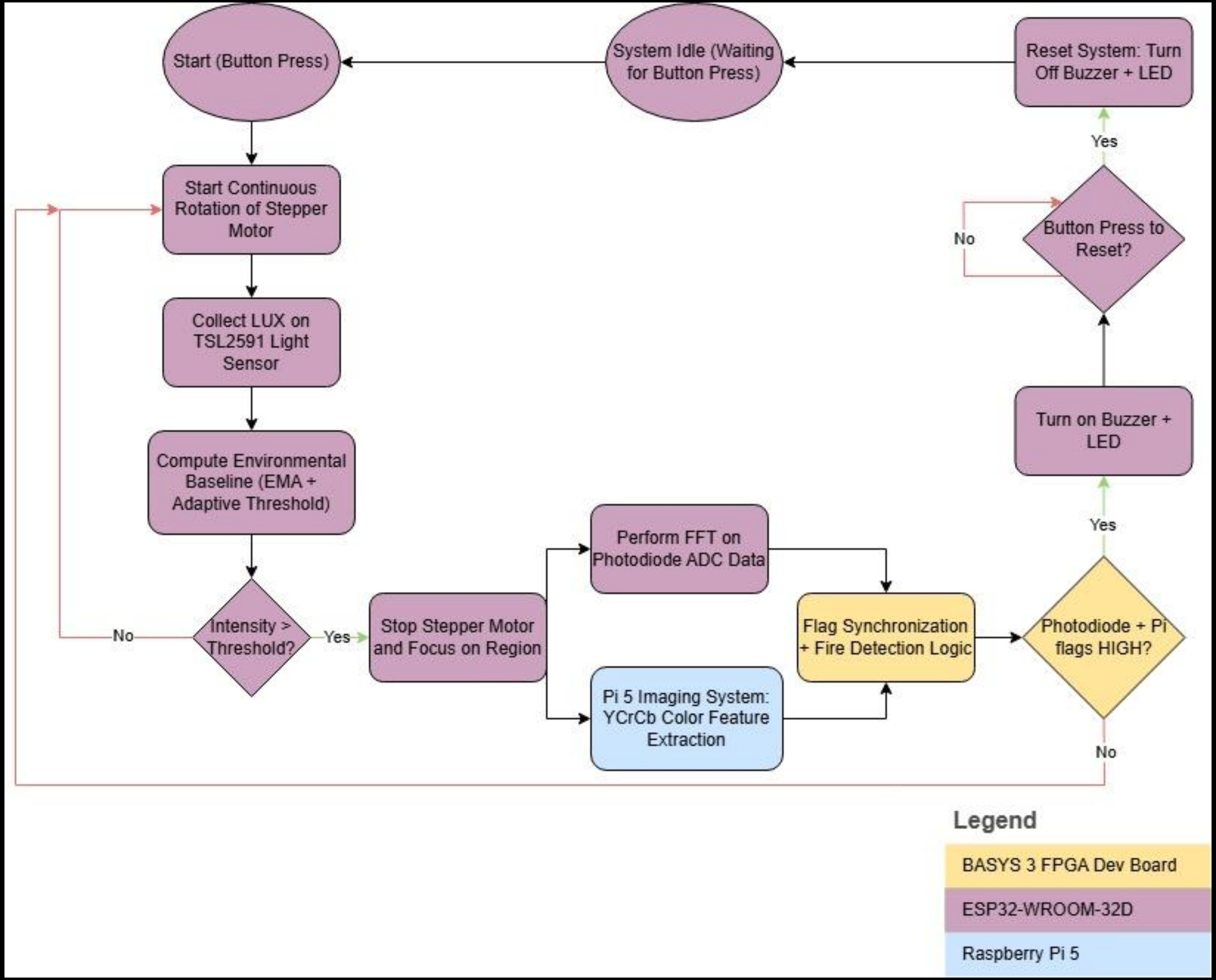
Hardware Communication



Software User Diagram



Software Full Activity Diagram



Software Selection: Env. Baseline & Initial Detection

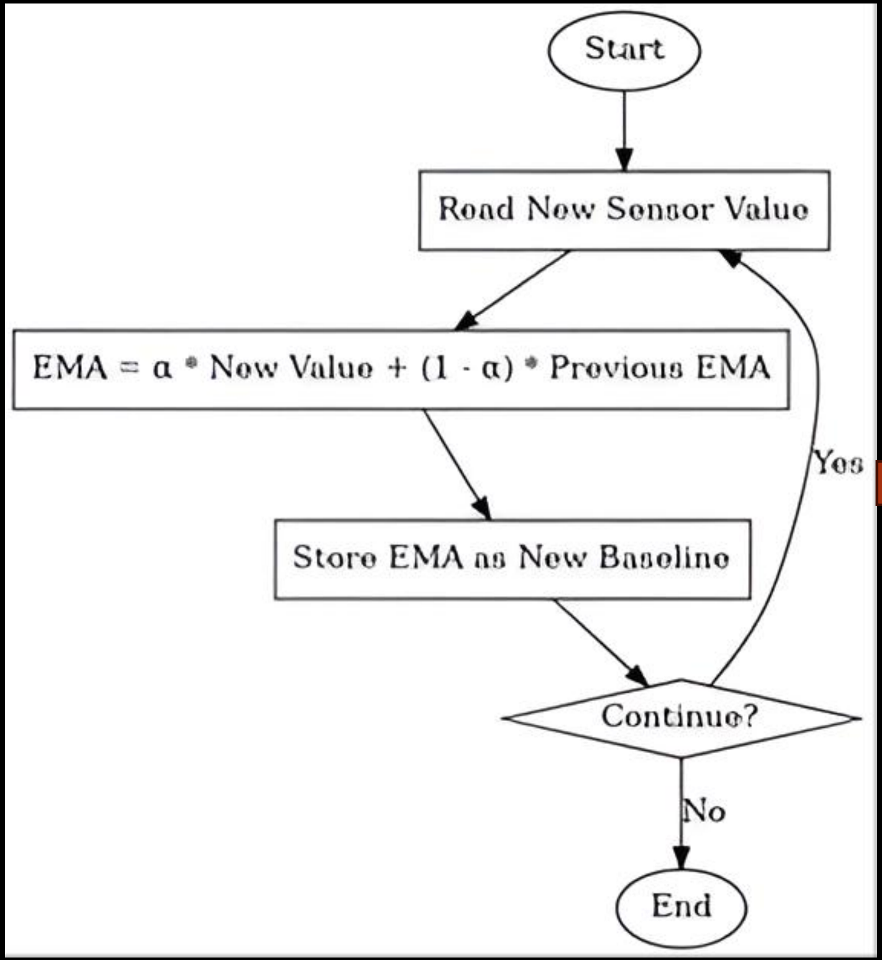
Filtering Technique	Latency	Accuracy	Short-Term Stability	Computational Complexity	Implementation Complexity
Moving Average Filter (MAF)	Very Low	Low to Moderate	High	Low	Very Simple
Exponential Moving Average (EMA)	Low	Moderate to High	Moderate	Low	Simple
Kalman Filter (KF)	Moderate	High	High	High	Complex (Tuning Required)
Wavelet Transform	High	Very High	High	Very High	Very Complex

Baseline Calibration Technique	Latency	Accuracy	Computational Complexity	Implementation Complexity
Adaptive Thresholding	Low	Moderate	Low	Simple
Polynomial Regression	Moderate	High	Moderate	Moderate
Principal Component Analysis (PCA)	High	Very High	High	Complex

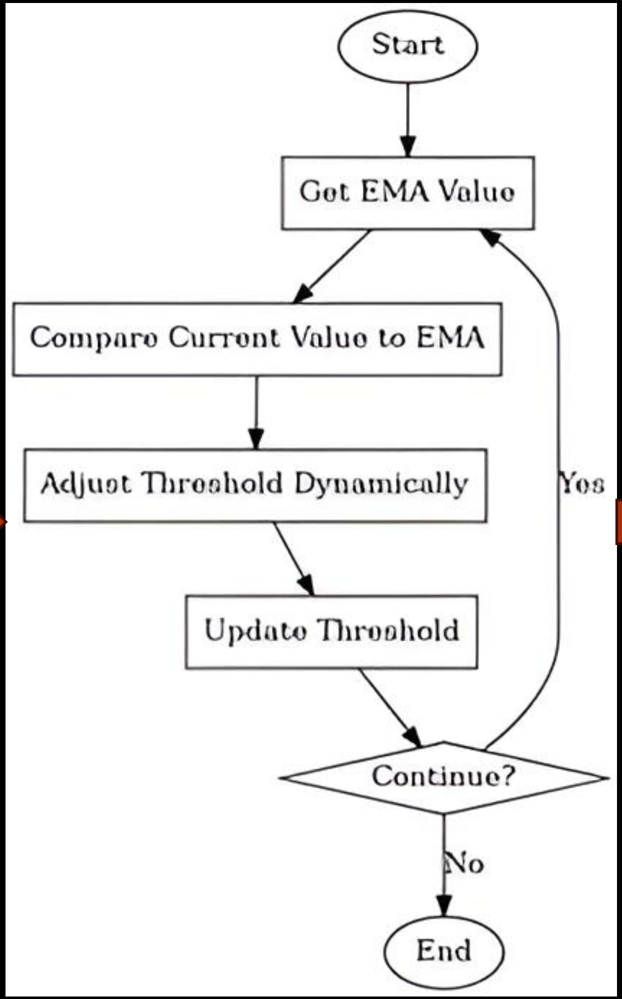
Anomaly Detection Technique	Latency	Accuracy	Computational Complexity	Implementation Complexity
Z-Score Anomaly Detection	Low	Moderate	Low	Simple
CUSUM Control Charts	Moderate	High	Moderate	Moderate
Hidden Markov Models (HMMs)	High	Very High	High	Complex

Software Flowcharts:

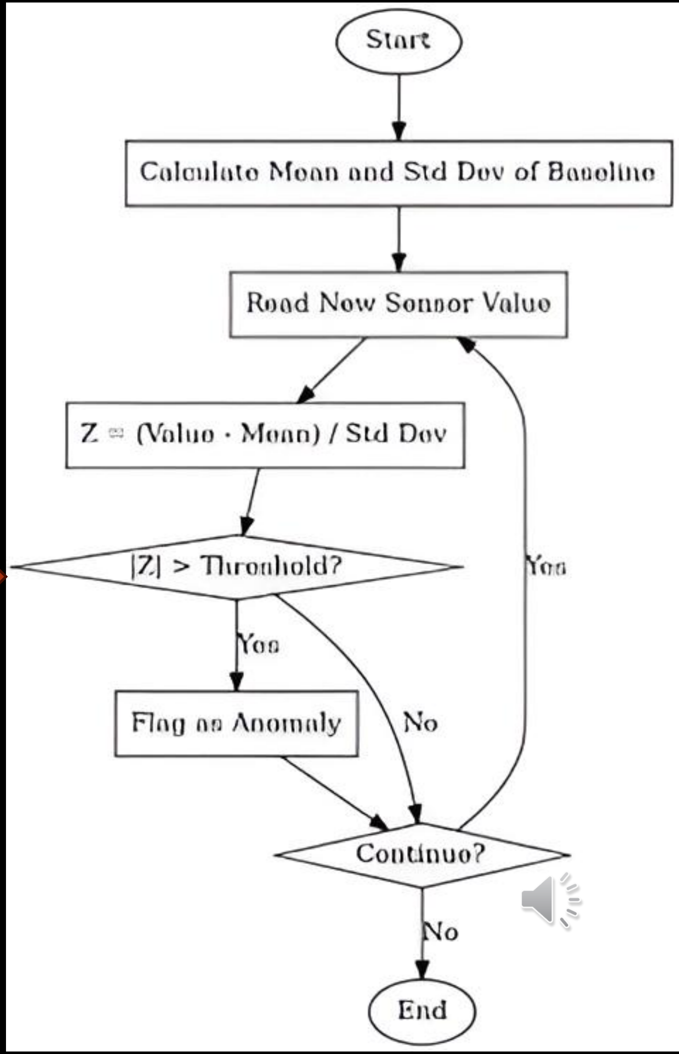
EMA



Adaptive Thresholding



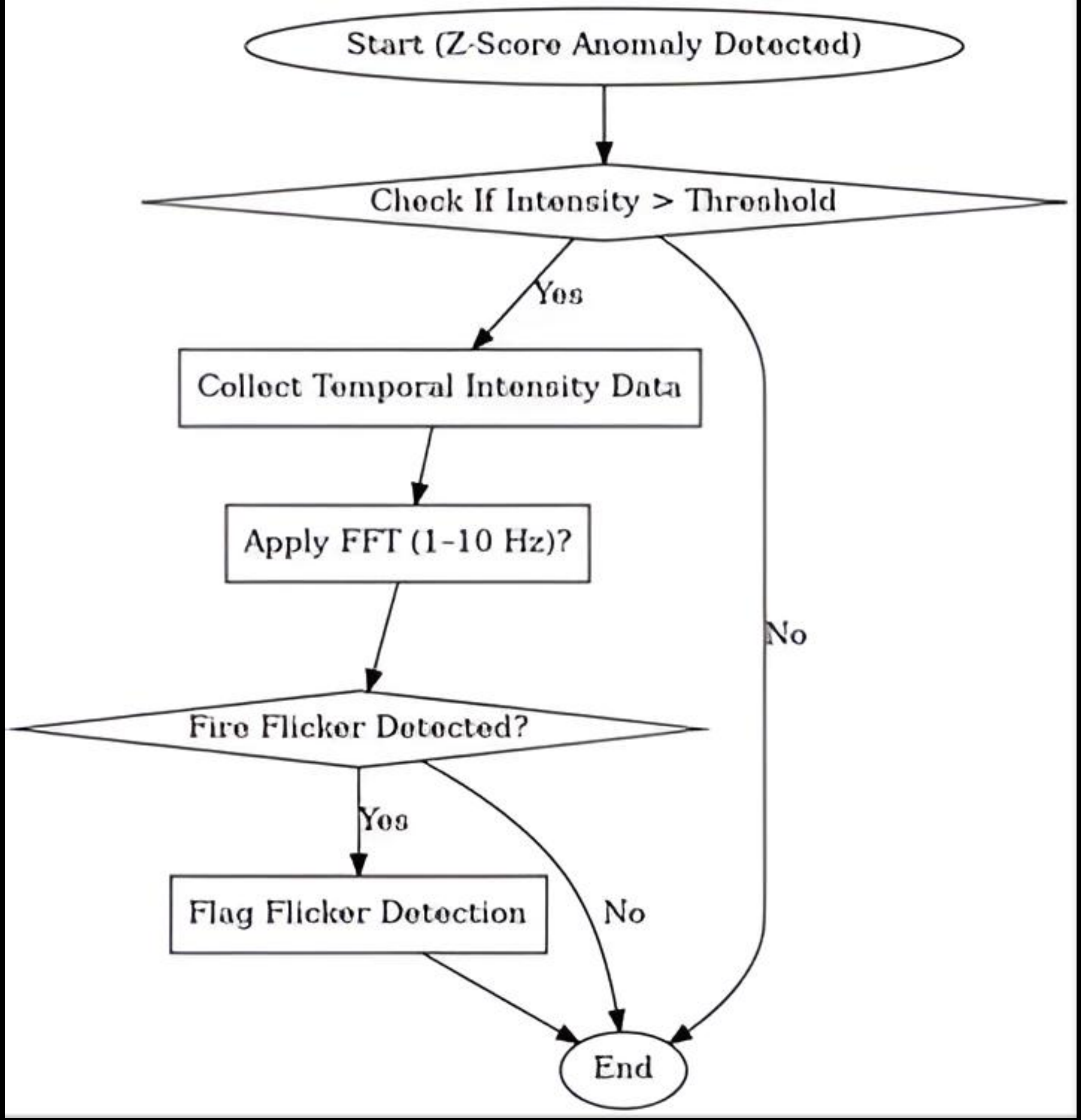
Z-Score Anomaly



Software Selection: Temporal Fluctuation

Algorithm Type	Latency	Accuracy	Computational Complexity	Implementation Complexity
Fast Fourier Transform (FFT)	Moderate	High	High	Moderate
Wavelet Transform	High	Very High	Very High	Complex
Autoregressive (AR) Modeling	Low	Moderate to High	Moderate	Moderate

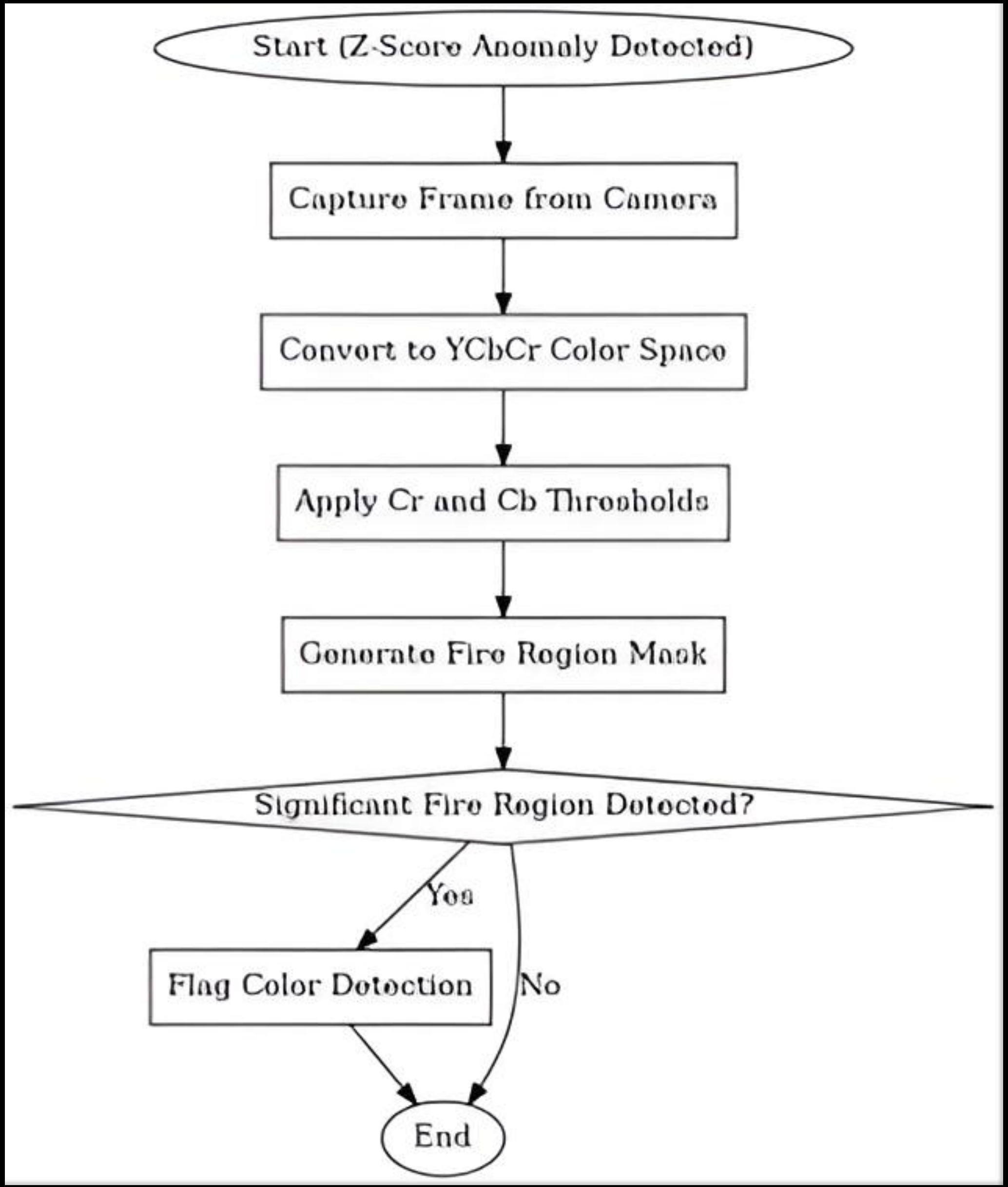
Software Flowchart: FFT



Software Selection: Color Feature Extraction

Algorithm Type	Latency	Accuracy	Computational Complexity	Implementation Complexity	OpenCV Compatibility
HSV Thresholding	Very Low	Moderate	Low	Very Simple	High
YCbCr Fire Region Extraction	Low	High	Moderate	Moderate	High
Gaussian Mixture Model (GMM)	High	Very High	Very High	Complex	Moderate

Software Flowchart: YCbCr Color Extraction



Motor Driver Testing With Load

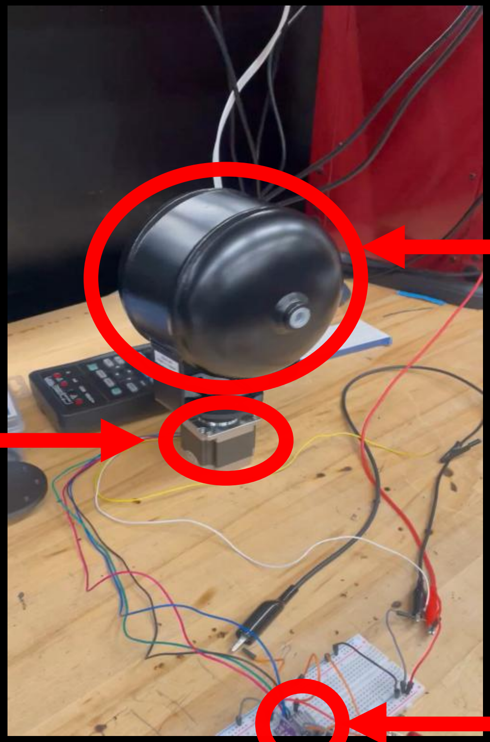
- Max Weight of Load Approx: ~8 lb
- Tested weight: 4.5 lb
- Approximate weight of FLAMES: <5 lb
- Stall Current of Nema 23: 0.39 A

<u>Issues Faced:</u>

- Nema 23/DRV8825 reached high temperatures (approximately above 90 degrees) during initial testing

<u>Solution:</u>

- Tuning reference voltage to limit current to 1 A per coil as it is the maximum amperage per coil as specified in the datasheet

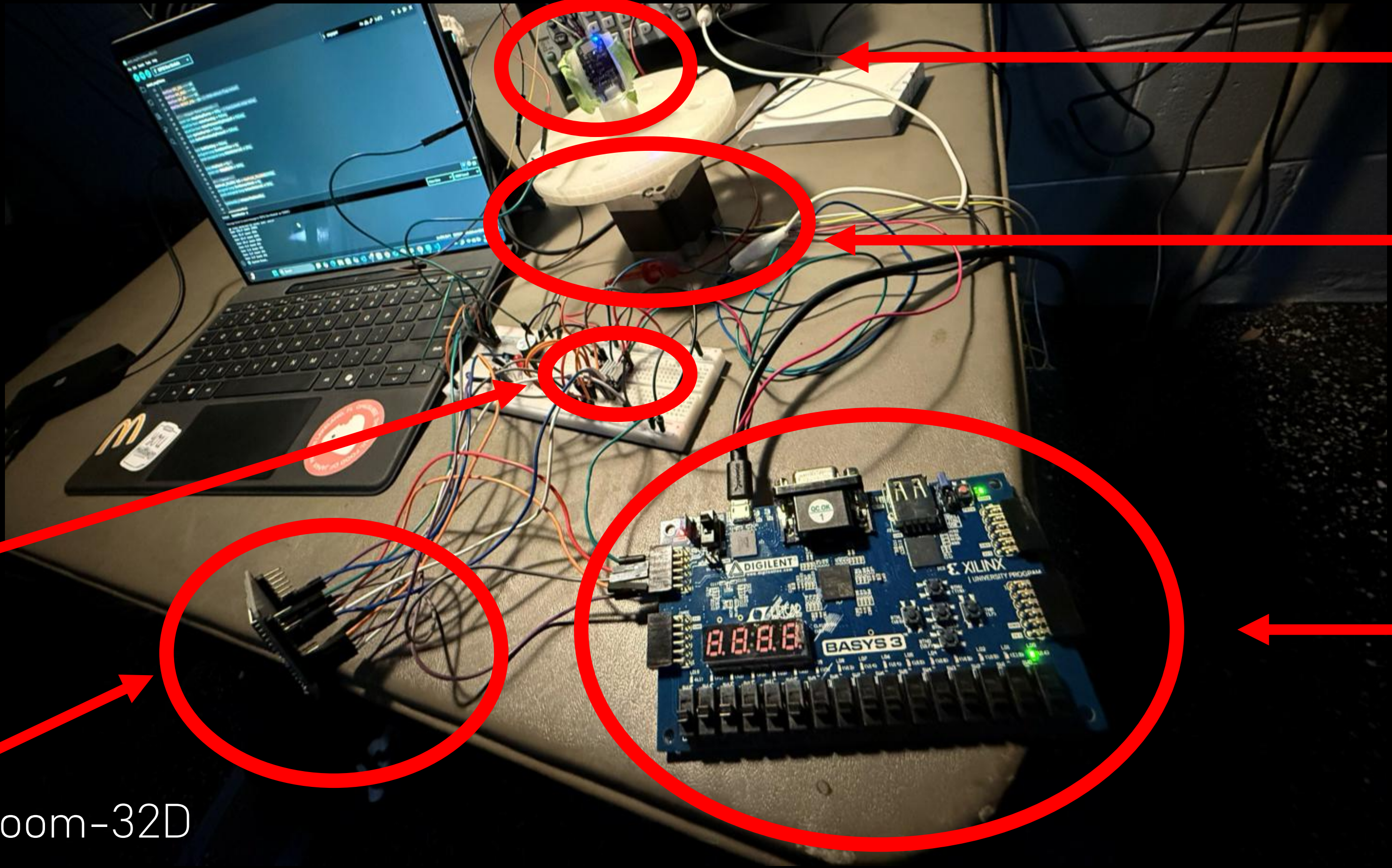


Tested Load of ~4.5 lb

Nema 23 Motor

DRV8825 Motor Driver

Baseline Experimental Setup



Aspheric, 50mm EFL, Polycarbonate lens utilized for focusing light onto TSL 2591 Sensor

Nema 23 Stepper Motor

DRV8825 Motor Driver

BASYS 3 FPGA Dev Board

ESP32-Wroom-32D

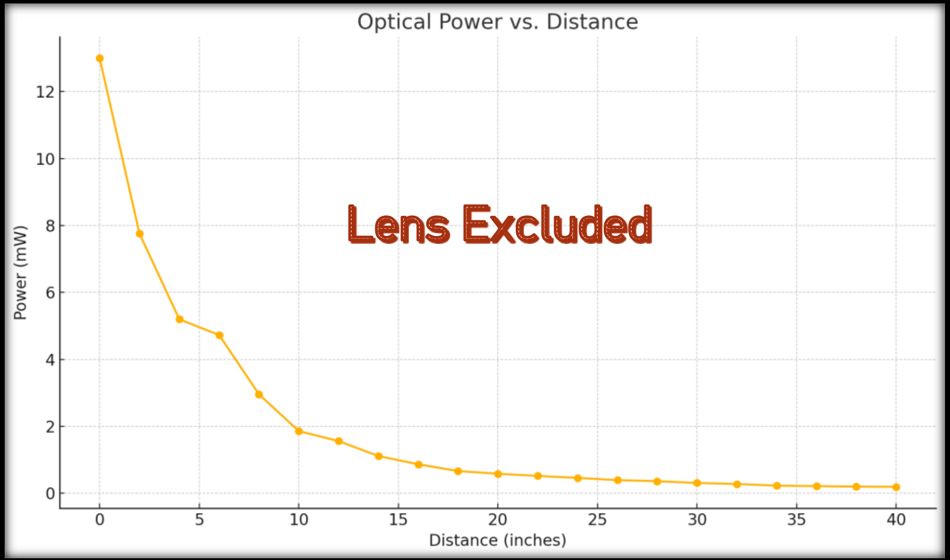
Initial Environmental Baseline Testing

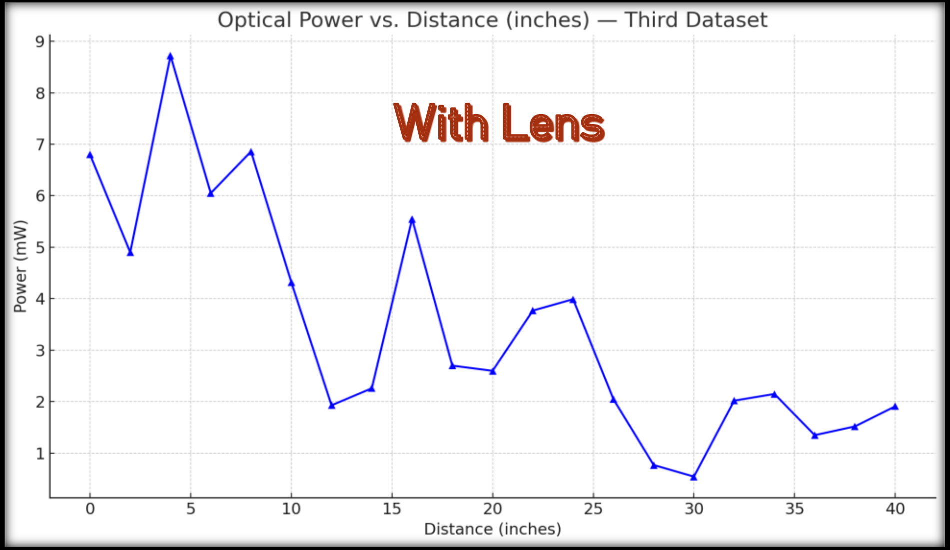
Light Sensor Detection Results using TSL2591 at 1m and 3m

- Includes EMA, Adaptive Thresholding and Z-Score
- Motor starts at same spot (90° off from flame) and stops at fire detected
  - **1m detects earlier** (index **8** vs 12)
  - **3m has higher peak** (**56** vs 42 LUX)
    - Likely due to excess ambient light leaking into the sensor's field of view as the fire becomes smaller and less dominant

- Difficulty: Detection varies with distance. 1m detects faster, 3m detects higher lux
- Problems:
  - **3m:** Slower detection, but at a higher LUX
- Proposed Solutions:
  - Use multi-step confirmation to strengthen motor positioning for further detection analysis

OE Sensors Testing: FDS1010 Si Photodiode





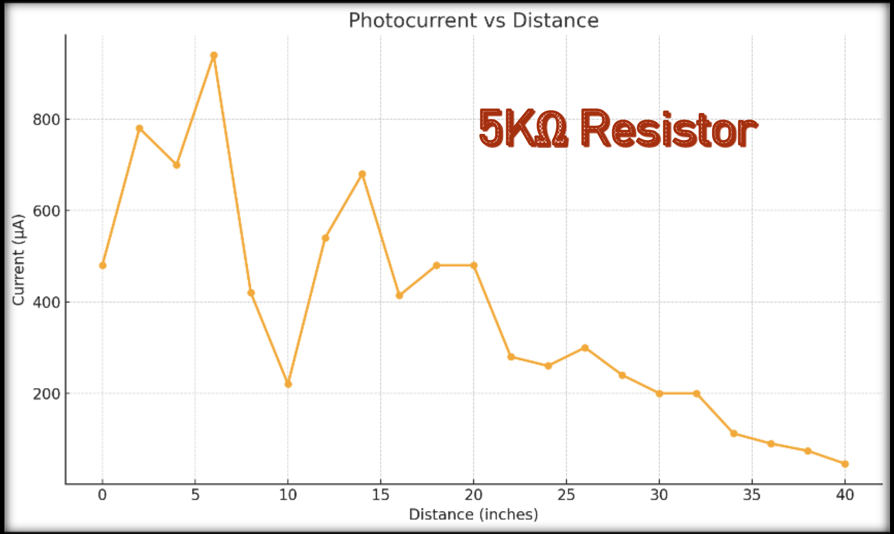
Power Vs. Distance Testing:

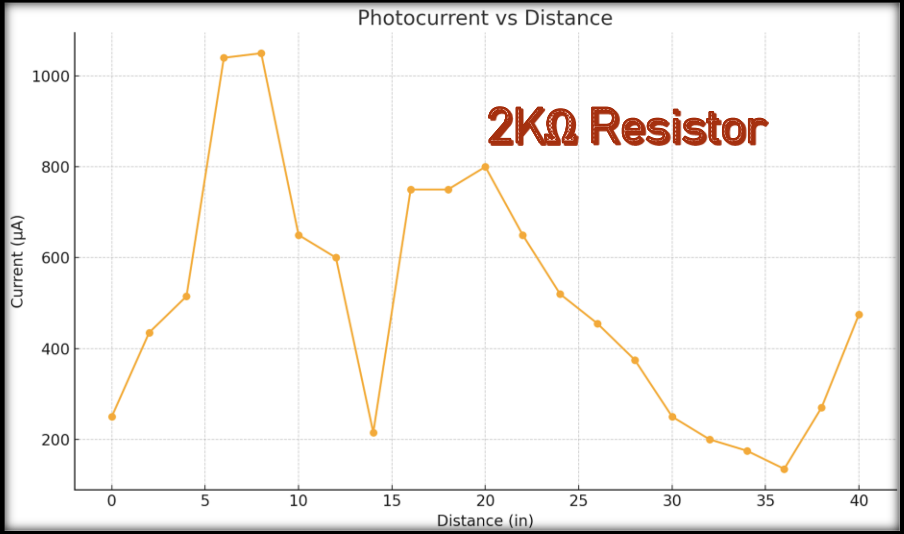
- Optical Power of Source @700 nm = 13mW
- Vary position of optical source on axis, in 2 in increments
- Characterize $\frac{1}{r^2}$ optical power drop off at distance of 1 meter (39.37 in)
- Experiment done excluding lens and including the lens
- Lens used: NBK7 PCX, 75mm Dia, 100mm Focal Length

Interpretation of Results:

- Better characterized $\frac{1}{r^2}$ power drop off when lens is excluded
- With lens, focused spot position and density on detector dictates power
- Cause of spikes with lens: Lens not held steadily

OE Sensors Testing: FDS1010 Si Photodiode





Photocurrent Vs. Distance Testing:

- NBK7 75mm Dia, 100mm EFL Used to focus light onto Photodiode
- Introduce defocus into system to increase spot size density at tail end of 1m
- Experiment Repeated with 5KΩ and 2KΩ resistors
- Vary Gain → Obtain More photocurrent
- $I_{photo} = \frac{V}{R_{Load}}$

Interpretation of Results:

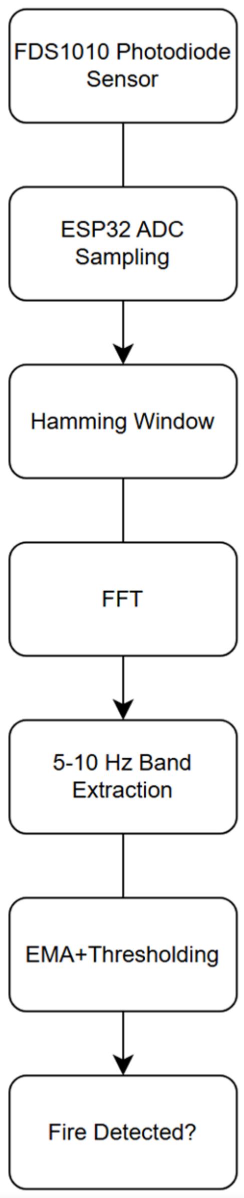
- 2kΩ resistor → higher I_{ph} @ 1Meter Away
- I_{ph} decreases with distance, inverse square law
- Faster frequency response @ 2kΩ, increased BW

FDS1010 Si Photodiode: FFT Testing

Data Collection
- ESP32 captures 1024 12-bit samples at 100 Hz from an FDS1010 photodiode.
- Samples are centered (−2048) to enable bipolar signal analysis.
- Low-Pass Filter applied before processing to smooth high-frequency noise.

Signal Processing
- Apply a Hamming window to minimize spectral leakage.
- Perform FFT to convert the signal to the frequency domain.
- Extract magnitude spectrum.

Fire Detection
- EMA is computed for 5–10 Hz to track ambient baseline.
- Threshold = EMA + 60.
- A flame is detected if:
    - ≥0.5 Hz in the 5–10 Hz range exceed the threshold, and
    - Their magnitude sum > 3.5× threshold.



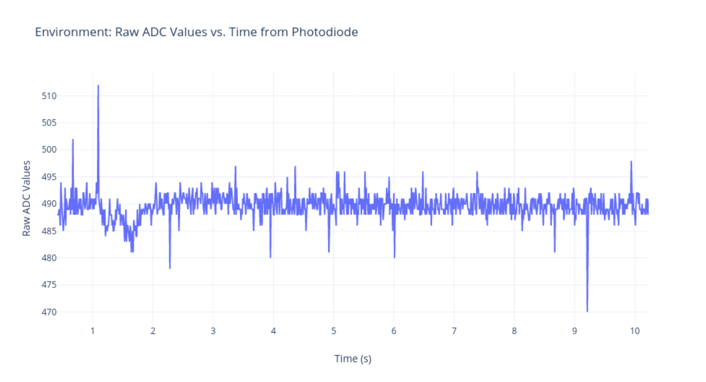
FDS1010 Si Photodiode: FFT Testing

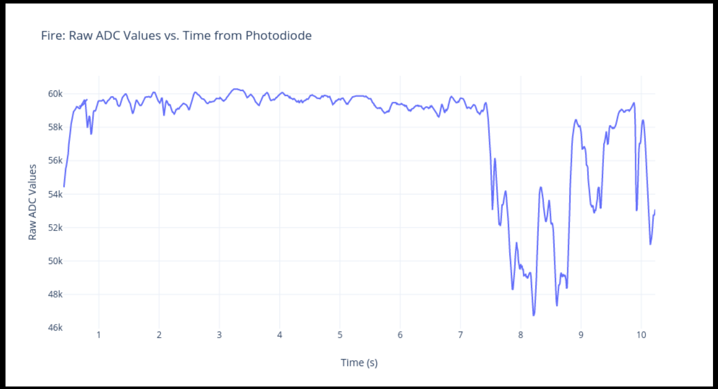
Dark Environment

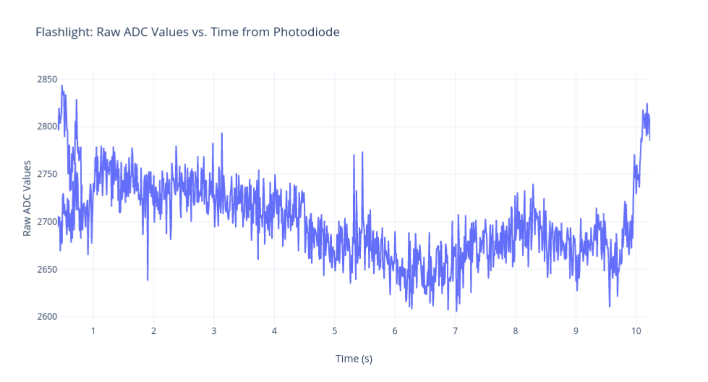
Flame

Flashlight

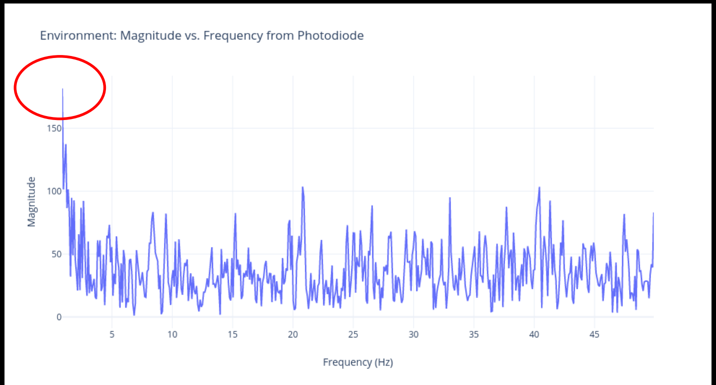
Raw ADC vs Time

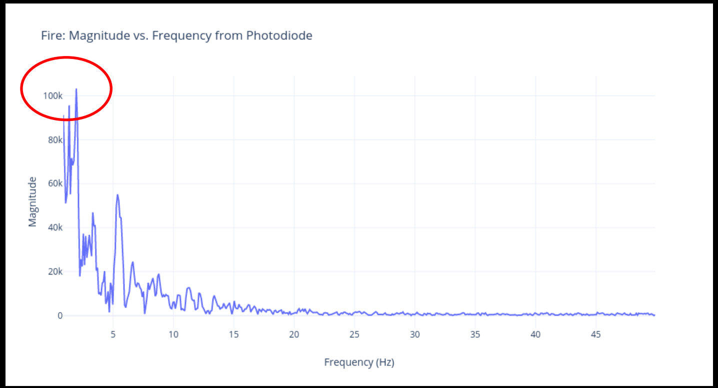


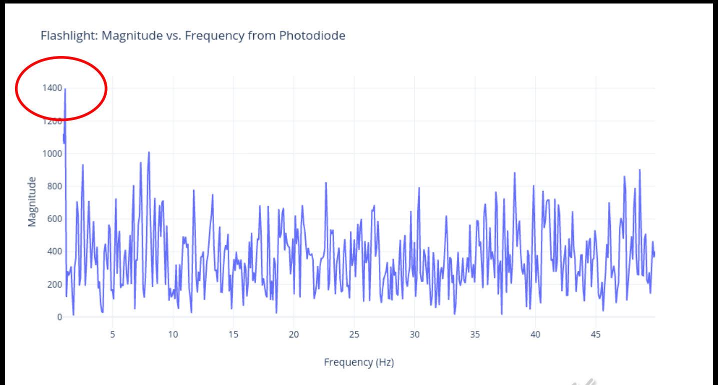




Magnitude vs Frequency







Adaptive Threshold: 1029.13
Adaptive Threshold Met? No
Sum Magnitude Exceeded Threshold: 0.00

Adaptive Threshold: 17196.34
Adaptive Threshold Met? Yes
Sum Magnitude Exceeded Threshold: 474688.30

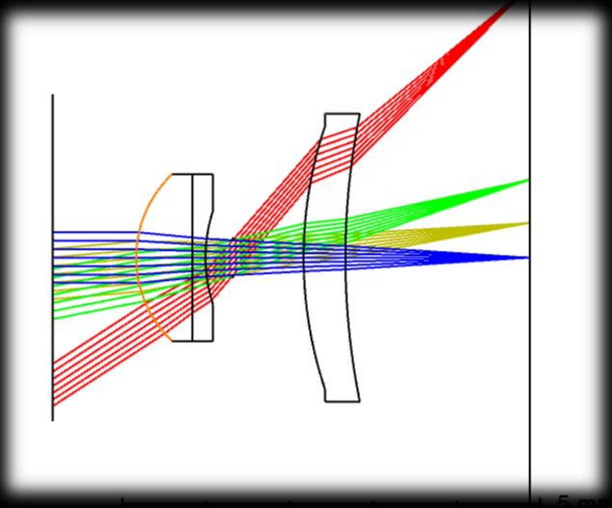
Adaptive Threshold: 1198.78
Adaptive Threshold Met? No
Sum Magnitude Exceeded Threshold: 0.00

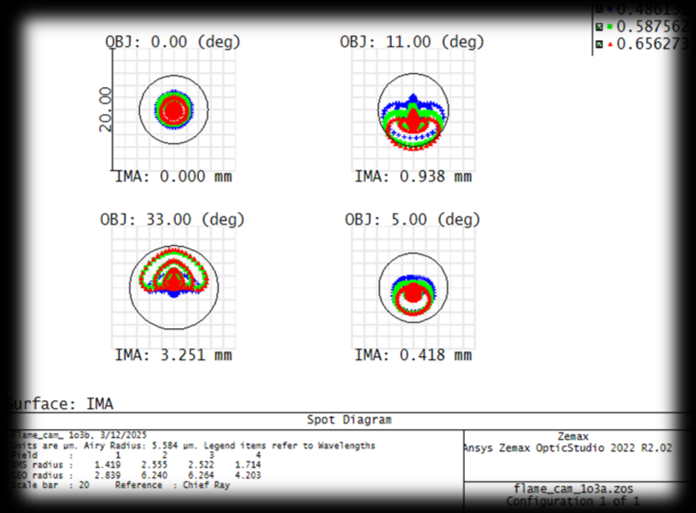
Lens Design: Ras-Pi Custom Imaging System

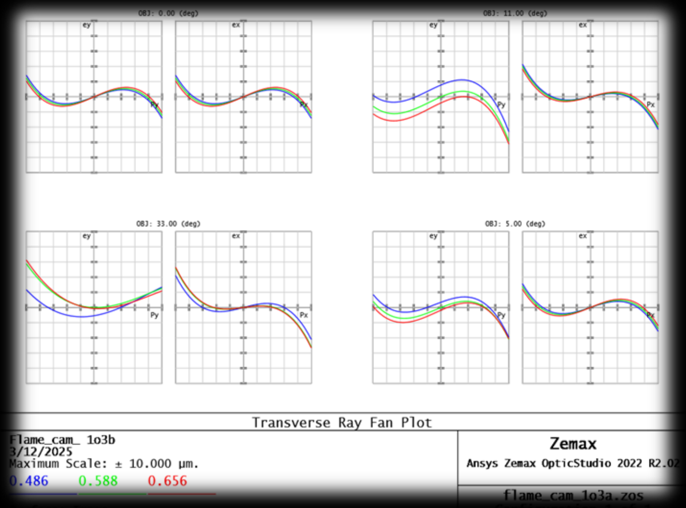
Initial Lens Design Constraints:

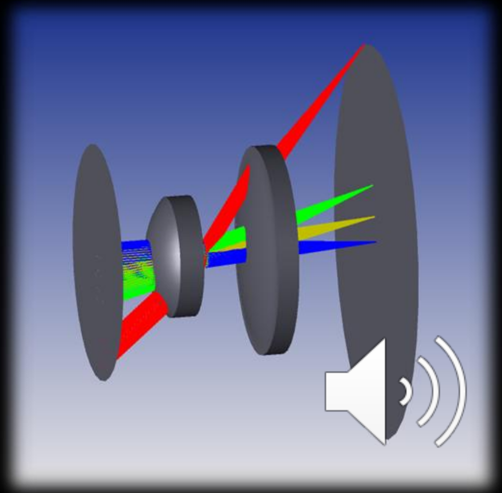
- 66° Target FOV
- 4.85 mm EFL Target
- f/10 System
- Inclusion of Pinhole → Increase Depth of Field
- Reduction of Chromatic Aberration
- Diffraction Limited Performance Off Axis

Output Camera Simulated Image Quality:

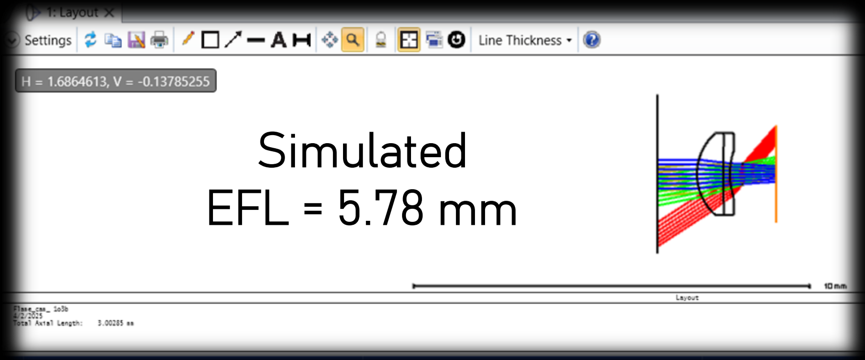


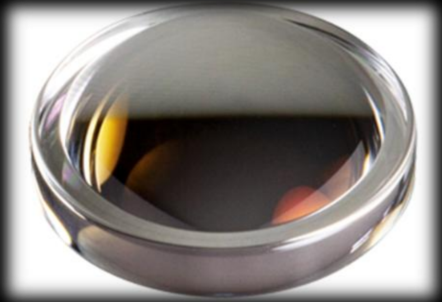






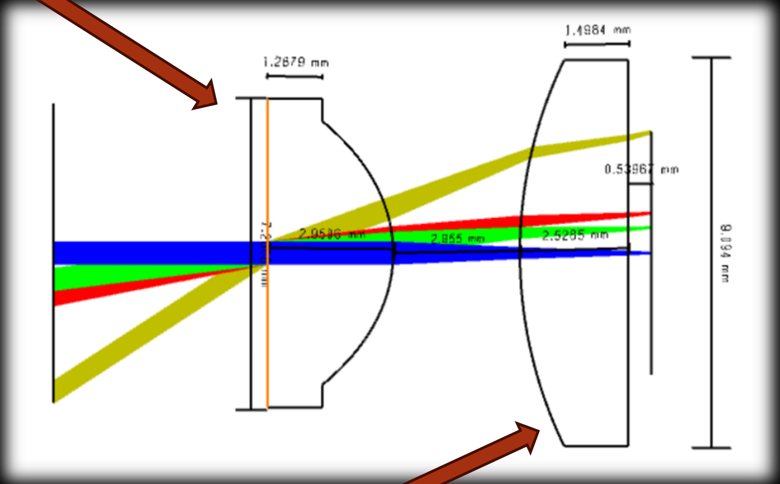
Hardware Selection: Raspberry Pi Imaging Lenses

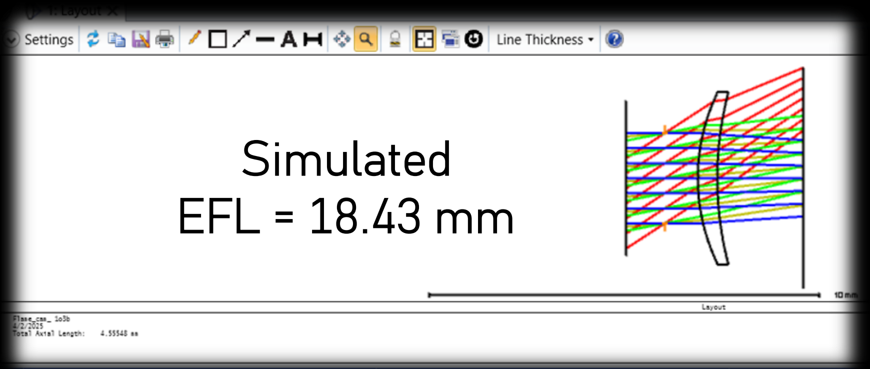


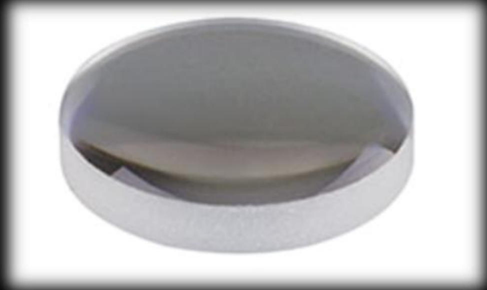


354105-A ***f = 5.5 mm*****, NA = 0.60, WD = 3.1 mm, Unmounted Aspheric Lens, ARC: 350 - 700 nm**

Simulated
EFL = 4.84 mm



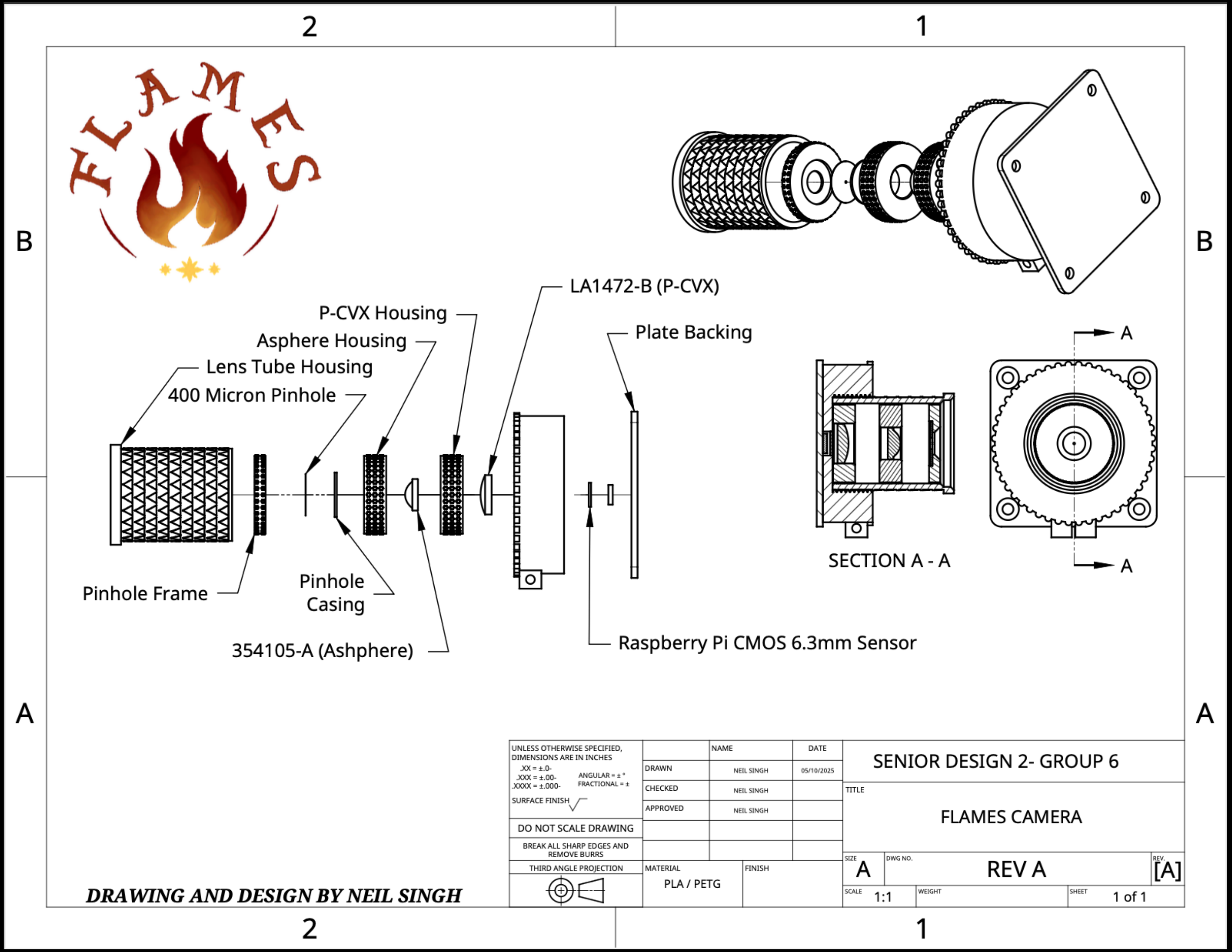


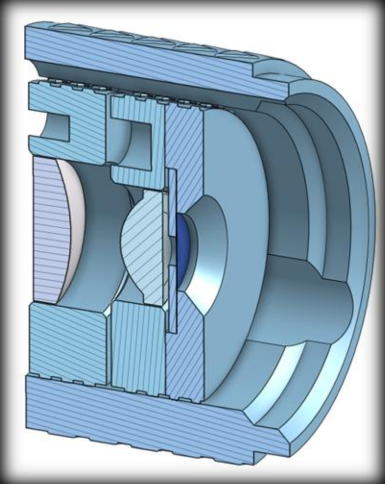


LA1472-B - N-BK7 Plano-Convex Lens, Ø9.0 mm, ***f = 20 mm*****, AR Coating: 650 - 1050 nm**

Theoretical Design → Off the Shelf Lenses

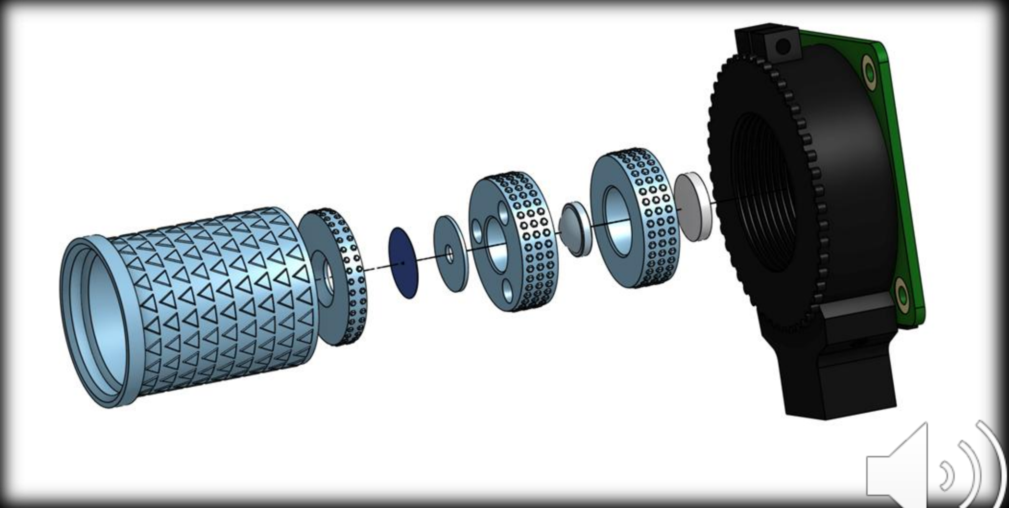
Ras-Pi Imaging System Assembly



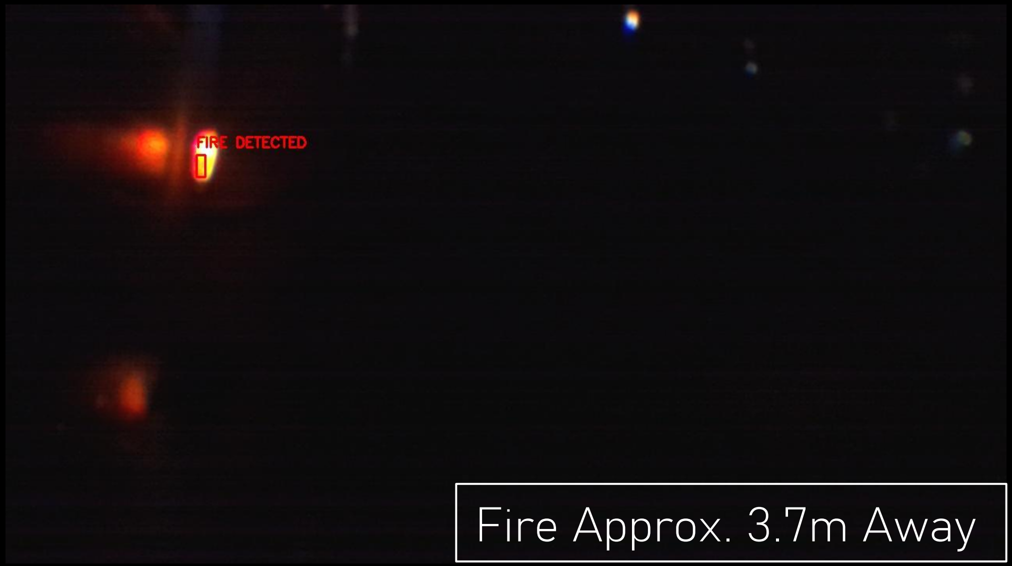


BOM

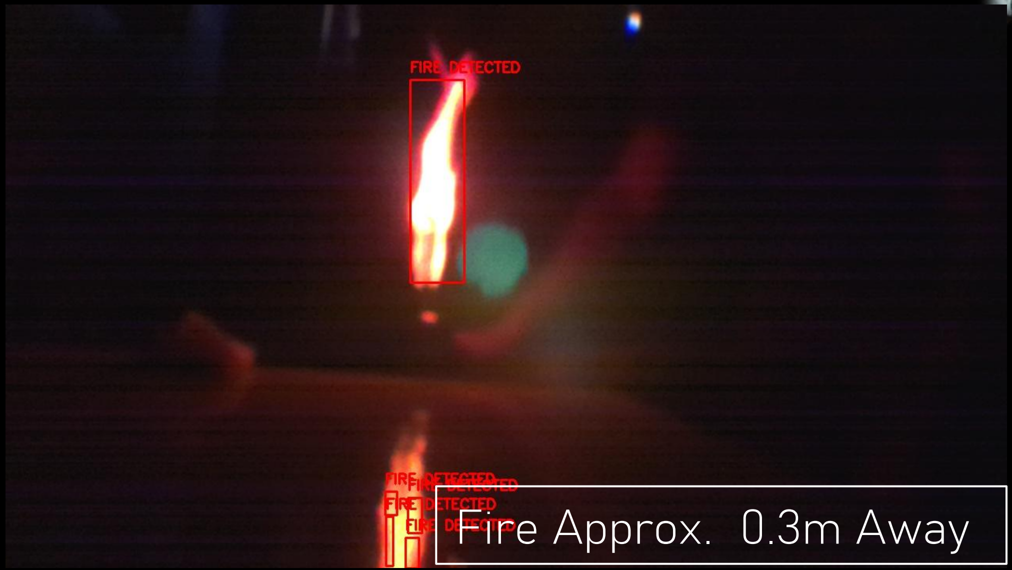
- 400 Micron Pinhole
- LA1472-B (P-CVX)
- 354105-A (Asphere)
- Raspberry Pi GSB Shutter CMOS Array



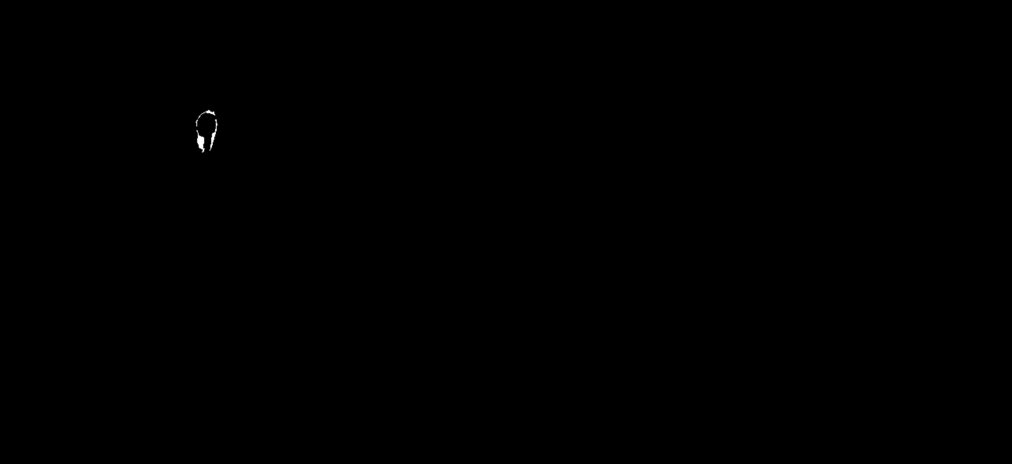
Raspberry Pi 5 Custom Lens System Testing



Fire Approx. 3.7m Away



Fire Approx. 0.3m Away

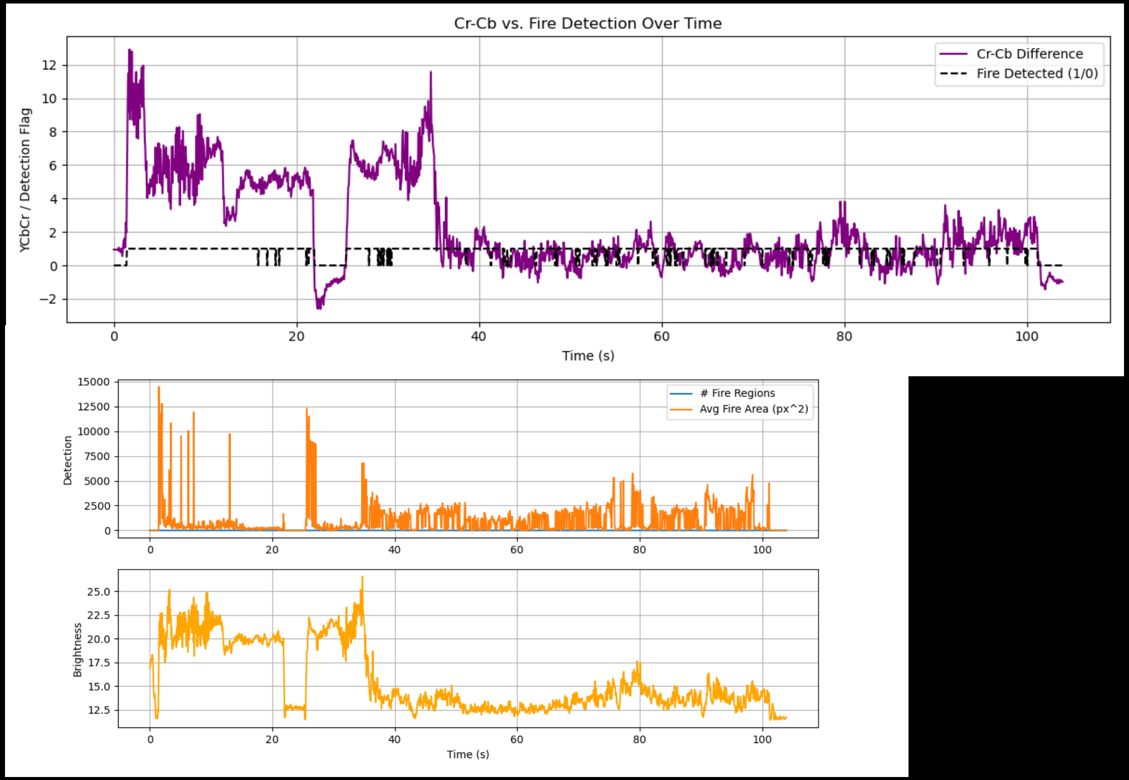


YCrCb Mask

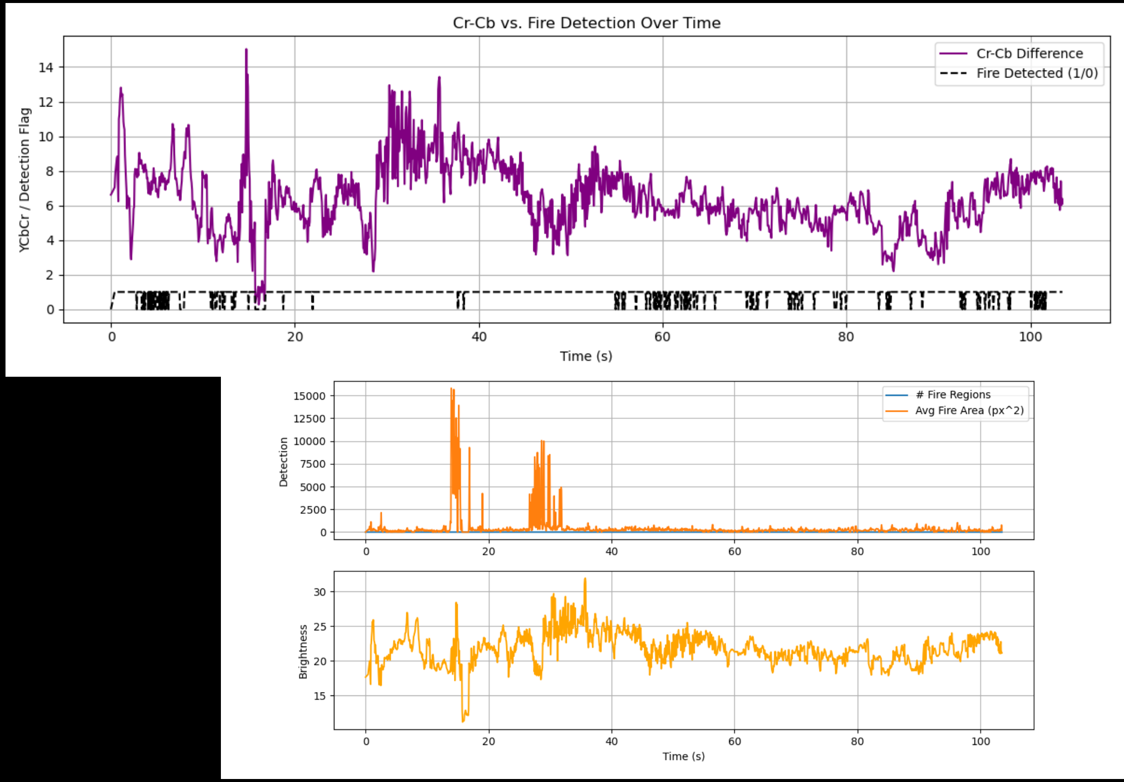
YCrCb Mask

Raspberry Pi 5 Camera: YCbCr Color Extraction Testing

Moving Fire Source



Still Fire Source



Condition	Moving Fire Source	Still Fire Source
Reaction Time for First Detection	≈2.5 seconds (measured with ruler)	≈0.6 second (measured with ruler)
Challenge	Slightly longer detection time for moving fire source	
Potential Solution	Use motion tracking or adaptive filtering to reduce detection delays for moving fire sources	

Imaging System Testing: Output Imagery

Video

Testing Observations:

- Fire detectable by software from distances 0.3 – 3.7 meters away
- Fire Detectable within approx. 66° FOV
- Can Clearly see low frequency flicker of the flame

Issues Faced:

- Minor Chromatic Aberration
- Tilt induced Spot due to lens Mounting
- Housing material made of PLA → Potential to melt

Full System Testing

Issue Faced: YCrCb-Based Visual Flame Detection not differentiating sparks from flames.

Potential Solution: Add object or shape-based filtering to distinguish flames from brief sparks.

Flame

Trial #	Distance (m)	Light Intensity Anomaly Detection	Frequency Domain Fire Detection	YCbCr-Based Visual Flame Detection	Time (s)
1	1	yes	yes	yes	10.22
2	1	yes	yes	yes	10.31
3	1	yes	yes	yes	10.51
4	1	yes	yes	yes	9.29
5	1	yes	yes	yes	10.18
6	1	yes	yes	yes	10.3
7	1	yes	yes	yes	9.76
8	1	yes	yes	yes	10.32
9	1	yes	yes	yes	10.3
10	1	yes	yes	yes	10.27

Sparkler

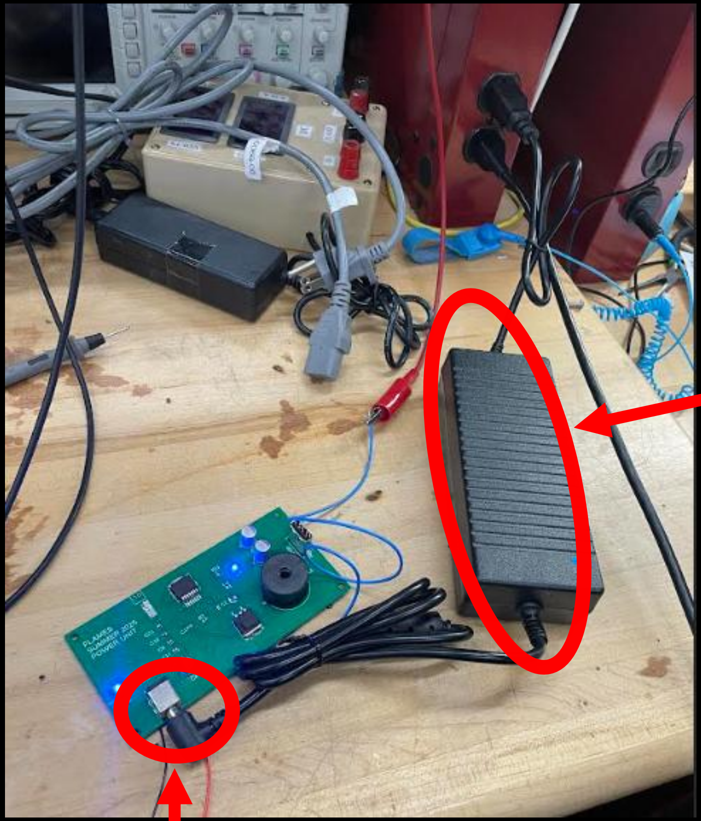
Trial #	Distance (m)	Light Intensity Anomaly Detection	Frequency Domain Fire Detection	YCbCr-Based Visual Flame Detection	Time (s)
1	1	yes	no	yes	10.43
2	1	yes	no	yes	11.38
3	1	yes	no	yes	10.23
4	1	yes	yes	yes	9.78
5	1	yes	no	yes	10.5
6	1	yes	no	yes	10.67
7	1	yes	no	yes	10.32
8	1	yes	no	yes	10.45
9	1	yes	no	yes	10.45
10	1	yes	no	yes	9.77

PCB 5V Regulator Testing

- Input: 12V
- Output: 5.2V

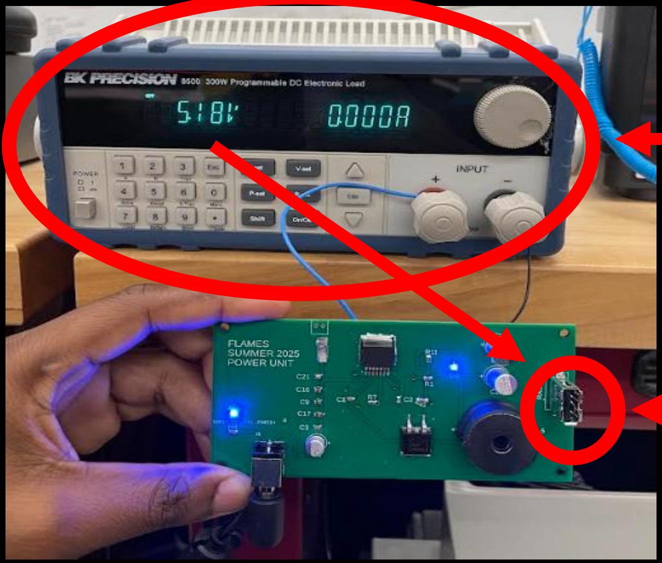
<u>Issues Faced:</u> Resistor was left floating in schematic resulted in 2.5V Output

<u>Solution:</u> Connect resistor as intended in schematic manually all images: results of solution are shown in following images



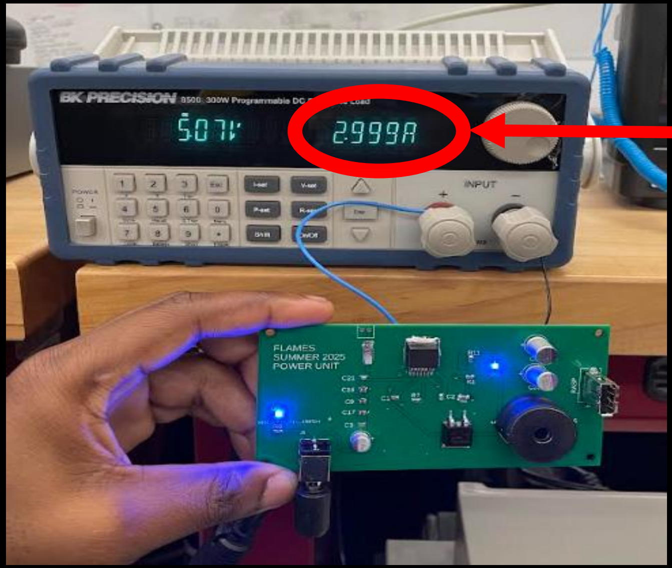
12V Input

ADC



Electronic Load with 0A

5V Output



3A Load

Budget

Component	Total Price
Electrical Components	Motor + Motor Driver + TIA + ADC + Power Supply $166.74
Optical Components	TSL2591 + 3in (P-CVX) + P-CVX lens + 400 uM Pinhole + Asphere + Polycarbonate lens + Si Pd $369.55
Computer Components	FPGA Board + Raspberry Pi 5 + ESP32 + Testing Power Supplies + Raspberry Pi 5 Heat Sink $340.91
Shipping	$221.10
PCB Manufacturing	$333.19
Total	$1431.49

Work Distribution

Team Member	List of Tasks
Ronex Faustin	PCB design, electrical hardware integration, and system power management
Neil Singh	Optical lens design (custom Imaging System), photodiode selection, and optical signal acquisition lens system, and all mechanical design / 3d printing manufacturing
Lauren Caccamise	Software development, FPGA/MCU/Pi integration, fire detection algorithms, and testing