



FLAMES

FIRE DETECTION AND MONITORING FOR EMERGENCY SITUATIONS

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Chapter 1 – Executive Summary

FLAMES is a senior design project developed at the University of Central Florida by a team of undergraduate students specializing in electrical, computer, and optical engineering. The system is designed to detect and monitor fire events using optoelectronic components and a combination of embedded processing platforms. With the need for early and reliable fire detection in sensitive indoor environments such as CNC machines and laboratories, FLAMES provides a solution that is both safe and precise.

The system employs a lux sensor, photodiode, CMOS sensor, and optical lenses to monitor light intensity and color features indicative of fire. These signals are processed in real time using a microcontroller, a Raspberry Pi 5, and an FPGA, which collaboratively perform signal conditioning, anomaly detection, and temporal analysis to identify fire-specific patterns. Emphasis is placed on accuracy, low-latency response, and environmental adaptability to maintain safety in controlled spaces.

FLAMES is intended for fixed infrastructure deployment in research facilities, semiconductor cleanrooms, and other indoor spaces where traditional fire detection systems may be too delayed or intrusive. Its design allows for integration into broader building management or safety systems and supports scalability across multiple rooms or zones.

This document outlines the design process of FLAMES, including the theoretical foundations, enabling technologies, and rationale behind part selection. It further details system architecture, hardware schematics, and firmware implementations. Standards and constraints guiding the project are discussed, followed by documentation on fabrication, prototyping, and administrative considerations. Final conclusions and recommendations for future improvements are presented, along with appendices containing technical references and permissions.

Chapter 2 – Project Description

2.1 Project Background and Motivation

The 20th century revolutionized fire detection. Before the advent of electricity, fire prevention relied on manual and error-prone methods, such as fire brigades patrolling with buckets of water. Innovations like Francis Robbins Upton's "Portable Electric Fire Alarm" and later, smoke and carbon monoxide detectors, marked significant progress but had limitations, including high costs, limited lifespans, and a tendency for false positives. For instance, ionized smoke detectors using Americium-241 disrupted electrical currents to detect smoke but were only reliable for about 10 years despite the isotope's long half-life [1].

The National Fire Protection Association (NFPA) reports 896,500 false alarms annually, underscoring the need for improvement [2]. Our senior design project aims to develop a cost-effective optical fire detection system to address these challenges. Unlike existing optical detectors designed for commercial use, our system integrates optical hardware and

electronic processing to minimize false positives and provide accurate, affordable fire detection.

The FLAMES project demonstrates the feasibility of using off-the-shelf hardware for fire detection while serving as a collaborative learning experience for students in optical, computer, and electrical engineering. This interdisciplinary effort allowed each team member to explore their areas of interest while ensuring seamless integration of hardware and software components. Through brainstorming and refining ideas, we developed a functional system that emphasizes teamwork, problem-solving, and real-world application—skills essential for interdisciplinary collaboration in the workplace.

2.2 Current Commercial Technologies and Existing Projects

2.2.1 Americium in Ionization Smoke Detectors

Ionization smoke detectors were introduced in the 1960s and became widely available for residential use by the 1970s. These detectors utilized Americium-241, a radioactive isotope, to ionize air within the detection chamber. When smoke particles entered the chamber, they disrupted the electrical current, triggering the alarm.

This technology shares similarities with FLAMES, as both systems leverage available technology to optimize fire detection. Ionization detectors improved upon manual and less reliable early methods but faced challenges such as false alarms. FLAMES builds on this legacy by explicitly addressing false alarms through a sophisticated multi-layer optical analysis, further enhancing fire detection accuracy. FLAMES, also, since it utilizes optics, does not have an expiration date as americium in ionization smoke detectors do.

2.2.2 Heat Detectors “Initiating Devices” NFPA Code

Heat Detectors, also known as ‘Initiating Devices,’ are fire detection components designed to respond to temperature changes associated with fire events. They detect fire by responding to changes in temperature, either through a fixed temperature threshold or a rate-of-rise in temperature. Upon activation, these detectors send signals to the fire alarm control panel, initiating appropriate responses such as alarms of suppression systems. Heat detectors are best used in high-dust areas, environments with high humidity and areas with extreme temperature fluctuations. These make them resistant to false alarms caused by dust, steam, or fumes that often affect smoke detectors.

The fixed temperature detectors are activated when surround temperature exceeds a pre-determined threshold, typically set between 135° F (57° C) and 165° F (74° C) [3]. They are common in environments where gradual temperature increases are less likely to cause false alarms such as storage rooms or mechanical spaces.

Rate-of-Rise (ROR) detectors are activated when the temperature increases rapidly, regardless of the absolute value, typically a rise of 15° F (8.3° C) per minute or more [4]. They are ideal where fires can escalate quickly such as kitchens or manufacturing facilities. Then combination heat detectors are fixed temperature detectors mixed with rate-of-rise detectors for enhances reliability in varied environments.

Heat detectors and FLAMES share similarities in their layered detection approach. Heat detectors confirm fire presence using fixed temperature and rate-of-rise methods, while FLAMES employs multi-layered optical signal analysis, including spectral filtering and temporal evaluations. Both systems trigger alarms based on specific criteria and are designed for challenging environments: heat detectors excel in high-dust or humid areas, whereas FLAMES addresses false alarms and detects fires across varied temperature conditions. Their signal processing differs, with heat detectors analyzing temperature changes and FLAMES processing optical photocurrent data for fire identification.

2.2.3 Aspirating Smoke Detectors

Aspirating smoke detectors (ASDs) are advanced fire detection systems that actively draw air samples from a protected area through a network of pipes into a central detection unit. Within this unit, highly sensitive sensors analyze the air for smoke particles, enabling the detection of fires at a very early stage, often before visible signs are present. ASDs provide early detection by identifying minute concentrations of smoke, offering prompt alerts that allow for swift intervention. These detectors are ideal for environments such as areas with high airflow, large open spaces, and locations where traditional smoke detectors may be ineffective. By continuously sampling air and using advanced filtration techniques, ASDs minimize false alarms caused by dust or other particles [3].

Both aspirating smoke detectors and FLAMES emphasize early fire detection to enable swift responses and reduce damage. While ASDs rely on active air sampling, FLAMES utilizes optical photodetectors and FPGA-based multi-layer analysis. ASDs mitigate false alarms through filtration and particle analysis, whereas FLAMES reduces them with spectral, temporal, and pattern-based photocurrent intensity profile source analysis. Each system is tailored for challenging environments: ASDs excel in high airflow or large open spaces, while FLAMES is optimized for confined spaces. Additionally, FLAMES stands out for its affordability, compact design (eliminating the need for extensive piping or air sampling systems), and advanced multi-layer optical analysis, offering a versatile and promising fire detection solution.

2.2.4 FLAMEX YMX 5000

The FLAMEX YMX 5000 is an industrial-grade spark and flame detector designed for high-demand machining and manufacturing environments. According to FLAMEX, the detector operates primarily in the infrared region, utilizing photo transducers to monitor lens degradation by analyzing changes in generated photocurrent. These photo transducers are coated with a proprietary infrared filter to enhance detection accuracy [5]. A key advantage of this system is its self-monitoring capability, which supports targeted wavelength detection through infrared and UV-blocking optical components, reducing false positives. While the system is primarily optimized for spark detection, FLAMEX asserts it can also detect flames. However, one potential area for improvement is expanding its spectral coverage to enhance versatility. FLAMES shares similarities with the system in its use of optical lenses to capture radiated light from a distant source and algorithmically detect stochastic light sources, such as sparks. However, it differs in the range of wavelengths detected. Unlike the FLAMEX system, which primarily operates in the infrared region, our senior design project focuses on detecting visible light. Additionally,

the optical components vary significantly. NBK7, a commonly used material for visible imaging applications, is employed in our system, whereas infrared imaging typically requires materials such as germanium selenide or chalcogenide glass, though their specific use is not detailed on the FLAMEX website.

2.2.5 Honeywell IFM System

The Honeywell IFM system is meant to detect and monitor flame behavior in industrial processes. The Honeywell IFM system excels at its ability to detect in UV and IR. This ultimately contributes to a broader detection range allowing for detection of welding, and other near infrared light sources [6]. The IFM offers programmable signal processing however it can be sensitive to false alarms based on the programming thresholds. Both the F.L.A.M.E.S system and the IFM utilize sensors to capture the radiated light and analyze signal variations to determine the presence of a potential fire hazard. Additionally, both systems incorporate algorithmic signal processing to enhance detection accuracy and reduce the number of false positives. However, there are key differences in their approach and application. The IFM is targeted for industrial flame monitoring (specifically in combustion and burner management applications). In contrast, FLAMES focuses on detecting stochastic light sources, such as sparks from various ignition events, with an emphasis on visible light rather than infrared. The optical components also differ significantly, with FLAMES utilizing NBK7 lenses optimized for visible wavelengths, whereas the Honeywell system employs UV and IR-sensitive materials.

2.2.6 Spectrex 40/40 Series

Spectrex employs a multi-spectrum design to enhance detection accuracy over long distances while reducing false alarms. The FLAMES system relies on an FPGA-based processing unit for signal analysis, whereas Spectrex integrates sensitivity selection to prevent detection zone crossover, providing a more controlled detection environment.

One key difference is the environmental adaptability of each system. Spectrex is designed for harsh industrial conditions, featuring a heated window to prevent snow, ice, and condensation from interfering with detection [7]. In contrast, FLAMES does not currently incorporate environmental compensation mechanisms and is tailored more toward controlled indoor or semi-outdoor environments. Additionally, while Spectrex supports multiple industrial communication protocols such as HART, RS-485, and Modbus, allowing for seamless integration into industrial safety systems, FLAMES primarily operates with standard FPGA-based communication and motor control for finer positional accuracy to then capture as much light from the scene as possible.

2.3 Goals and Objectives

Below are the goals and objectives we established for FLAMES. The goals define the broad vision and purpose of the project, while the objectives outline specific, measurable deliverables that guide its development and implementation. There are also stretch goals and objectives outlined which are goals and objectives beneficial to the project, but beyond the scope of our implementation.

2.3.1 Goals

Basic Goals:

- Create a compact enclosed system to detect fire hazards and potential fire hazards such as stochastic sources of light ranging from 400 nm – 800 nm (i.e. grinding sparks) in various small-contained areas such as a lab or within CNC machines.
- Detect wavelengths contained in fires with an optoelectronic device.
- Perform algorithmic and signal processing computation tasks using a customizable computer (FPGA) as opposed to an MCU.

Advanced Goals:

- Mount the FLAMES system such that the entirety of the system rotates 360 degrees and collects baseline intensity information in tandem with a customized computing algorithm for intensity threshold determination and halt in the general vicinity intense optical emission.
- Discern incoming light via the use of temporal signal processing techniques in tandem with color extraction.
- Minimize power consumption to enable continuous, low-power operation by implementing a “low power mode” whereby the system consumes less power when electrical components are not active.
- Apply environmental baseline to accurately identify and detect source of optical intensity (i.e. flame) .

Stretch Goals:

- Log analysis of triggers onto third-party PC via FPGA communication with external database.
- Incorporate machine learning into pattern matching off trained data for another layer of detection results.
- Introduce filter wheel containing UV, IR, and wavelength-specific filters to characterize different types of fires such as chemical and electrical fires.

2.3.2 Objectives

Basic Objectives:

- Implement an audible buzzer alarm and LED light that triggers post detection, to warn others in area of the presence of fire.
- All optical components and supporting electronic hardware is contained in a singular 3D printed package with no optical alignment required from the user.
- Designed and implemented temporal and spectral fire detection algorithms on the FPGA using raw photodiode voltage samples. The system uses adaptive filtering

and frequency-domain analysis on $V(t)$ data to detect fire flicker patterns, while a TSL2591 lux sensor provides real-time baseline monitoring to distinguish fire from other sudden optical events.

- Environmental Baseline Calibration: Utilize Exponential Moving Average (EMA) filtering for real-time intensity baseline calibration, ensuring low-latency adaptation to environmental changes. Implement adaptive thresholding to dynamically adjust sensitivity while filtering out low-intensity, non-fire signals.
 - Anomaly Detection: Apply Z-score anomaly detection for real-time identification of abrupt intensity deviations.
 - Temporal Flicker-Based Fire Detection: Use Fast Fourier Transform (FFT) analysis to identify fire's characteristic 5–10 Hz flicker frequency, differentiating it from steady artificial light sources such as LEDs and fluorescent bulbs and other stochastic sources such as a children's sparkler.
 - Color Feature Extraction: Utilize YCbCr fire region extraction to accurately detect fire-colored regions while minimizing false positives, ensuring a balance of accuracy and computational efficiency for FPGA implementation.
- Utilize an MCU to manage communication, temporary debugging data logging, power for alert system, and alert triggering.
 - Establish a baseline threshold by measuring environmental conditions when the start button is pressed. This baseline accounts for pre-fire conditions specific to the current environment and resets automatically in each new environment via button press to maintain accuracy and integrity of signal.

Advanced Objectives:

- Configure the MCU to output a pulse-width modulated signal for desired motor position, rotation speed, and direction.
- A broadband 350-1100 nm silicon detector (photodiode) captures wavelengths from stochastic light sources, such as sparks from various ignition events or flames. Potential fire sources are characterized by the digital voltage output from the photodiode, analyzed by an FPGA.
- A transimpedance amplifier is implemented and paired with an ADC to convert AC current into a digital voltage signal for further signal processing.
- Implement parallel processing for intensity analysis algorithms, enabling immediate alerts if fire detection criteria are met.
- Calibrate detection algorithms for 90% accuracy, differentiating fire from other high-intensity stochastic sources, such as sparks.

- Maintain total system power consumption to remain below 44 W during active detection.
- The ESP32, Raspberry Pi, and Artix-7 BASYS3 FPGA development board communicates via GPIO flag signals, enabling efficient parallel real-time fire detection and system control.

Stretch Objectives:

- Log fire detection events with key details (intensity, timestamps, and results) to the MCU as it facilitates data access for the PCB by acting as an interface through USB.
- An external database checks the FPGA logs for time stamped information and record a log of triggers. This will ideally be useful for analysis of equipment that is in operation during operational hours.
- An additional layer of fire-detection capability will involve machine learning training to identify patterns in frequency signal trends derived from prior Fast Fourier Transform (FFT) conversions of intensity data. This approach will enable the system to continuously adapt to new environments and improve its accuracy over time.
- Expanding on the existing design, a rotating filter wheel will rotate in front of the photodiode to induce changes in the output photocurrent. The fluctuations in photocurrent will be reflective of the type of light source being imaged onto the photodiode. For example, by layering a blue filter with a red filter we can change the amount of photocurrent being output if viewing an electrical or chemical fire.
- Achieve data processing latency under 10 ms to allow near real-time fire detection and alerting.

2.3.3 Hardware

Fire Detection System – Basic Goals:

The FLAMES optical fire detection system's primary function is to identify potential hazards effectively across diverse darkened small room environments including confined laboratory spaces, ducts, CNC machines, and confined spaces where ambient light is not normally detected. The system leverages a customized optical setup that comprises of a series of visible spectrum rated lenses to capture the light from the confined darkened space. The series of lenses will be aligned such that the secondary photodetector lies on the optomechanical axis of the enclosed unit. Light from the area in which the motor is stopped will fall incident on two components which I will specify in detail in the following sections. The first component will be photodiode number one (frontmost detector), which is a silicon photodiode made by Thorlabs (FDS1010) suitable for detection between 400 and 1100 nanometers. A transimpedance amplifier and supporting analog to digital circuitry will be electrically connected to the output of the photodiode to gather ambient intensity readings in the form of photocurrent. The ambient light shall be used as a reference for the type of optical emission being analyzed whether that be stochastic or a true flame that has sustained emissions. Under the condition that the source in question is a stochastic source, the

expected photocurrent to be generated should embody a higher frequency, non-periodic signal that has an increased energy spectral density. In the case of a flame (which resides predominantly in the mid 600 nanometer range), the expectation is that a portion of the light is refracted by the lens system and the light is then focused onto the secondary photodetector.

As mentioned previously, the optical signals generated are in the form of photocurrent and are processed through a custom computer that is enabled via the use of an FPGA, which performs advanced computational tasks, including threshold analysis, temporal behavior analysis, and flicker pattern analysis to ensure rapid and accurate fire identification. The choice of FPGA over traditional microcontrollers enables real-time decision making. FLAMES is designed to provide audio and visual alerts, ensuring prompt responses to potential threats indicative of a fire.

To further enhance the attractiveness of the system towards a larger population, the flame detection system is built to function in varying environmental conditions, utilizing adaptive thresholds and automatic calibration to adjust to minor changes in light levels and ambient light noise. This makes the FLAMES system ideal for confined spaces such as laboratory environments.

FPGA, MCU & Pi Integration – Basic Goals:

The FPGA, MCU, and Raspberry Pi integration in the fire detection system provides distinct and complementary roles in managing hardware communication. The FPGA is responsible for flag synchronization and data analysis, as outlined in the software section, and the Raspberry Pi communicates with the CMOS sensor via CSI connector, while the MCU coordinates interactions with various hardware components. Communication between the FPGA, MCU, and Raspberry Pi is facilitated via GPIO bit-signaling, ensuring efficient real-time data transfer for the FLAMES system.

The MCU serves as a communicator, data logger, power manager, and alert trigger within the system. The MCU employs Pulse Width Modulation (PWM) to interface with the alarm system, activating the buzzer and LED when fire detection is confirmed by the FPGA. It also processes input from a button to initiate the threshold baseline process.

For precise data acquisition, the MCU connects to the photodiode array through its ADC pins, enabling it to read analog signals from each photodiode's output. This integration ensures accurate and reliable fire detection within diverse operational environments.

Thermistor – Stretch Goal:

Adding temperature feedback to FLAMES can be beneficial as it will allow for verification of results obtained by the photodetectors. When scoping out temperature detection hardware, two items come to mind. Thermistors and thermocouples. We will begin with discussing the latter. The thermocouple is a temperature detection device capable of detecting the proportional change in voltage between two dissimilar metals that have been electrically bonded together [8]. Thermocouples tend to be less accurate due to the conversion from millivolts to a reading in temperature. Although thermocouples may not be as responsive as thermistors, they excel at operating on extremums of varying conditions. An hermetically sealed thermistor, which detects the change in resistance per degree

Celsius are ideal for rapidly changing environments [8]. or the FLAMES project, a thermistor is an optimal choice due to its precision and responsiveness to rapid temperature changes. It will be integrated into the system's front fascia to continuously monitor ambient temperature and transmit data via a standard communication protocol such as I2C. This temperature data will complement ambient intensity readings, aiding in baseline environmental detection. When a significant temperature increase exceeds the calibrated noise floor, the FPGA can issue a stop command to the motor, providing a more efficient method for halting system movement.

Engineering Components

Optical Engineering requirements specification for the components that will be used in this project to build the envisioned system.

Table 1. Optical Components Specifications

Discipline	Component	Parameters	Specifications	Units
Optical	Plano Convex Lens	a) Focal Length b) Diameter c) Coating d) Material	a) 10mm b) 75mm c) No d) N-BK7	a) mm b) mm c) – d) –
Optical	Asphere 354105-A	a) Focal length b) Diameter c) Radius of curvature d) Coating	a) 5.5 b) 7.2 c) -3.21 d) BBAR	a) mm b) mm c) mm d) –
Optical	Plano Convex Field Flattener Lens	a) Focal length b) Diameter c) Radius of curvature d) Coating	a) 20 b) 9 c) 10.3 d)BBAR	a) mm b) mm c) mm d) – e) –
Optical	Silicon Photodiode	a) Active area b) Junction Capacitance c) Operable Wavelength Range d) Rise Time	a) 10 b) 375 c) 350-1100 d) 65	a) mm ² b) μF c) nm d) ns
Optical	Dual visible, Infrared Lux detector	a) Active Area b) Dynamic Range c) Communication Protocol type d) Irradiance e) Responsivity Visible Irradiance f) Responsivity Infrared	a) 1 b) 600M:1 c) I2C d) 3513.5 e) 4406	a) mm ² b) – c) – d) $\frac{\text{Counts}}{\frac{\mu W}{cm^2}}$ e) $\frac{\text{Counts}}{\frac{\mu W}{cm^2}}$

Optical	Raspberry Pi GSC	a) Optical Format b) Sensor Readout c) Mounting Type d) Pixel Size e) Resolution f) Output	a) 1/2.9 – 6.33 dia b) Global Shutter c) CS-Mount d) 3.45 x 3.45 e) 1.58 f) RAW 10	a) mm b) – c) – d) μm e) Mega Pixels f) –
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Table 2. Computer Engineering Components Specification

Discipline	Component	Parameters	Specifications	Units
Computer	Raspberry Pi 5	a) Processor b) Memory (RAM) c) I/O Pins utilization d) Power Input	a) 2.4 b) 8 c) 3/40 d) 5, 5	a) GHz b) GB c) count d) V, A
Computer	ESP-WROOM-32D (ESP32 Module)	a) Processor Frequency b) Memory (RAM) c) Flash Storage d) I/O Pins utilization e) Power Input	a) 240 b) 520 a) 4 b) 14/34 c) 3.3	a) MHz b) KB c) MB d) count e) V
Computer	BASYS3 Dev. Board with Artix-7 FPGA Chip	a) Logic Cells utilization b) Block RAM c) Clock Frequency utilized d) Flip-Flops utilization e) I/O Pins utilization f) Operating Voltage Range g) Global Buffers utilization h) Total On-Chip Power i) Power Input	a) 8/20,800 b) 0 c) 100 d) 12/41,600 e) 8/106 f) 1.2-3.3 g) 1/32 h) 0.072 i) 5	a) count b) count c) MHz d) count e) count f) V g) count h) W i) V
Computer	Macronix MX25L3233FMI-08G BASYS3 SPI Flash memory	a) Maximum Operating Frequency b) Operating Voltage Range c) Maximum Active Current (ICC) d) Standby Current (ISB2) e) Data Retention Age	a) 133 b) 2.65-3.6 c) 17 d) 20 e) 20 @ 85°C	a) MHz b) V c) mA d) μA e) years

Table 3. Electrical Engineering Components Specification

Discipline	Component	Parameters	Specifications	Units
Electrical	Nema 23HS22-1006S	a) Step angle b) Holding Torque c) Rated Current/phase d) Voltage e) Type	a) 1.8 b) 0.9 c) 1 d) 7.4 e) Unipolar	a) Degrees b) Nm c) A d) V e) -
Electrical	DRV8825 Motor Driver	a) Max Current b) Voltage Range c) Micro steps d) Resolution	a) 2.2 b) 8.2-45 c) 1/32 d) 0.05625	a) A b) V c) Micro steps d) degrees
Electrical	ADS 8319 ADC	a) Resolution b) Sampling Rate c) Input Voltage Range	a) 16 b) 500k c) 0-5.5	a) Bit b) SPS c) V
Electrical	Kingbright L-934SRD LED	a) Forward Voltage b) Current Drawn c) Luminous Intensity	a) 1.8 b) 20 c) 600	a) V b) mA c) mcd
Electrical	Mallory Sonalert PS-12 Buzzer	a) Sound Output b) Operating Voltage c) Resonating Frequency d) Type	a) 85-100 b) 5-15 c) 2.8k d) Active	a) dB b) V c) Hz d) -
Electrical	TS02 Tactile Switch Push Button	a) Rated Voltage b) Rate Current c) Operating Force	a) 1-12 b) 0.01-50 c) 1.1-2.1	a) V b) mA c) N
Electrical	LM2679 Voltage Regulator	a) Max Output Current b) Switching Frequency c) Input Voltage Options d) Output Voltage Options	a) 5 b) 260k c) 8V-40V d) 3.3-37	a) A b) Hz c) V d) V
Electrical	LeTaoXing Power Supply	a) Input Voltage Rating b) Output Voltage d) Output Current	a) 100-240 b) 12 c) 8	a) VAC b) VDC c) A

2.3.4 Software

Fire Detection Analysis – Basic Goals:

The FPGA and MCU implement an initial three-layer detection system to verify whether a detected light source is a fire before issuing an alert. The first layer performs an EMA-based baseline analysis, adaptive thresholding, and Z-score anomaly detection to establish

environmental context. This is followed by temporal analysis to confirm that the signal is sustained and not a transient anomaly. Frequency and wavelength characteristics are then extracted via FFT on intensity data to identify fire-like patterns.

A third detection layer is handled by the Raspberry Pi, in parallel with the temporal analysis, which uses a CMOS sensor with a custom imaging lens to extract YCbCr color data from the light source. This format enables effective discrimination of fire by isolating luminance and chroma components, allowing accurate identification of red, orange, and white hues common to flames, even in low-light environments.

Analysis Display with Third-Party Compatibility – Stretch Goal:

As a stretch goal, we propose connecting the system to a PC via USB to visually display trigger logs from the fire detection system. Each time the two layers of analysis confirm a fire; the system will log the analysis data and conclusions. These logs could be further utilized for error-checking and, potentially, for training machine learning models to create more optimized and reliable detection systems with predictive capabilities. The logs would include the time of data collection, the range of data collection, and a corresponding wavelength/frequency/intensity vs. time plot.

Machine Learning Pattern Matching – Stretch Goal:

An additional stretch goal is to integrate a detection layer leveraging pattern matching through a machine learning algorithm trained on relevant data. This enhancement would enable the fire detection system to analyze input data and adapt to diverse scenarios and user-provided environments, thereby improving accuracy over time. Specifically, in our case, the system would identify trends in frequency and wavelength plots over time, derived from prior Fast Fourier Transform (FFT) conversions of intensity data. Notably, this training and adaptation process could occur during regular operation, removing the necessity for a separate training environment.

2.4 Required Specifications

Specifications:

Table 4. Specification of Optical Based Fire Detection System

Fire Detection System	
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	< 0.186 m ²
FPGA	
Logic Elements (LUTs)	33,280 LUTs
Signal Processing Capacity	(DSP Slices Unit)

On-Chip RAM (BRAM)	1,843,200 bits (1.8Mbits)
I/O Pins	106 Pins
Clock Management	Mixed-Mode Clock Manager (MMCM) and Phase-Locked Loop (PLL)
Internal Communication Interface	I ² C
External Communication Interface	(USB – Design Specific)
Supply Voltage	0.95V – 1.05V
Memory Type	SRAM
Maximum Supported Clock Frequency	464 MHz
Communication Error Handling	ACK/NACK for I ² C
Optoelectronic / Lens System	
Custom Imaging System Full Field of View	At least 66-Degree Full Field of View
Photodetectors Focus Spot Size	0.5 – 10 mm
Optoelectronics Detection Working Distance	0-1 meters radially

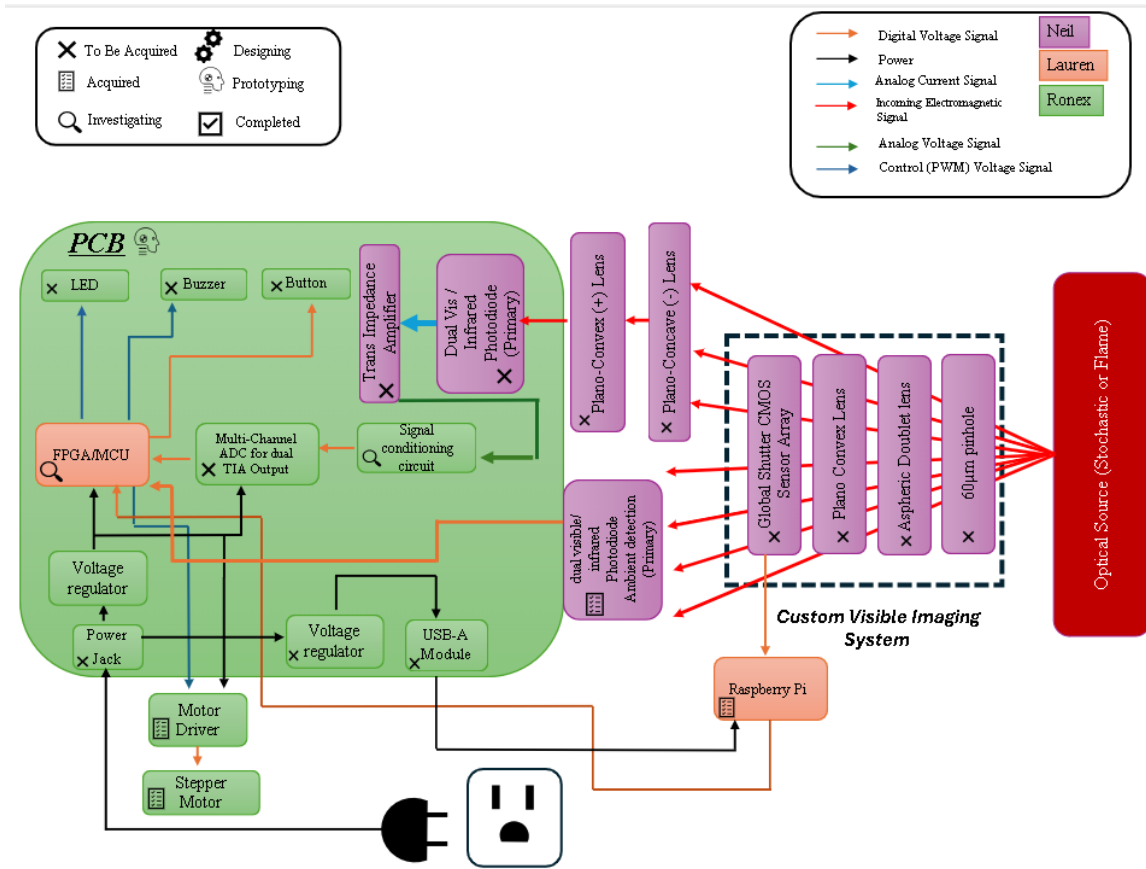


Figure 1. System Hardware Diagram by Authors

FLAMES hardware system diagram is shown above. This diagram demonstrates the core hardware components needed for FLAMES to conduct its detection. Separated by color, are the contributions by discipline. The arrows demonstrate the flow of detection, originating at the red “Source” on the right-hand side.

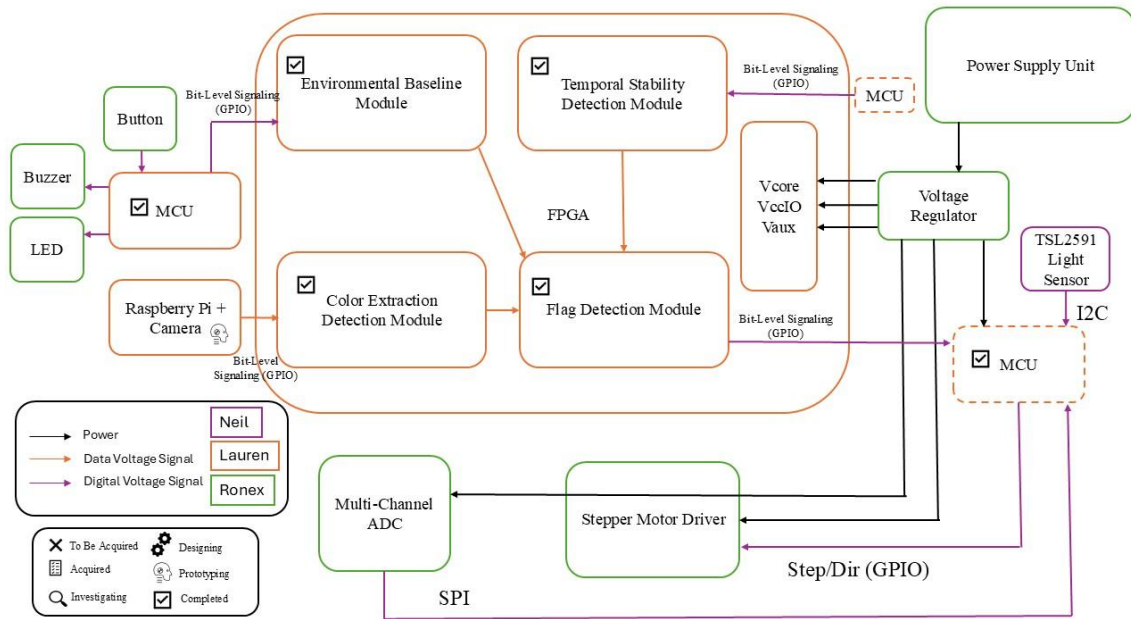


Figure 2. FPGA Hardware Diagram by Authors

This diagram illustrates the setup of FPGA conceptual modules for analysis and the integration of FPGA components with electrical hardware for power and control specifications.

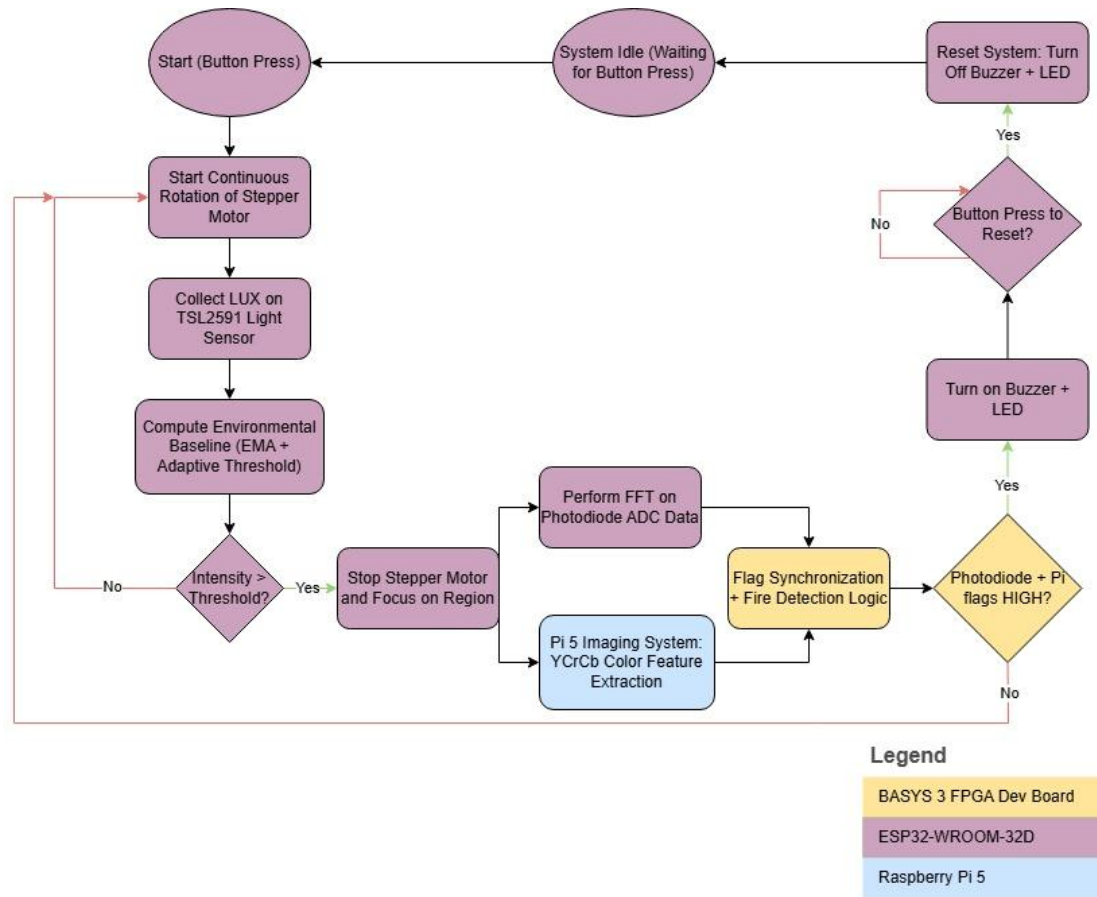


Figure 3. Software Flowchart by Authors

The Software Flowchart outlines the process FLAMES follows for detection, including multiple layers of analysis, motor control software, and alarming mechanisms through a buzzer and LED for the MCU and FPGA.

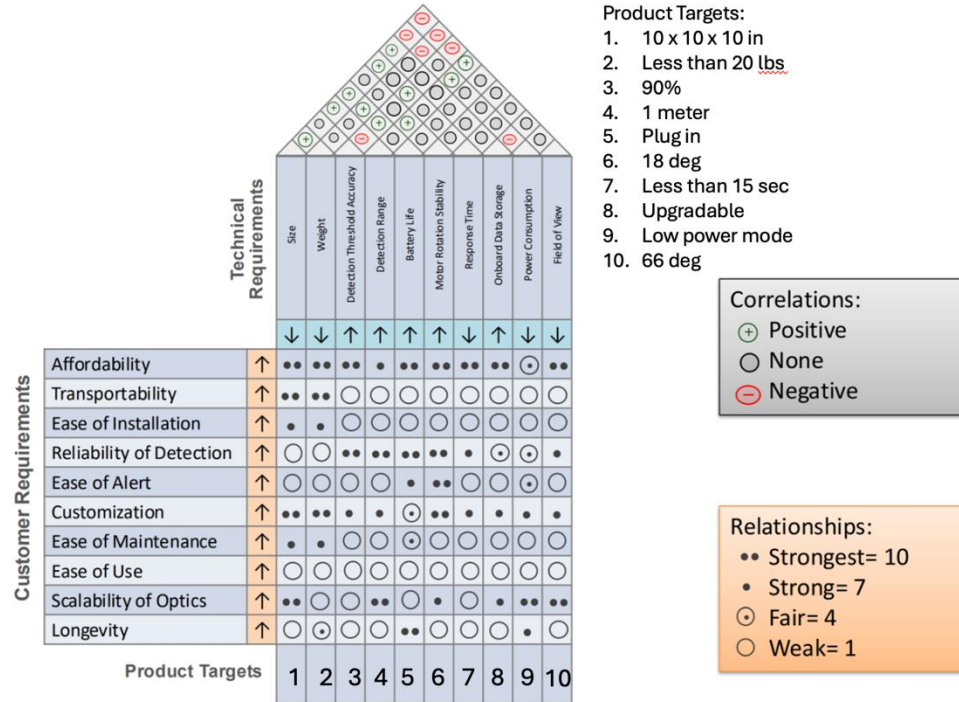


Figure 4. House of Quality

Pictured above is the house of quality which provides a visual aid of engineering characteristic tradeoffs. The left-handed columns depict features that are deemed important to the end user. The columns located at the top of the table demonstrate the features that could potentially be traded off during engineering parameter considerations.

2.5 Optical Hardware Description

2.5.1 Infinite Object Focusing Lens Assembly

The optical system employed in FLAMES is designed to shape the impinging wavefront from the detected source, ensuring precise light collection and focusing. For fire detection within the visible wavelength range, BK7 glass has been selected as the primary lens material due to its high optical clarity, cost-effectiveness, and versatility. As discussed in Chapter 2, infrared and ultraviolet optical materials differ significantly in their properties, but BK7 remains an optimal choice for visible-light applications. Its availability in various focal lengths and diameters allows for a more tailored optical design, optimizing wavefront shaping and light collection. The lens system in FLAMES must effectively capture light from sources within a 0 to 2-meter range and focus it onto a 10 mm² detector, necessitating precise optical design considerations. The initial design consists of a three-lens configuration, incorporating two plano-convex lenses and one biconvex lens. The first lens, a large-diameter plano-convex collection lens, is responsible for efficiently gathering light, with its exact focal length and optical power to be determined through Zemax simulations.

The second lens forms a relay lens system, positioned relative to the focal point of the first collection lens to collimate the light before it reaches the final focusing optic. The third lens, a biconvex focusing lens, is selected for its ability to refine the wavefront and focus the light to approximately 10 mm, aligning with the detector's active area. This multi-lens configuration ensures optimized wavefront shaping, improved signal collection, and enhanced detection accuracy, making it well-suited for the system's fire detection objectives. Through rigorous simulation and precise alignment, the lens system will be fine-tuned to maximize optical efficiency, ensuring that the detected light is effectively concentrated onto the sensor for accurate analysis.

2.5.2 Focusing Lens System Schematic

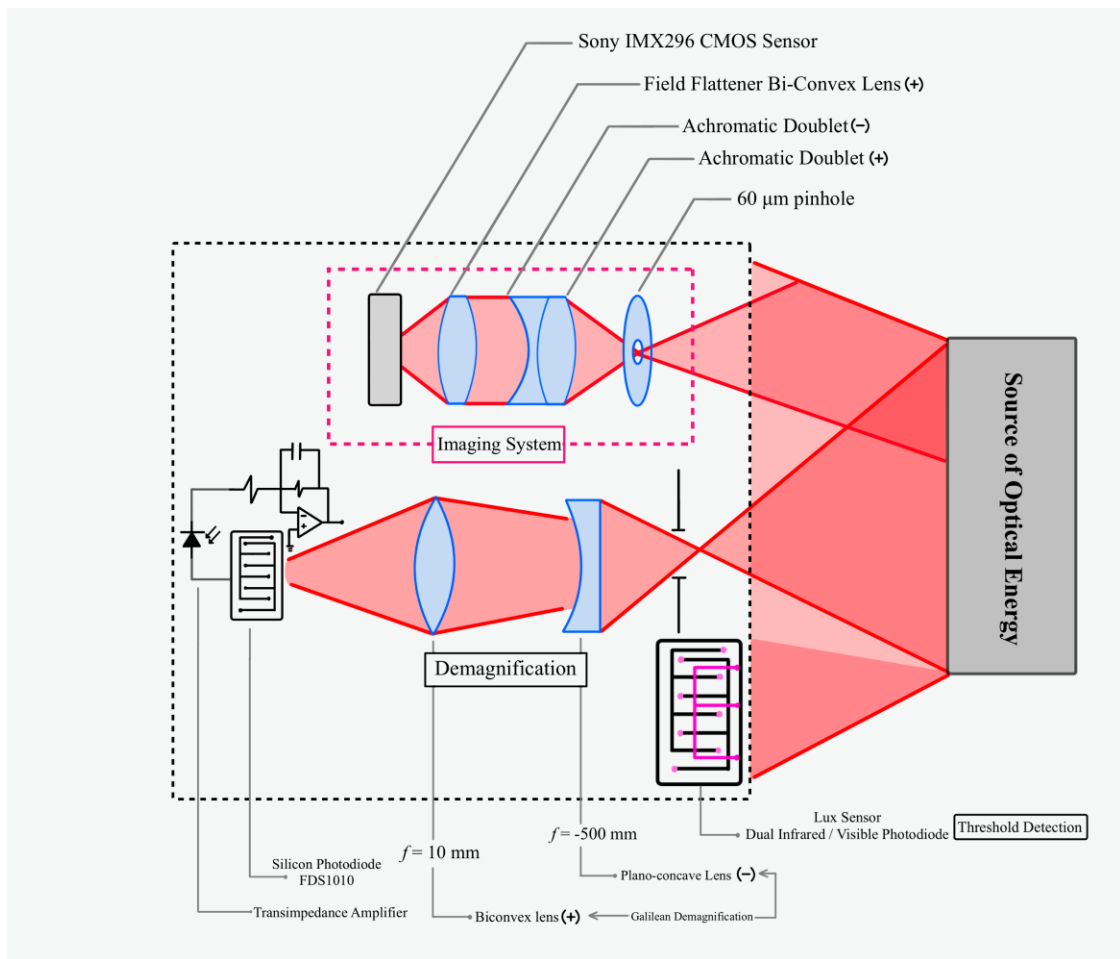


Figure 5. Optical System Schematic

Top view of lens system showcasing the customized imaging system, demagnification system, and threshold detection optoelectronics. Shown here is the lens system with descriptions of focal lengths and distribution of optical energy from the Lambertian source.

The lens system outlined in Section 2.5.1 is depicted in Figure 5 illustrated, a portion of the light emitted from the source is directed toward the ambient light detection silicon photodiode, labeled “Unfiltered”. At this interface, the incident light generates a photocurrent, which is then converted into a voltage signal using a transimpedance amplifier. The ESP32 processes the intensity data from this unfiltered photodiode and compares it with the intensity measurements obtained from the filtered photodiode positioned behind the wavelength-selective filter. This comparison enables precise differentiation between stochastic light sources and fire emissions based on spectral characteristics. In order to convert the output signal of the photodiode from a current signal to an input voltage signal, a transimpedance amplifier is needed in addition to an analog to digital converter. The transimpedance amplifier is comprised of a feedback resistor and parasitic capacitor which are electrically connected to an operational amplifier. By fine tuning the gain of the operational amplifier, the photocurrent that was previously in the micro ampere range can now be converted into the volts range at the input of the ESP32.

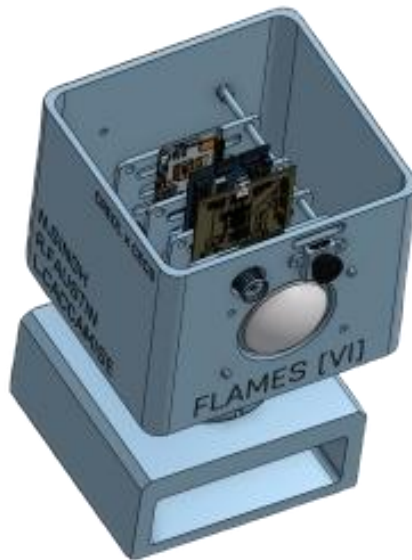


Figure 6. 3D Rendering of Enclosed Unit

3D rendering of enclosed system with positions of lenses and filters labeled. To ensure that the system is portable, a space efficient design was created that allows for the lenses to be protected while housing all electrical peripheral components.

2.6 Photodiode Selection – Wavelength Influence

Flames tend to emit light with a dominant wavelength range of 400 to 800 nanometers in the visible spectrum bleeding into the near infrared, corresponding to its characteristic red, blue, and orange hues. While fire also emits radiation strongly in the near-infrared (NIR) region, the focus of this project is specifically on detecting visible light emissions and excluding radiation in the shortwave infrared (SWIR), midwave infrared (MWIR), and longwave infrared (LWIR) regions, which fall outside the detection range of the selected

photodiode. This decision allows the system to concentrate on the visible spectrum while avoiding the complexities associated with longer-wavelength infrared detection.

The choice of photodiode is critically tied to the wavelength range the team aims to detect. Silicon photodiodes are ideal for this application because of their high sensitivity in the visible (400–700 nm) and NIR (700–1100 nm) regions, particularly aligning with the wavelengths emitted by fire. By tailoring the photodiode to this specific spectral region, the system can achieve both cost-efficiency and effective performance in detecting firelight.

A key factor in differentiating flames from stochastic sources is the variation in their frequency characteristics. Stochastic sources such as sparks caused by grinding, emit across a broad spectrum and often exhibits distinct temporal intensity fluctuations compared to firelight. These differences are critical for distinguishing between the two phenomena. To better understand this, the team investigated the frequency domain characteristics of fire and stochastic sources by simulating their emissions. The figures shown below present the results of the time-domain analysis. These figures show the temporal intensity fluctuations characteristic of fire and welding, which are used to extract their respective frequency profiles. By analyzing the resulting intensity peaks, the team aims to quantify how the frequency characteristics of the stochastic sources differ from those of fire. This analysis not only validates the system's ability to distinguish between the two but also forms the basis for optimizing the detection algorithm. Further investigation will focus on leveraging these frequency characteristics and intensity fluctuations to refine the system's thresholding and decision-making capabilities, ensuring accurate distinction between fire and stochastic sources. This distinction is essential for the successful operation of the detection system in environments where both phenomena may coexist.

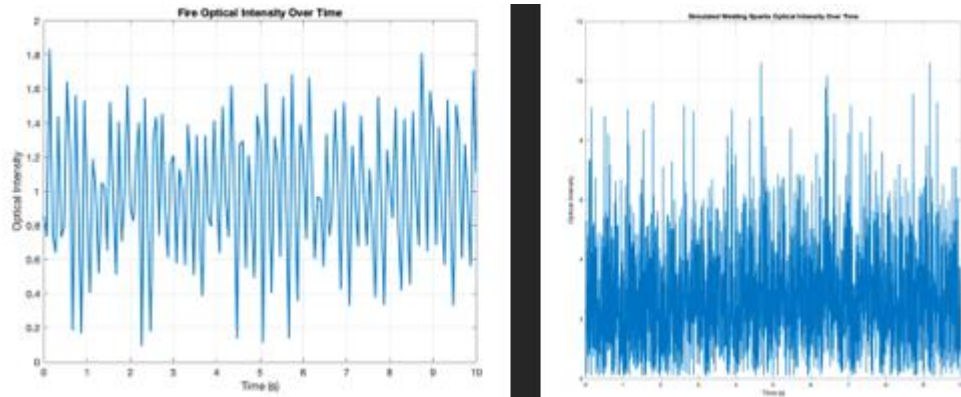


Figure 7. Flame and Sparks Temporal Characteristics

The figure above pictures the expected intensity profile fluctuation of a flame after being focused onto the rear filtered photodetector. A shown the signal seems to be relatively periodic and is indicative of a lower energy spectral density. The Rightmost image shows a higher frequency stochastic source (i.e. welding) indicative of a higher energy spectral density.

Although the patterns vary slightly in time domain, doing the Fourier transform reveals that the frequency patterns are governed the source of optical emission. Another signal processing method that can be employed is evaluation of the energy spectral density of the gathered signals. The energy spectral density of a signal is found by squaring the magnitude of the Fourier transform of the signal. The energy spectral density reveals key differences about the spectral energy distribution and the dominant frequencies. In theory, stochastic sources should render non-periodic after evaluating the ESD distribution. On the contrary, sources that are periodic in nature are taken to be symbolic of flames.

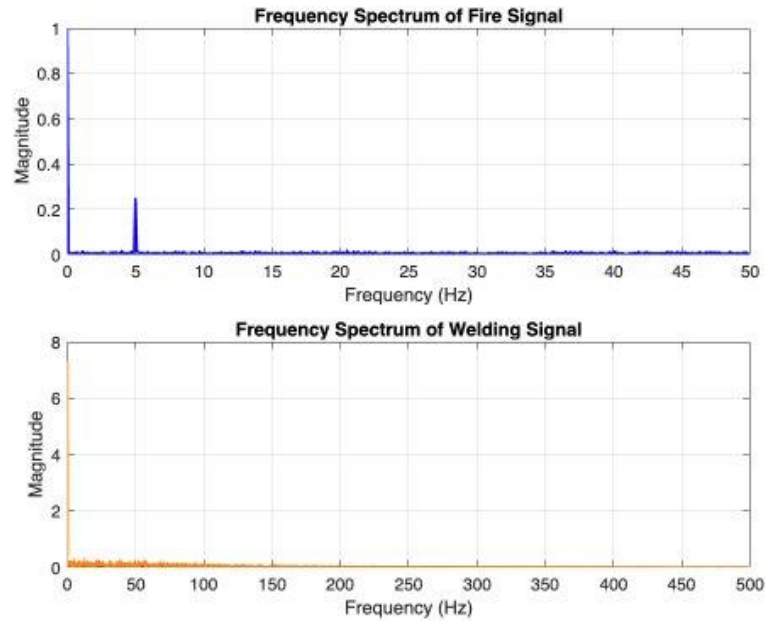


Figure 8. Frequency Domain Representation

The frequency domain explicitly shows a difference in peaks between stochastic sources and flames. This is governed by the intensity versus time relationship. Further signal processing techniques such as evaluation of the energy spectral density can enable more concrete determinations of how the signal behaves and allow us to characterize the type of source increasing the overall accuracy of the system.

A red filter bounded between 600-700 nm can be employed as a bandpass filter to selectively allow light components containing red photons to pass through. This filter effectively isolates the red wavelength region, corresponding to the dominant emission range of firelight, while blocking other wavelengths, such as those associated with sparks in the blue and white regions (400–475 nm).

By allowing only the filtered red photons to reach the photodetector, the system ensures that the photocurrent generated on the secondary filtered photodiode is primarily influenced by light emissions characteristic of fire. This targeted approach not only enhances the detection system's sensitivity to fire but also reduces interference from other optical emissions, such as welding sparks or ambient light, that may otherwise contribute to noise in the detection signal.

The inclusion of the wavelength specific bandpass filter, serves as a critical step in refining the system's selectivity, enabling it to reliably distinguish between fire and other high-intensity stochastic light sources in the environment.

Chapter 3 – Research on Current Technology

3.1 Broadband Source Lens System

3.1.1 Reflecting vs. Refracting Optics – High level Overview

The primary goal of the primary lens assembly is to capture light from a broad range of wavelengths caused by either stochastic sources or flames. To collect enough light, we considered the use of reflecting or refracting optics. In this section, I will specifically be focusing on the associated pros and cons of using reflective optics (parabolic mirror) versus the use of refractive optics (lenses). The project aims to collect light up to 2 meters away, meaning that a large collection diameter will be necessary regardless of the choice between refractive or reflective optics. I will first focus on the analysis of the parabolic mirror. The 12'' parabolic mirror from Edmund Optics (stock number #53-875) has a large diameter which satisfies the project need for large light collection area. This mirror also includes a short focal length at 3'' which is ideal for detector placement. Parabolic mirrors excel at focusing light to a singular point without introducing spherical aberration which can complicate detector placement. The mirror in consideration although nearly satisfactory, comes with several negative attributes. Due to the large size of the mirror (12''), mounting and aligning the optical axis with peripheral detectors will be difficult. It should be noted that the mirror selected for analysis includes a 1'' through hole for use in a Cassegrainian telescope. Currently, there are no commercially available kinematic style mounts rated for a 12'' parabolic mirror for purchase.

Refractive optics, broadly speaking lenses, are commercially available in sizes ranging from 0.5mm to 75mm. Not to mention, lenses are available in different geometries allowing for the light being focused to be shaped by the lenses and focused via the combination of multiple lenses. For the scope of this project, we require that light collection efficiency be maximized. The ideal solution to maximize light collection efficiency would be to utilize a large area parabolic mirror. Naturally, parabolic mirrors focus light to a fine point and do not suffer from chromatic aberrations. The practical solution is to utilize a lens system. As a broad statement, the types of lenses used in this design shall prioritize light collection efficiency (focusing system) and minimization of chromatic aberrations in the imaging system. Refractive optics, although more expensive due to the increased number of components, reduce the weight of the system and allow for the unit to be alignment free from the user.

3.1.2 Fire / Spark Light Collection Design

Collection Lens

The Collection lens should ideally be large in diameter, have a short focal length, and have a high numerical aperture. Numerical aperture is a measure of the maximum angle that light can be accepted. In our project, we are aiming to collect light from roughly 2 meters

away and focus it onto a detector that is 100 mm². The formula for numerical aperture is shown below.

$$NA = n \cdot \sin \theta_{max} \quad (1)$$

Because we will be collecting light and the intermediate refractive index is air, we shall neglect the influence that air has on the maximum acceptance angle θ_{max} . Before beginning the comparison, I would like to iterate that there are many combinations of lens geometries, glass materials, and focal lengths. Incorporating a lens with a high numerical aperture, ensures that light emanating from multiple wavelengths and field angles can be transmitted through the system or onto the next optic. Lenses such as plano convex, concave, or biconvex / concave do not typically have high numerical apertures. Standard lenses such as the ones mentioned previously, are not typically manufactured for applications that involve large amount of light collection. Due to the geometry of spherical lenses, they lack the ability to collect large amounts of light. Field angles that originate grossly off axis will not be collected therefore eliminating spherical lens geometry as a viable option.

Aspheric lenses on the contrary are well suited for such applications. Their geometry allows for minimized aberration control. Traditional spherical lenses suffer from spherical aberration. Since the goal of this lens system is not aimed at imaging, the weight that the aberration carries will not severely influence my ending decision. Aspheric lenses also have tighter focus capabilities than spherical lenses. Our goal is to maximize the illumination on the detector. Our object will be relatively far away (2 meters) therefore we will treat our object as if it was originating from an infinite distance. The following equation provides insight into how the focal length of our lens will be chosen. Because of the high numerical aperture capabilities of aspheric lenses, we will be proceeding with the aspheric geometry.

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f} \quad (2)$$

The distance S_1 is the object distance and the distance S_2 is the distance from the lens to the image plane. For the purposes of this project, S_1 is treated as infinity. The distance S_2 is effectively the focal length. To minimize the number of losses, I would like to achieve as short of a focal length as possible. The desired focal length of the focusing system should be roughly 50mm or a little less than 2 inches. Now that I have established some of the main criterion for the optics, I can start narrowing the types of optical elements that shall be used in the focusing lens assembly. Aspheric condenser lenses are well suited for illumination applications. Some of the key features of aspheric condenser lenses include high numerical apertures and fast convergence (lower $f\#$). As mentioned previously, we are aiming to focus onto a 10 mm x 10 mm photodiode. Using an asphere, we can effectively minimize the amount of transverse spherical aberration in which the rays converge at different points in space. Spherical aberration can negatively impact the system and reduce the amount of light energy incident on the photodiode. Aspheric lenses are manufactured in such a way that the light can converge to a single point. The formula for thin a thin lens is shown below.

$$\frac{1}{f} = (n - 1) \cdot \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (3)$$

For spherical lenses, the focal length can easily be calculated, however with aspherical lenses, this formula becomes invalid and is no longer a reasonable approximation. An asphere deviates grossly from a sphere leaving little merit for using paraxial approximations, as the thickness of the lens is not considered. Utilizing software such as Ansys Zemax, we can simulate the focal lengths of different aspheric condenser lenses. Lens 46-244 from Edmund Optics has been chosen for its large diameter (75mm), high numerical aperture, and its short focal length. Paired with the “right” focusing lens, we can begin to simulate the effective focal length of the combined optical system. As shown in Figure 9 The rays do not converge simultaneously on the same image plane.

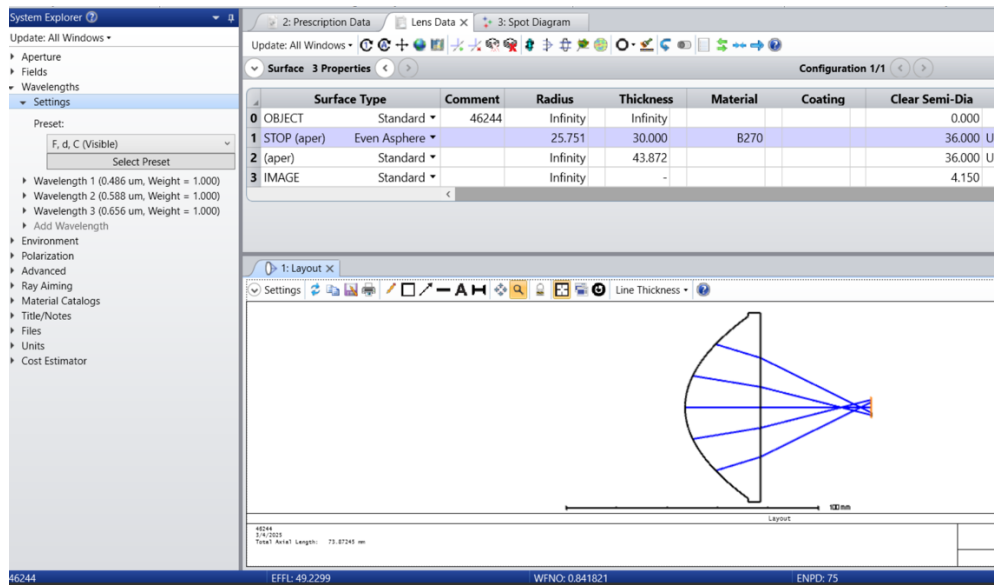


Figure 9. Edmund Optics 46-244 Aspheric Condenser Zemax Simulation

Lens prescription and geometry for Edmund Optics lens 46-244. The wavelengths shown in the Zemax simulation are visible C,D,F line wavelengths. As shown, the rays do not focus on the same image plane as highlighted in the red circle. The Approximate vertical spread of the beam is 6mm.

The estimated radial spot size of the lens is approximately 3.512 mm. This is quite smaller than the size of the detector, giving rise into the necessity of including a focusing optic which will be explained in the following section. Because this project is self-funded, we would like to restrict the system to be two lens elements while still emphasizing that the rays be focused onto the detector.

There are limited degrees of freedom in an optical system regarding designing with off the shelf components. By restricting ourselves to using the 75mm diameter lens with an effective focal length of 50mm, we can simulate the effect that the focusing lens has on the composite lens system. A figure of merit for our composite lens system that we designed

with respect to is the ray spot size and minimization of divergence on the image plane. As shown in the Zemax simulations, we accounted for multiple wavelengths (c,d,f line) and field angles. In doing this, we highlight a more realistic scenario and showcase the degradation of lens performance of the aspheric condenser lens. The spot diagram generated by Zemax is shown below for a better visualization of the ray concentration when imaged from an infinite distance with visible line wavelengths and multiple field angles. The values from this analysis will be used as the baseline for future optimizations with the focusing lens. Table 5 below showcases the specifications of the aspheric condenser from Edmund Optics, simulated spot size via Zemax, and the estimated divergence with visible wavelengths.

Table 5. Edmund Optics Aspheric Condenser Specifications

Specification	46-244 Aspheric Condenser
Effective Focal Length	50 mm
Simulated EFL	49.229 mm
Diameter	75 mm
Geometry	Asphere
Numerical Aperture	0.75
Coating	Uncoated
Zemax Spot size (On-Axis)	3.512 mm radius
Divergence at Image plane	6.5 mm

Focusing Lens

To make the spot size roughly 10 mm in diameter, we need need to introduce another optical element that has the purpose of focusing the light from the first optic onto the 100 mm² photodiode. The main degree of freedom that we have in our optical system is the variation in lens diameter, geometry, and focal length. Once a focusing lens has been chosen, we can begin to vary the distances between the last surface of lens 1 and the first surface of lens 2. This will directly affect the effective focal length of the system and spot size of rays on the image plane (detector plane). Intuitively, the diameter of the second optical element should be large enough such that the rays transmitted from optic 1 are not blocked. Essentially, we do not want to create a field stop by choosing an optic that is so small that light energy is lost. Another crucial consideration is that the optic should not be so large that a larger portion of the clear aperture is not being used to its full capacity.

Galilean Style Demagnification System

A Galilean astronomical telescope system consists of one positive lens and one negative diverging lens, where the distance between the lenses is the sum of their focal lengths. One of the lenses will act as an objective and the other lens will act as an eyepiece. Because I am attempting to focus light from an approximate distance of 2 meters away or 2000 mm, I will need to find an appropriate lens system to accurately demagnify the incident light. The Keplerian system is a simpler system that only utilizes two lenses. For our purposes the fire is approximated to be roughly half a meter in width while our detector is 10mm in width. Using the formula listed below, I can deduce the correct magnification ratio of the

lenses. The ratio of the image size (detector) to the object size (flame or spark) shall be equivalent to the ratio of focal lengths between the positive and negative lenses.

$$\text{Magnification} = \frac{\text{Image Size}}{\text{Object Size}} = \frac{f_2}{f_1} \quad (4)$$

In computing this, I found that the focal length ratio is 50x. This simply means that the focal length of optic 1 shall be 50 times smaller than optic 2 to ensure that I achieve the correct spot size of 10mm on my photodiode. The Galilean telescope system is primarily useful for magnification of objects at far distances. For this project, I will need to ensure that the negative diverging lens is placed ahead of the positive focusing lens. An issue I encountered when sourcing negative lenses was that I am not able to find commercially available negative lenses with a large diameter. Finding positive lenses with a large diameter, and short focal lengths also prove to be difficult to find on the market. Another issue with the Galilean demagnification design is that the system length is governed by the following equation.

$$\text{System Length} = f_{\text{objective}} - |f_{\text{eyepiece}}| \quad (5)$$

In terms of our application, the diverging lens would have to a focal length of roughly -500 mm while the positive lens would need to have a focal length of 10mm while still having a large diameter. Another alternative to combat this issue is by combining a third positive lens to change the effective focal length of the positive lens system. This would require that the lenses be spaced close together such that the distance between them is zero. Using the effective focal length equation below, I am able to find a combination of lenses that satisfies the 10mm focal length constraint.

$$\frac{1}{f_{\text{eff}}} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \quad (6)$$

The total system length would be roughly 490mm or 19.3 inches in length. Despite not being able to find suitable lenses on the market, this would violate our system compactness goal. Although the system would be able to theoretically collect the light from a distance of 2000 mm away, there will be significant losses when the light propagates the 490mm distance in between the lenses. This effectively results in a weaker signal at the interface of the diode. For this reason, I do not believe that the Galilean demagnification system is a feasible option for this project.

3.1.3 Glass Materials

Visible Wavelength Glass Materials

The optical glass materials that we intend on using govern the transmissivity and aberration control that we have over our system. In this section I aim to cover two distinct portions of our project separated by optical design type. Namely, the broadband focusing lens assembly and the imaging lens system that will aid in image acquisition for the global shutter style CMOS sensor. I will begin with the prior. Glass materials are classified by their refractive index and abbe number, which dictate their dispersive and overall performance properties. High refractive index glasses, such as flint glasses provide stronger

bending of light rays but often suffer from the increased chromatic aberration. Conversely, crown glasses which are known for having a lower refractive index and higher abbe number exhibit lower dispersion making them ideal for applications requiring minimal chromatic spread. For the broadband focusing lens assembly, the selection of glass must account for efficient light transmission across a wide spectral range. Since our system is designed to detect visible and near-infrared light, we require a material with high transmittance and low absorption in these wavelengths. Optical-grade fused silica is a strong candidate due to its exceptional UV to near-infrared transmission, low thermal expansion, and resistance to environmental degradation [9]. Alternatively, N-BK7, a widely used borosilicate glass, offers a balance between cost and optical quality, making it suitable for broadband applications.

The imaging lens system, which feeds light to the global shutter CMOS sensor, demands materials that minimize aberrations and provide a well-corrected image across the sensor plane. In this case, an achromatic doublet, composed of a combination of crown and flint glass elements, will help mitigate chromatic aberrations and improve overall image sharpness. Additionally, anti-reflective coatings will be applied to the lenses to maximize transmission efficiency and reduce unwanted reflections. By carefully selecting and optimizing the glass materials for both optical subsystems, we ensure that our FLAMES system achieves high efficiency in light collection, focusing, and imaging, ultimately enhancing its ability to distinguish between fire and other sources of bright, transient light. Table 6 highlights some of the key takeaways and project specific information that will aid us in determining the best glass material to use for both types of optical systems.

Table 6. Comparison of Glass Material Types

Material	Refractive Index	Abbe Number	Transmission Range	Application
Fused Silica	~1.46	High, (low dispersion)	UV-NIR	Broadband focusing lens assembly
N-BK7	~1.51	Medium (moderate dispersion)	VIS-NIR	Alternative due to Fused Silica due to cost
Flint Glass	~1.6 – 1.8	Low (highly dispersive)	VIS	Achromatic doublet pair for imaging system
Crown Glass	~1.5 – 1.54	High (low dispersion)	VIS	Achromatic doublet pair for imaging system

3.1.4 Photodiode Detector Selection

Semiconductor Material Choice

Initially, when first deciding on the detector choice, the team was between two semiconductor materials. The first material that was considered was InGaAs, which has exceptional responsivity for wavelengths between 900 nm and 1700 nm [1]. When observing a flame, we can see that the fire has strong emission in the visible spectrum. We also feel the thermal radiation being emitted by the fire. The peak wavelength of the

responsivity graph occurs at 1550 nm. Considerably, we are not able to use commercially available InGaAs photodiodes because they are generally more expensive and have smaller active areas than silicon photodiodes. Although, the radiation can be detected by the InGaAs photodiode, this project does not aim to detect the far infrared regions. Naturally, the next choice of material is Silicon. Silicon is an ideal choice because it is well suited for visible detection applications. Silicon has a peak responsivity at wavelengths ranging between 850 and 950 nm with a responsivity of 0.6 A/W [11], and covers wavelengths between 350 nm and 1100 nm. The F.L.A.M.E.S project aims to detect the visible spectrum predominantly, wavelengths between 600 nm to 900 nm. Silicon will be better suited and provide better responsivity when detecting fires or sparks. Another benefit of using silicon is that it comes in larger sizes. Below, we have discussed two choices of diodes, both of which have a large active area of 10mm².

Table 7. Comparison of Silicon and InGaAs Semiconductor Substrates

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

FDS1010

The Thorlabs FDS1010 diode is a silicon photodiode that has an active area of 10mm by 10mm. Because the diode is silicon, the wavelengths that are covered range from 350 nm to 1100 nm. The peak responsivity of 0.725 A/W occurs at a wavelength of 970nm. The flames project requires that ambient light and light from the stochastic source and or flames be impingement on the photodiode. The main attraction to the FD1010 is the large active area. The responsivity will not be a deciding factor because it is a function of the material and not the diode. Focusing broadband light from a distant source will be quite difficult leading us to place a higher importance on active area. The next specification that is valuable to the project is the junction capacitance. A higher junction capacitance limits the speed of detection and may also limit the bandwidth of the circuit. The FDS1010 has a junction capacitance of 375pF when biased at 5 volts. Ideally, we would like to have the junction capacitance as low as possible to increase the sensitivity and speed of detection. The photocurrent data from the diode will need to be interpreted and processed by the

ESP32 to detect the threat in a correct and timely manner. A low dark current would also enable the photodiode to have more sensitivity in lowlight conditions. The F.L.A.M.E.S unit will be placed in a dark location and is ideal for lowlight detection. The FDS1010 has a dark current of 5 volts at 600 nano amperes for context. Other important considerations are the rise time response and bandwidth. The rise time is a quantitative value that measures the time it takes the signal to progress from 10% to 90% of its final value. Having a faster rise time would allow for faster signal processing and reduce the time delay between initially detecting the threat and classifying it. When detecting sparks especially, it is imperative that the rise time be low. The last factor that will be considered is the signal to noise ratio. Table 8 displays the specification parameters from the FDS1010 datasheet. Table 9 displays the formulas that will be involved in calculation. It should be noted that values have been picked to reflect conditions like when the system will be demonstrated, thus we have not used peak responsivity values in calculation.

Table 8. Specification Parameters of FDS1010 Silicon Photodiode

Specification	Variable	Suggested Value
Junction Capacitance	C_j	375 pF
Responsivity	R	@ 700 nm $\rightarrow$ 0.48 A/W
Dark Current @ 5V	I_d	600nA
Circuit Bandwidth	F_{BW}	Calculated: 4244.12KHz
Rise Time ($R_L = 100$ Ohm)	t_R	Calculated: 82.7 ns
Output photocurrent	I_{Photo}	Calculated: 4.8 mA
Signal To Noise Ratio	SNR	Calculated: 27.42
SNR dB	SNR_{DB}	Calculated: 104.72 dB

Table 9. Empirical Formulas used in Calculation of Estimated Photocurrent and SNR

Specification	Formula
Circuit Bandwidth	$f = \frac{1}{2\pi RC} \quad (7)$
Rise Time	$t = \frac{0.35}{f} \quad (8)$
Output Photocurrent	$I = R \cdot P \quad (9)$

The calculated results showcase the photodiodes performance in relation to our project. The bandwidth of 4.24 megahertz allows for rapid sparks to be detected and processed on the backend by the ESP32. A response time of 82.47 ns indicates that the circuit will respond to changes in intensity quite rapidly especially if sparks occur in light bursts in the microsecond pulses. With flames pulsing in the millisecond range we should ideally have the capacity to resolve the signal and distinguish between the fire and the sparks. Although

the photocurrent is in the milliamp range, the inclusion of a transimpedance amplifier circuit will allow for the signal to experience gain and become amplified.

FDS10X10

The FDS10X10 photodiode from Thorlabs is very similar in size to the FDS1010. The 10x10 features a 100mm^2 area, making it comparable to the FDS1010. The way in which we chose the photodiode follows the same structure of priority as stated in the previous paragraph. One of the most significant changes on the 10x10 is that its peak responsivity of 0.62 A/W is achieved at 960 nm. While the delta in wavelength ranges may not be significant (10 nm), the responsivity delta between the FDS1010 and the FDS10X010 is significantly large. The following Table 10 displays mock values that are closely related to trial environment conditions. For calculation purposes, we made the assumption that there is 10 mW of incident power on the photodetector. Much like the comparison done in the previous section, I aim to highlight the key performance metrics of the FDS10X10 against the FDS1010. The same formulas referenced in Table 10 will be used in the upcoming analysis.

Table 10. Resultant values of Estimated Calculation

Specification	Variable	Suggested Value
Junction Capacitance	C_j	380 pF
Responsivity	R	@ 700 nm $\rightarrow$ 0.42 A/W
Dark Current @ 5V	I_d	200 pA
Circuit Bandwidth	F_{BW}	Calculated: 4188.28 KHz
Rise Time ($R_L = 100 \text{ Ohm}$)	t_R	Calculated: 83.57 ns
Output photocurrent	I_{Photo}	Calculated: 4.2 mA
Signal To Noise Ratio	SNR	Calculated: 25.81
SNR dB	SNR_{DB}	Calculated: 101.61 dB

Table 11 displays the numerical results of the FDS1010 and the FDS10X10 photodiodes. The results show that the bandwidth, rise time, and SNR are not major differentiating factors between the diodes. The FDS1010 provides marginally better sensitivity performance and SNR than the FDS10X10. One factor that has not been mentioned is price points of the photodiodes. Due to the performance specifications of the diode being closely related, the price point will ultimately have a larger impact on our choice of photodiode. We have elected to proceed with the FDS1010 for its price point primarily as its performance does not deviate drastically from the FDS10X10 with simulated values.

Table 11. Silicon Photodiode Selection

Specification	FDS10X10	FDS1010
Price	\$125.92	\$61.18
Circuit Bandwidth	4188.28 KHz	4244.12KHz
Rise Time	83.57 ns	82.7 ns
Output Photocurrent	4.2 mA	4.8 mA

Signal to Noise Ratio (SNR dB)	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

TSL2591 Lux Sensor Module: Dual Material Detector Module

The TSL2591 lux sensor from Adafruit contains a dual photodiode arrangement. The photodiodes are meant to capture visible light and infrared light. The first photodiode while not specified in the datasheet is a silicon diode rated for visible to near infrared wavelengths. The second diode is rated for infrared wavelengths. The module operates on the principle that the two intersecting infrared regions will cancel therefore leaving the user with visible lux information. Lux is abbreviated for luminous flux which measures the “incident luminous flux per unit area” [12]. It is important to note that one lux (lx) unit equals one lumen per square meter. Additionally, one lumen (lm) is a unit that measures the amount of visible light emitted by a source. The higher the luminosity of a source the brighter our eyes perceive it. The human eye response to a fire and the human eye response to a spark is noticeably different. The TSL2591 lux sensor essentially simulates a visual response to rapid changes in luminosity. Knowing this, we can combine both pieces of data collected from each photodiode on board and process its lux value independently. The lux of a fire will be different than that of a welding spark for example. Additionally, according to the data sheet, the gain and integration time of data collection can be altered allowing for precision tuning of a sample set. The Silicon photodiodes have a sever drawback in this respect. To process the data faster, we have implemented a specialized op amp that is capable of handling high capacitance photodiodes which may present issues when performing the signal processing on the ESP32. The variable gain and timing ranges allow for detection of lux between 188 μ Lux and 88,000 Lux. Another area where the TSL2591 excels is in its ability to capture data in low light conditions. In our project, we aim to set the scene in a dark environment where at any time, a fire could break out. This type of analysis potential is highly advantageous for our intended purpose. In using the Lux sensor, we can expect to see slower drifts in lux amongst flames and rapid adjustments to the lux values with sparks. On the post processing side, we can use this variation or delta in lux values to establish carefully tailored responses to fires or sparks accordingly.

The TSL2591 has significant dynamic range of 600,000,000:1. This simply means that it can measure extreme low light conditions alongside extreme bright light conditions. The data sheet of the TSL2591 showcases a normalized responsivity versus wavelength graph. From the provided info, I was able to deduce that because of the two-channel response (dual photodiode) the lux values can be tuned regardless of the transmissivity of the glass substrate. This means that our goal of creating a seamless and compact design can be achieved by covering the unit with a glass substrate similar to how infrared LED’s are kept in remote controllers. The module is split into two distinct channels as mentioned before. Channel 0 records the visible and infrared responsivity of the incident light in units of counts per microwatt per square centimeter. Channel 1 solely records the infrared responsivity of the incident light. In the table listed below, I have highlighted some of the key optical specifications that are most comparable to the FDS1010 and FDS10X10. The higher the value of responsivity indicates a merit of how efficient the TSL2591 sensor

converts the irradiance (power per unit area) into digital counts. Therefore, the higher the digital count the more effective the conversion from light energy to electrical energy. By splitting the channels into two, we can still complete the ratio analysis of the infrared regions of the incident light to the visible. When distinguishing flames versus sparks, we cannot ignore the impact that heat may have on our systems readings. With the single photodiode counterpart, thermal effects may skew data while this module effectively enables us to compare the photocurrent generated due to the rise in temperature.

Table 12. Specifications of Adafruit TSL 2591 Lux Sensor

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)	$264.1 \frac{\text{Counts}}{\frac{\mu W}{cm^2}}$
Max Irradiance Responsivity channel 1 (Infrared only)	$34.9 \frac{\text{Counts}}{\frac{\mu W}{cm^2}}$

3.1.5 Imaging Sensor Comparison

CMOS Vs. CCD

The two predominant sensor types commonly available to the market is the CMOS versus CCD architecture. Both devices operate under the same principle that incident light energy (photons) impinge on the array and electrical signals are output. In the CCD array, the electrical charge is shifted per the pixel in comparison to the CMOS where each pixel is read out directly [13]. By not shifting the charge per pixel as in the CCD configuration, the CMOS excels at reading out the information faster. With the inclusion of microlens arrays on the modern CMOS offerings, the sensitivity is enhanced. Higher framerate values can be achieved with the CMOS offering. Our project requires that we have low light sensitivity to be able to image rapid sparks and flames. Ultimately, the decision between CCD versus CMOS comes down to framerate speed, and mitigation of pixel blooming. If the CCD is overexposed the excess charge will be spilled into the neighboring pixels causing defects in the final image. For our project, the intensity of the Flame or spark can vary highly, therefore there is no protection against pixel blooming. In sections 3.1.5.2 and 3.1.5.3, the rolling shutter artifact is explained in depth. The goals and objectives of this project require that the system respond quickly to rapidly changing sources i.e. flames or sparks. The CMOS sensor offers the speed and mitigation of pixel bleed that will enable us to decrease the time in between a threat and conclusively classifying the threat. We would also like our sensor configuration to have low noise sensitivity.

Table 13. CCD Versus CMOS Sensor Functionality

Specification	CCD	CMOS
---------------	-----	------

Pixel Readout Speed	Column-Row / Column-Column readout (Slower)	Parallel Readout per pixel (faster)
Resistance to Blooming	Overexposed pixels Leak charge	Microlenses Array mitigates blooming effects
Pixel Signal	Electron Packet	Voltage
Noise level	Low	High

Raspberry Pi Global Shutter Camera

When searching for an imaging sensor, there are two shutter options that are commercially available. Global shutter and rolling shutter. Rolling shutter cameras read out the sensor line by line. Every line will be read sequentially meaning that if the object that is being imaged moves, there will be a level of distortion induced [14]. On the contrary, global shutter cameras capture light from every pixel at once essentially taking a snapshot of the object at once. Because global shutter cameras read every pixel simultaneously, the distortions are minimized. The total exposure time is also minimized for the purposes of the flames project, we aim to image a moving spark and similarly flame for layered detection. By observation, flames tend to fluctuate less rapidly than sparks making the global shutter option an idea choice. The global shutter offering from Raspberry Pi contains a larger pixel format size of $3.45\mu\text{m} \times 3.45\mu\text{m}$. The larger pixel size enables for more light to be captured by the accompanying optical lenses. Essentially, the global shutter camera is a high-speed photography device. The global shutter camera also utilizes the Sony IMX296 sensor. The optical format size for the IMX296 sensor is 1/2.9 format suggesting that the diagonal measurement is roughly 6.4mm. The Raspberry Pi website states in their product description that the more pixels a sensor contains the more difficult it is to process the resulting image. Downsizing the image and subsequently cropping the image is unnecessary for the global shutter camera [15] due to the image being captured as one frame. The camera sensor shall be paired with lenses that are capable of appropriate magnification and field of view.

Larger format sensors such as the sensor contained in the global shutter camera, also have increased lowlight sensitivity. In general, due to the limited number of pixels, the image resolution of the global shutter camera will be less than that of a sensor containing more pixels. The resolution of the global shutter camera is 1456×1088 compared to the other offerings from Raspberry Pi which will be discussed later. Another important consideration for choosing the right sensor for imaging flames and stochastic sources is understanding the importance of optical size. The Sony IMX296 has a shallow depth of field meaning that it is imperative that the correct optics be chosen to accurately image the object. The Sony data sheet also provides a recommended $f\#$ of $f/2.8$ or larger. The following equation governs the geometry of the lenses that are capable of imaging onto the $3.45\mu\text{m} \times 3.45\mu\text{m}$ sensor.

$$f_{\#} = \frac{\text{Focal Length}}{\text{Lens Dia}} \quad (10)$$

The IMX296 is highly sensitive to over exposure from light. Using a lower $f_{\#}$ lens implies that the diameter of the lens is increased allowing too much light to enter through the

aperture therefore causing overexposure and saturating the image. This said, the IMX296 (Raspberry Pi Global shutter camera) supports smaller diameter lenses. As a package, the global shutter camera offers lower image resolution with the benefit of reduced image distortion. For the benefit of accurately detecting the object, I believe that trading resolution for limited distortion aberration is beneficial. The rolling shutter camera mechanism is explained in the following section.

Raspberry Pi AI Camera

The Raspberry Pi AI camera, as mentioned in the prior section uses a rolling shutter mechanism to capture the object and process the data. The rolling shutter mechanism works by reading out each row of pixels limited by a factor called the line time. This time is commonly on the order of microseconds. The resulting image will have a small-time delay from when the image is captured to when the full image is processed after being transposed row by row. For larger sensors, this can be an issue due to the increased line processing time during calculation [16]. This time delay is mostly present when viewing distorted images caused by motion blur. In the case of F.L.A.M.E.S, we are actively attempting to image a spark or a flame, both of which move quite rapidly. Rolling shutter artifacts can cause ghosting where the object has moved faster than the rolling shutter could process it. The AI camera houses a Sony IMX500. The IMX500 has a 12.3 megapixels sensor capable of higher resolution imaging compared to the 1.58-megapixel global shutter camera. The diagonal image size format is 1/2.3 which is roughly 7.857 mm. The size of each pixel is 1.55 μ m. Using similar reasoning as in the previous section I can conclusively say the following. The resolution of the AI camera will be stark in comparison to the global shutter camera. Due to the smaller format of the sensor, special considerations need to be made when choosing the type of lenses that accompany the sensor. The IMX configuration offers better light collection and wider field of view however, because the sensor format is larger, the depth of focus is shallower.

To take full advantage of the sensor format, accompanying lenses should have a larger numerical aperture, and reduce chromatic aberration. The IMX500 boasts combining an image sensor with a DSP, and on-chip SRAM to enable AI object detection analysis without needing an external server [17]. The IMX500 is capable of classification, detection of multiple objects, and pose detection. Our project can greatly benefit from the use of the IMX500 by classifying spark versus flames. One of the features that stands out amongst others is the semantic image segmentation, where image classification can be done down to the pixel level [17]. Semantic object analysis can be best utilized in applications where the object is not moving rapidly, creating a blurring effect due to rolling shutter artifacts. As stated before, the movement of the flames and rapid frequency fluctuation changes of sparks do not allow us to make the best use of this feature. The lens system that is specially designed for this sensor will need to reduce vignetting, control chromatic aberrations, and avoid diffraction effects. This can be especially challenging given the complexity that is required to image onto a smaller pixel array. Using the AI camera would mitigate the need to use complex software's such as OpenCV for image processing. One potential concern that arises with a higher resolution camera such as the Raspberry Pi camera is the latency impact on the speed of detection. Naturally, one of the limiting factors is the exposure time of the camera [18]. The longer the exposure time, the more light that can be collected, although processing speeds will increase. In the case where the exposure

time is too little, there is a possibility that there will be an insufficient amount of light causing the captured area to not be imaged clearly.

Imaging Sensor Selection

Table 14. Imaging Sensor Comparison Through Product Type – Raspberry Pi AI

Camera Vs. Raspberry Pi Global Shutter Camera

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 μm^2	Yes, larger Pixels 15.5 μm^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 Megapixels
Sensor	Sony IMX500 (AI)	Sony IMX296
Price	\$70	\$50

This table highlights the key aspects of the camera sensor that influence my choice in choosing the best imaging sensor style. The vertical and horizontal field of views have been calculated using the following formula shown below.

$$FOV = 2 \cdot \tan^{-1} \left(\frac{\text{Sensor Dimension}}{2 \cdot EFL} \right) \quad (11)$$

It is imperative that this field of view not be taken as the final field of view. After designing and implementing a customized lens system the field of view specified in the table will vary. The dimensions of the sensor (image) plane will still be important in understanding the field stop size of the imaging sensor. For this projects scope, there is a higher priority placed on the horizontal field of view to be able to detect a wider area such as a shop floor.

3.1.6 Camera Imaging System: Existing Imaging Systems

First Order Telephoto lens

The first order telephoto lens consist of two main lens components a positive lens and negative lens [19]. The telephoto lens system is useful for capturing objects at long distances. In other words, the telephoto lens system has an effective focal length that is greater than its total track length. Recall that in our application, we would like to capture

an image that is between 3 and 5 meters away. While, this may seem ideal for our project's application, the telephoto lens has significant drawbacks. A telephoto lens system has a narrow depth of field, indicating that it is relatively simple to achieve system blur when the subject moves in either direction of plane of best focus [20]. For machine vision applications, a telephoto lens system is not ideal as having background blur can hinder the system's ability to resolve an image carefully and extract meaningful data. In the context of our project, the area in which the fire or sparks can be located can vary between 0 and 2 meters. For best image processing results, the imaging system should be able to tolerate and resolve images that are formed within this distance. As a rule of thumb, the $f_{\#}$ has serious effects on the depth of field. The higher the $f_{\#}$ the deeper the depth of field. The telephoto lens system is not optimized for low light conditions. This configuration may not be suitable because our project aims to be deployed in low light settings. In the upcoming section regarding pinhole cameras, I will explain in depth the importance of depth of field for our application. Telephoto lenses traditionally narrow viewing angles, meaning that they also have relatively lower $f_{\#}$ for fixed $f_{\#}$ systems. Traditional small $f_{\#}$ systems can tolerate less blur as the object deviates from the plane of best focus. In our application, the flame or spark can be anywhere within 0-2 meters as mentioned before, leaving a large margin of error regarding tolerable blur. For this reason, the telephoto lens system will not be ideal for capturing images of the flame or fire for verification.

CCTV Lens System – WFOV

Wide-field-of-view (WFOV) lenses are commonly used in survey and astronomical applications where capturing large portions of the sky or scene is necessary. However, for the FLAMES project, which aims to detect and classify sparks and fires from 3 to 5 meters, a WFOV lens is not the optimal choice. A wider field of view disperses incoming light across a larger sensor area, reducing the intensity of the detected signal and making it harder to resolve fine details of transient light sources like sparks. Additionally, WFOV lenses can introduce optical aberrations such as field curvature and coma, which could distort the appearance of sparks, potentially affecting classification accuracy. Since our system relies on precise signal fluctuations and spectral energy analysis to differentiate welding sparks from fire, a more focused optical design with a moderate field of view is necessary to enhance resolution and minimize background interference. By selecting a lens system optimized for light collection and controlled imaging, we ensure that the FLAMES project achieves accurate and reliable detection of fire hazards in real-world conditions.

A wider field of view also increases the probability of capturing unrelated background light sources, which creates the opportunity to introduce false positives in fire versus spark applications. By limiting the field of view, the system can focus on a specific region, improving detection accuracy by mitigating extraneous light sources. The optical throughput, which is defined by the product of the aperture size and field of view must be optimized for the detection task. WFOV lenses tend to prioritize scene coverage over contrast, which results in a lower contrast to background ration for small high intensity light sources such as sparks.

Pinhole Camera - Achromatic doublet and field flattener lens

An achromatic doublet is a type of lens that reduces the amount of lateral and longitudinal color aberrations present in visible imaging systems. A lens with a higher dispersion

constant called Abbe number is bonded with a lower dispersion lens. This allows for a minimization of lateral color for the composite lens. In chapter 6 I have shown how I design the optimal lens system for imaging while reducing lateral color. Through testing, it is observed that at extreme field angles, there is a larger amount of distortion and field curvature. In chapter 6, this will also be highlighted. To reduce the amount of field curvature, a lens with a positive focal length will be strategically placed close to the image plane to allow for focusing without field curvature. While this system may be ideal for objects that are relatively nearby or within the focal plane, we can extend the depth of field with the inclusion of a pinhole. Depending on the size of the pinhole, we extend the extent of the tolerable blur distance. This physically translates into a system that can tolerate larger deviations from the rated image plane. Combining the achromatic doublet, field flatter, pinhole, and imaging sensor enables us to capture images that may range be within a specified range. This range will have to be established at the time of testing. Some of the drawbacks of this system is related to the sizing of the optics. Due to the size of the imaging plane (sensor angle of 6.3 mm) the optics that go Infront of it are severely limited in sizing. We shall see in chapter 6, how we go from the ideal lens design model to an off the shelf model using Zemax optimization.

3.2 Technologies

3.2.1 FPGA

FPGA vs. MCU

When evaluating the differences between FPGAs and MCUs within the scope of FLAMES, it is essential to determine which platform is best suited for each aspect of fire detection. Given that the system must perform rapid optical analysis and distinguish between fire hazards and other stochastic light sources, FPGAs provide a crucial advantage in their ability to process high-speed data in real-time, execute parallel computations, and reconfigure hardware as needed. The project-specific nature of FLAMES demands an approach that prioritizes low-latency spectral filtering and high-speed signal differentiation to detect hazardous emissions effectively.

FPGAs offer notable advantages for optical detection, including parallel processing, enabling simultaneous execution of multiple operations. This makes them ideal for high-speed data tasks such as real-time signal analysis and optical detection. They also provide flexibility and reconfigurability, allowing for design modifications without altering hardware [21]. Additionally, FPGAs enable the creation of custom hardware, tailored to specialized application needs like our FLAMES algorithm analysis for each layer of fire detection.

Despite their advantages, FPGAs do have some drawbacks, including higher power consumption and complexity in programming. However, their ability to conduct optical detection tasks at a high speed, coupled with their flexibility in handling signal processing techniques such as pulse-width modulation for servo control and spectral analysis for fire classification, makes them indispensable for the system. MCUs, while more efficient in power consumption and easier to program, are better suited for auxiliary tasks such as data logging, alert triggering through buzzer and LED activation, and managing low-power states when the system is not actively processing detection data.

The decision between FPGAs and MCUs, as discussed, depends on their specifications. A table summarizing these differences is provided below in Table 15.

Table 15. FPGA Vs. MCU Comparison

Specification	FPGA	MCU
Processing Power	High , tailored to specific tasks.	Moderate , limited to sequential tasks.
Parallel Processing	Yes.	No.
Flexibility	Highly flexible , can be reprogrammed.	Fixed hardware, limited flexibility.
Cost (Per Unit)	Higher.	Lower.
Power Consumption	Higher.	Lower , ideal for portable devices.
Custom Hardware	Yes.	No.
Real-Time Tasks	Excellent for high-speed real-time processing.	Good for simple real-time tasks.

Why FPGA?

We have discussed the general differences between FPGAs and MCUs and highlighted the benefits of using an FPGA. I will now go into the specific reasons why an FPGA is deemed superior for this application.

When doing analysis on intensity data inserted from an optical detection system there needs to be several parallel processing tasks done to perform the real-time data effectively. As discussed previously, MCUs can handle real-time processing but only on a small-scale level. A similar analysis has been done by Savitribai Phule Pune University [22] where they had implemented a real-time FIR filter on both an FPGA and an MCU and recorded the performance metrics including processing speed, latency, and resource utilization. The data can be seen below in Figure 10 this demonstration is relevant to the real-time analysis since FIR filters are fundamental in processing and analyzing signal intensities.

Parameters	Performance Comparison	
	<i>Microcontroller @60 MHz</i>	<i>FPGA @50MHz</i>
Signal Fmax	Approx 30 KHz	50 MHz
Latency	Approx. 30 usec	3 Clocks = 30 nsec
Sampling rate	Filter order dependent	Filter order independent
Performance	Poor	Good

Figure 10. SPUP Real-Time FIR Filter Analysis

As demonstrated by the findings from SPUP [22], the maximum signal frequency (Signal Fmax) for the MCU is limited to approximately 30 kHz, whereas the FPGA can handle signals with frequencies up to 50 MHz. This significant difference highlights the FPGA's

ability to process high-speed data on a much larger scale than the MCU. Additionally, the FPGA offers lower latency, making it particularly well-suited for applications that require real-time responses. Its sampling rate is also independent of filter order, enabling the FPGA to handle more complex filters or higher processing demands without sacrificing performance. This capability is further emphasized by the overall performance rating, with the FPGA being classified as "good" compared to the MCU's "poor" performance.

Another crucial difference between FPGAs and MCUs that is important for the FLAMES project is the hardware customization available on FPGAs compared to MCUs. Part of the reason this is so important is for real-time processing capabilities like discussed previously. Some other reasons include allowing the system to specifically be tailored for optical data analysis tasks, to allow for parallel processing, to adapt to environmental variations, and to allow for seamless integration of components.

FPGAs excel in implementing complex threshold detection mechanisms due to their customizable logic blocks. This allows for the creation of precise and efficient detection circuits tailored to specific application requirements. For instance, in sensor systems, FPGAs can process multiple input signals simultaneously, enabling rapid and accurate threshold assessments [23]. This parallelism ensures that critical events are detected in real-time, a feat challenging for MCUs that process signals sequentially.

Likewise, the reconfigurable nature of FPGAs allows them to adapt to varying environmental conditions dynamically. Unlike MCUs, which rely on fixed hardware architectures and software adjustments, FPGAs can modify their hardware configurations in response to environmental changes. This adaptability is crucial in applications like wireless sensor networks, where environmental factors can influence signal integrity and processing requirements. Research from the Faculty of Engineering Sciences at Vrije Universiteit Brussel (VUB) indicates that FPGAs can implement dynamic power management and voltage scaling, adjusting their operation to maintain performance while conserving energy in fluctuating conditions [23].

When analyzing our project to determine why certain components utilize an FPGA over an MCU, we prioritized latency since our fire detection system heavily relies on both speed and accuracy. A study conducted at the University of Maiduguri explored FPGA-based vision fire detection and developed a hardware accelerator for this purpose, offering valuable insights into the use of FPGAs with photodiode sensors [24].

The FPGA could have interfaced with the photodiodes to establish an environmental baseline for temporal fluctuation analysis, leveraging its key advantages. FPGAs enable high-speed parallel data processing, allowing rapid detection of changes in light intensity, which is critical for identifying flames early. Additionally, their re-programmability facilitates updates and optimizations to fire detection algorithms without requiring hardware modifications, ensuring adaptability to evolving methodologies and environmental conditions. Lastly, the study highlighted how FPGA architecture supports the implementation of advanced signal processing techniques directly on the hardware, enhancing fire detection accuracy by analyzing patterns and fluctuations in photodiode sensor data [24].

After completing the analysis, the FPGA could have connected to the stepper motor to ensure the fastest possible stopping mechanism for analysis while maintaining seamless communication throughout the detection process. FPGAs enable precise and responsive control of servo motors by executing complex control algorithms with minimal latency. This is particularly important in applications like fire detection, where accurate positioning and speed regulation are critical for timely and reliable system responses [25].

I, also, want to take this opportunity to deepen my understanding of FPGAs beyond their advantages over MCUs for analysis. Through this project, I explored the differences between various FPGA models, their integration with optoelectronics, the specifications relevant to our use case compared to traditional MCUs, and strategies for overcoming FPGA-related challenges.

Altera FPGA Series

While it has been established that using an FPGA is more suitable than an MCU for the FLAMES project, choosing the appropriate FPGA series also involves evaluating various tradeoffs. To make an informed decision, we will compare the Altera FPGA series MAX, Cyclone, Arria, and Stratix, highlighting their differences and identifying if any of these are the most suitable option for this project.

The differences between each of the Altera series we were deciding between can be seen below.

Table 16. Altera Series Comparison

Series	Target Application	Performance Level	Key Features
MAX	Control path applications, I/O expansion, configuration, and power management.	Low	Non-volatile architecture, low power consumption, instant-on capability.
Cyclone	Industrial automation, automotive, and consumer electronics.	Low to Mid	Low power, cost-effective, suitable for high-volume applications.
Arria	Mid-range applications like wireless, broadcast, and military.	Mid	Balanced performance and power efficiency, integrated transceivers.
Stratix	High-end applications such as data centers, high-performance computing, and	High	High performance, advanced transceivers, extensive DSP resources.

	advanced communication systems.		
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As seen by the table above, the Altera FPGA series varies significantly across different models [26]. The best FPGA for FLAMES depends on several factors, including performance, cost, power consumption, ease of integration, and scalability.

Given the FLAMES project’s need for real-time signal processing, spectral filtering, and intensity thresholding, the Cyclone series from Intel’s FPGA lineup is the most suitable choice. The Cyclone series is designed to meet low-power, cost-sensitive design needs, enabling faster time to market [27]. Within the Cyclone family, the Cyclone V FPGAs offer lower total power consumption compared to previous generations, efficient logic integration capabilities, and integrated transceiver variants. These features make them well-suited for applications requiring a balance between performance and power efficiency.

For fire detection analysis, the Cyclone series provides key benefits such as efficient power management, which ensures continuous operation in environments where energy efficiency is critical. The ability to implement real-time spectral filtering allows the FPGA to distinguish between different types of light emissions, reducing false positives from non-fire stochastic sources. Additionally, as seen in Table 16 the Cyclone series’ high-speed parallel processing capabilities enable rapid intensity thresholding, allowing the system to detect sudden optical spikes indicative of fire hazards with minimal latency. This is crucial for ensuring quick response times in hazardous conditions.

However, some trade-offs must be considered when applying the Cyclone series to fire detection. While its lower power consumption is beneficial for continuous monitoring, the computational resources may be limited compared to higher-end FPGAs, potentially restricting the complexity of machine learning algorithms that could be implemented for enhanced detection accuracy. Additionally, while the Cyclone FPGAs provide robust support for various I/O standards, their processing power may be constrained in large-scale fire monitoring deployments requiring extensive data fusion from multiple sensors.

The Cyclone 10 series further reduces cost and power consumption compared to previous generations. The Cyclone 10 GX models, for example, offer high-bandwidth performance with 10.3G transceivers, 1.4 Gbps LVDS, and support for up to 72-bit wide 1,866 Mbps DDR3 interfaces. These features can be advantageous depending on the project’s data throughput needs [28]. Cyclone FPGAs also support a wide range of I/O standards, including LVTTTL, LVCMOS, and PCI, ensuring compatibility with various digital systems and interfaces [29]. This versatility simplifies integration into diverse application environments.

The Cyclone series includes multiple generations, such as Cyclone IV, Cyclone V, and Cyclone 10, each offering a range of device densities and capabilities. This range of options enables designers to select an FPGA that meets current project needs while ensuring scalability for future enhancements. With up to 10,000 logic elements in certain models, Cyclone FPGAs offer sufficient resources for implementing complex digital designs. This capacity ensures that as project complexity grows, the FPGA can accommodate additional

functionalities without necessitating a complete redesign [29]. Overall, the Cyclone family is a strong contender for being the FLAMES FPGA of choice.

Xilinx FPGA Series

When evaluating FPGA options, it's essential to consider Xilinx, a prominent competitor to Altera (now part of Intel). Founded in 1984, Xilinx is renowned for inventing the first commercially viable field-programmable gate array (FPGA) and pioneering the fabless manufacturing model. In 2022, Advanced Micro Devices (AMD) acquired Xilinx, further enhancing its capabilities in programmable logic devices [30].

Compared to Altera, Xilinx offers a broader range of FPGA product lines under different series names. In this section, we will evaluate and determine the most suitable FPGA from the Artix, Spartan, Kintex, Virtex, and Zynq SoC series. The differences between these can be seen in the table below.

Table 17. Xilinx Series Comparison

Series	Target Applications	Performance Level	Key Features
Artix	Cost-sensitive applications requiring low power and high performance, such as portable medical devices and automotive infotainment systems.	Low to Mid	Low power consumption, optimized transceivers, suitable for small form factor designs.
Spartan	Entry-level applications, including consumer electronics and basic communication systems.	Low	Cost-effective, basic FPGA features, suitable for simple logic implementations.
Kintex	Applications demanding a balance between performance and cost, like wireless communication and video processing.	Mid	High DSP performance, efficient logic utilization, moderate power consumption.
Virtex	High-end applications such as data centers, aerospace, and defense systems.	High	Maximum performance, advanced transceivers, extensive DSP

			resources, high logic density.
Zynq SoC	Embedded systems requiring integrated processing capabilities, including industrial automation and automotive ADAS.	Varies	Combines ARM Cortex-A9 processors with FPGA fabric, offering flexibility for hardware-software co-design.

When evaluating FPGA options for FLAMES, the Artix and Kintex series emerged as the strongest candidates, offering a balance of performance, cost, power efficiency, scalability, and ease of integration. Since the FLAMES system requires continuous real-time spectral analysis, intensity thresholding, and low-latency optical signal differentiation, the chosen FPGA must meet these computational demands while maintaining energy efficiency for prolonged operation.

Artix is a strong competitor due to the cost and power efficiency, as Artix-7 FPGAs are optimized for low power consumption and cost-effectiveness, making them suitable for applications where energy efficiency is crucial [31]. Given that the system must operate continuously in fire detection environments, the 50% reduction in power consumption compared to previous generations ensures minimal energy draw while maintaining high-speed processing. This makes Artix-7 particularly well-suited for managing optical signal filtering and real-time thresholding, which are fundamental to identifying fire hazards. Additionally, its integrated DSP slices support advanced spectral filtering, allowing the system to process photodiode intensity variations more effectively. The Artix-7's support for DDR3 memory interfaces with data rates up to 1,066 Mb/s ensures efficient data storage and retrieval, critical for handling high-speed fire detection analytics [31].

On the other hand, Kintex-7 FPGAs deliver higher performance, making them suitable for applications that require substantial computational resources [32]. Their high-speed serial connectivity would be beneficial for systems with extensive data transfer needs, such as large-scale fire hazard monitoring across multiple zones. However, the increased power consumption and cost associated with Kintex-7 make it less favorable for a system designed for compact, low-power operation in controlled environments such as labs and cleanrooms. While Kintex offers superior computational throughput, the power efficiency requirements of FLAMES necessitate a more optimized solution.

The decision to use Artix was based on three key factors: adequate processing power, ensuring it meets the project's computational needs for real-time signal analysis; lower power consumption, aligning with the project's requirement for continuous operation without excessive energy draw; and cost-effectiveness, making it a budget-friendly yet capable solution. Artix-7 FPGAs provide the optimal balance between performance, power efficiency, and cost, making them the most suitable choice for FLAMES.

For our FLAMES project, we ultimately selected and successfully used the Artix-7 FPGA with part number XC7A35T-1CPG236C, implemented on the BASYS3 development

board. This choice proved highly effective due to the FPGA's abundant built-in GPIOs, integrated SPI Flash memory, and onboard debugging LEDs, all of which streamlined prototyping and system integration. Additionally, the board's support for Vivado made hardware design and testing more efficient throughout development.

Microchip FPGA Series

Microchip Technology has established itself as a key player in the FPGA industry by focusing on low-power, high-security, and reliable solutions. The company offers several FPGA families, including PolarFire, IGLOO, RTG4, and SmartFusion, which cater to applications ranging from industrial automation and medical devices to defense and communications. With innovations such as PolarFire's industry-leading power efficiency and SmartFusion's integration of an ARM Cortex-M3 processor, Microchip continues to provide FPGA solutions optimized for energy efficiency, security, and embedded system integration [33]. The difference between the Microchip FPGA series types can be seen in the table below.

Table 18. Microchip Series Comparison

Series	Target Applications	Performance Level	Key Features
PolarFire	Industrial automation, medical imaging, defense, low-power compute-intensive applications	Mid to High	Low power, cost-effective, integrated transceivers, scalable logic density
IGLOO	Low-density applications, consumer electronics, portable and automotive systems	Low	Non-volatile architecture, ultra-low power, instant-on capability, PCIe support
RTG4	Space, satellites, aerospace, and defense applications	High	Radiation-tolerant, high-speed serial interfaces, extensive I/O, reliable under extreme conditions
SmartFusion	Embedded systems, industrial control, medical devices, communications	Mid	Integrated ARM processor, low power, high security, hardware-software co-design

For the FLAMES project, the PolarFire series was initially considered a strong candidate due to its power efficiency and cost-effectiveness. PolarFire FPGAs consume up to 50% less power than comparable mid-range FPGAs, making them ideal for continuous

operation without excessive energy draw [34]. Given that FLAMES requires real-time optical signal processing, an energy-efficient FPGA ensures long-term reliability without overheating or excessive power usage. Additionally, PolarFire offers a cost-effective solution while still delivering mid-to-high performance, making it a strong alternative to more power-intensive FPGAs like RTG4. However, since FLAMES does not require radiation-hardening (RTG4) or embedded ARM processing (SmartFusion), the selection process emphasized factors such as clock speed, DSP capabilities, and development tool accessibility.

With transceivers up to 12.7 Gbps and scalable logic density ranging from 100K to 500K LEs, PolarFire delivers ample computational power for real-time spectral filtering and intensity thresholding, both critical for the FLAMES project [35]. Its flexible logic density also ensures scalability, allowing the FPGA to adapt to future project needs without requiring a complete redesign. However, the decision ultimately favored the Xilinx Artix series due to its superior processing speed and ecosystem support.

We selected the Xilinx Artix FPGA over the Microchip PolarFire series primarily due to higher operating frequencies, more efficient logic elements, and a mature development ecosystem. Xilinx Artix FPGAs offer higher clock speeds and better DSP performance, which are critical for the FLAMES project's real-time signal processing requirements. The 6-input LUT architecture in Artix FPGAs allows for more efficient logic implementation compared to the 4-input LUTs found in some Microchip FPGAs, leading to more compact and faster designs [36]. These advantages directly impact the efficiency of spectral filtering and intensity thresholding, ensuring that FLAMES can rapidly analyze optical signals for fire detection.

Additionally, Xilinx's development ecosystem played a key role in the decision. The Vivado Design Suite is widely adopted and well-supported, offering a comprehensive set of tools for synthesis, simulation, and debugging. In contrast, transitioning to Microchip's Libero SoC Design Suite could introduce a steeper learning curve and potential compatibility challenges, especially when working with industry-standard FPGA workflows [37]. Furthermore, Artix FPGAs have a proven track record in high-speed applications, ensuring long-term reliability for continuous operation. The combination of superior processing speed, logic efficiency, and industry-standard tools made Xilinx Artix the optimal choice for FLAMES over a Microchip alternative, guaranteeing the high-speed, low-latency performance required for real-time fire detection and hazard analysis.

Lattice FPGA Series

Lattice Semiconductor has established itself as a leader in low-power, small-form-factor FPGAs, focusing on applications in communications, computing, consumer electronics, automotive, and industrial sectors. The company offers several widely used FPGA families, including iCE40, MachXO, and ECP, each designed for energy-efficient and high-reliability applications. Lattice has gained recognition for its expertise in edge AI, embedded vision, and secure computing, providing cost-effective and power-efficient solutions for modern hardware designs. With continued advancements in low-power FPGA technology, Lattice remains a key player in the industry, catering to next-generation embedded and intelligent systems [38].

The characteristics and differences of each series type can be seen in the table below.

Table 19. Lattice Series Comparison

Series	Target Applications	Performance Level	Key Features
iCE40	Mobile devices, wearables, IoT edge devices	Low	Ultra-low power consumption, small form factor, instant-on capability
MachXO	System control, I/O expansion, interface bridging	Low to Mid	Non-volatile configuration memory, instant-on performance, robust I/O features
ECP	Data and control path bridging, video processing, industrial automation	Mid to High	High-performance SERDES, full-featured DSP blocks, state-of-the-art memory interfaces

For the FLAMES project, the ECP series was initially considered among the Lattice FPGAs due to its enhanced performance for real-time processing, data throughput, scalability, and its balance between power efficiency and computational capability. The ECP5 series, with its optimized DSP architecture, high-speed SERDES, and extensive I/O capabilities, appeared well-suited for applications requiring efficient data handling and rapid optical signal analysis [39].

However, while the ECP5 series provided a strong balance of power efficiency and industrial reliability, it ultimately fell short in meeting the full spectrum of performance requirements for FLAMES. The iCE40 series, though excelling in ultra-low power consumption and compact form factors, lacked the necessary computational resources for intensive spectral filtering and fire hazard detection. Similarly, the MachXO series, optimized for control and bridging applications, did not align with the high-speed data processing demands of the project. Thus, while the ECP5 series stood out as the most suitable option within Lattice's offerings, it was not the most effective FPGA for this particular fire detection application.

The Xilinx Artix series was selected over the Lattice ECP series primarily due to its superior development tools, higher logic element efficiency, and broader industry support. The Xilinx Vivado Design Suite, widely recognized for its robust synthesis, debugging, and optimization capabilities, offered a more streamlined development process, making implementation more efficient. In contrast, Lattice's development tools presented limitations that could introduce challenges in refining real-time signal processing algorithms for FLAMES, potentially impacting response time and detection accuracy.

Additionally, Artix FPGAs leverage 6-input Look-Up Tables (LUTs), enabling more complex logic functions per element, leading to a more compact and higher-performance design. This architectural advantage is particularly critical for high-speed optical signal processing, where efficient computation and precise spectral filtering are required to differentiate between stochastic light emissions and true fire hazards. While the Lattice ECP series offers competitive power efficiency and open-source toolchain support, the combination of superior tooling, industry-standard workflows, and optimized logic efficiency made Xilinx Artix the optimal choice for the FLAMES project, ensuring the most reliable and high-performance solution for fire detection and hazard mitigation.

3.2.2 MCU

Why Microcontroller?

In the FLAMES fire detection system, we have chosen to utilize a microcontroller unit (MCU) to manage the stepper motor, photodiode, button, LED, buzzer components. This decision is based on several key factors that align with the system's requirements for efficiency, cost-effectiveness, and simplicity.

MCUs are generally more affordable than Field-Programmable Gate Arrays (FPGAs). For tasks such as monitoring user inputs (buttons) and controlling output indicators (LEDs and buzzers), the computational demands are minimal. Implementing an FPGA for these functions would lead to unnecessary expenses without a corresponding benefit in performance. Therefore, an MCU provides a budget-friendly solution for these peripheral controls [40].

MCUs are designed for low power consumption, making them ideal for applications where energy efficiency is crucial. In contrast, FPGAs, while powerful, typically consume more power due to their reconfigurable nature and higher processing capabilities. Utilizing an MCU to handle the button, LED, and buzzer ensures that the system remains energy-efficient, which is essential for continuous operation in safety-critical applications like fire detection [41].

The tasks associated with buttons, LEDs, and buzzers involve straightforward digital input and output operations. MCUs are well-suited for these functions due to their integrated architecture, which combines a processor core with memory and I/O peripherals on a single chip. This integration simplifies the design and reduces the complexity of the system. Programming MCUs is also more accessible, often utilizing high-level languages such as C or C++, which streamlines development and debugging processes [42].

FPGAs excel in handling complex, high-speed parallel processing tasks, such as real-time parallel flag synchronization, which are central to the core functionality of the FLAMES system. By assigning the FPGA to manage these intensive computations and delegating the simpler peripheral control tasks to the MCU, we optimize the use of system resources. This division of labor ensures that each component operates within its strengths, leading to a more efficient and effective overall system design [43].

Employing an MCU for the button, LED, and buzzer control in the FLAMES fire detection system offers a cost-effective, power-efficient, and straightforward solution. This approach

allows the FPGA to focus on the demanding synchronizing tasks of real-time data processing and analysis, thereby enhancing the system's performance and reliability.

ESP32

For the motor, photodiode, button, LED, and buzzer system in FLAMES, the ESP32 was chosen due to its computational power, familiarity, and affordability. The ESP32 supports both Wi-Fi and Bluetooth 4.2 (including BLE), enabling seamless data transmission and device connectivity. This feature aligns with the stretch goal of integrating with a PC for data logging, allowing for extended system analysis and further development by external users [44].

In addition to its connectivity advantages, the ESP32 features a dual-core 32-bit LX6 microprocessor operating at up to 240 MHz, providing sufficient computational power for managing peripheral control and system interfacing. With 34 programmable GPIO pins, it allows flexible connections with various sensors and actuators, facilitating diverse hardware integrations. Moreover, its cost-effectiveness, with development boards priced around \$6 USD, makes it an accessible solution for embedded system applications, ensuring the project remains budget-friendly while delivering robust performance [45].

Despite these advantages, the ESP32 does present some drawbacks for the FLAMES project. It is known to be power-hungry, which could be a concern for battery-powered applications requiring extended operation. However, since FLAMES will be powered via an AC outlet, this limitation does not impact the system's functionality. Additionally, while the ESP32's Real-Time Operating System (RTOS) and complex CPU architecture can pose challenges for tasks requiring precise real-time control, this was successfully and easily implemented for our motor control, and master communication between the FPGA and Raspberry Pi.

Another limitation of the ESP32 is the reported non-linearity and noise in its analog-to-digital converters (ADCs), which may require calibration for precise analog measurements. However, as the MCU is not responsible for high-precision signal processing in FLAMES, since it used an Arduino IDE supported FFT library, this drawback does not hinder system performance. Additionally, the ESP32 supports only 2.4 GHz Wi-Fi networks and lacks compatibility with modern 5 GHz networks, which could be restrictive in environments where 5 GHz is prevalent. Nevertheless, for the intended deployment of FLAMES, the 2.4 GHz network suffices for data transmission and logging purposes [46].

While the ESP32 has some limitations, they do not significantly impact its role within the FLAMES project. The ESP32's advantages in connectivity, processing power, and cost-effectiveness outweigh its limitations, which made it an optimal choice for managing these peripheral control elements within the project.

Raspberry Pi

In evaluating the Raspberry Pi for managing the button, LED, and buzzer system within the FLAMES project, several advantages and disadvantages emerge. The Raspberry Pi provides a comprehensive set of General Purpose Input/Output (GPIO) pins, making it a viable option for controlling peripheral devices such as LEDs, buzzers, and buttons [47]. This versatility supports seamless integration with various components, which is crucial

for the interactive control elements within the FLAMES system. Additionally, Raspberry Pi's extensive user community offers numerous resources, including tutorials, libraries, and troubleshooting support, which could aid in simplifying development and debugging processes.

However, compared to microcontroller units (MCUs) like the ESP32, the Raspberry Pi presents several limitations that make it less suitable for the FLAMES project. One of the most significant concerns is its higher power consumption, with the Raspberry Pi 3 Model B consuming between 1.4 to 3.7 watts, which is excessive for a system where power efficiency is a consideration [48]. We were able to combat this power draw by implementing a camera-off mode when not in use. Since FLAMES is intended for continuous operation, optimizing power consumption is critical, making an MCU-heavy-based solution more appropriate.

Furthermore, while the Raspberry Pi excels in computational power, its capabilities far exceed the requirements for managing simple peripheral controls such as buttons, LEDs, and buzzers, but was computationally complex enough for the CMOS sensor with the CSI connection. Using a full-fledged Linux-based system for basic tasks introduces unnecessary complexity and resource overhead. Additionally, Raspberry Pi requires a complete operating system to boot, resulting in longer startup times, which could delay responsiveness in scenarios where immediate action is necessary.

Due to these factors, the ESP32 was ultimately chosen over the Raspberry Pi for the button, LED, and buzzer system within FLAMES. The ESP32 provides adequate processing power, built-in Wi-Fi/Bluetooth for potential wireless communication needs, lower power consumption, and a simpler implementation process. Given that real-time responsiveness is crucial for system operation, the ESP32's microcontroller-based architecture ensures immediate functionality without the boot-time delays associated with a full Linux system. While Raspberry Pi offers flexibility and a strong development community, its higher power consumption, unnecessary computational complexity, and longer startup times make it a less optimal choice for this specific role in the FLAMES project.

Arduino

When evaluating the suitability of Arduino for managing the button, LED, and buzzer system within the FLAMES project, several strengths and limitations emerge. Arduino platforms are widely recognized for their ease of use, making them a practical choice for basic input/output operations such as controlling LEDs, buzzers, and buttons. Their strong community support and extensive libraries provide a foundation for rapid development and debugging. Additionally, Arduino boards, such as the Arduino Uno, are highly energy-efficient, consuming minimal power, which can be advantageous for battery-operated applications.

However, in the context of the FLAMES project, Arduino's limitations outweigh its advantages. With a lower clock speed of 16 MHz and significantly less memory compared to alternatives like the ESP32 [49], Arduino struggles with handling more complex computations or supporting future scalability. Furthermore, most Arduino models lack integrated wireless communication, requiring external modules for Wi-Fi or Bluetooth

capabilities. This not only increases system complexity but also adds to development costs and potential compatibility issues [50].

Given the FLAMES project's need for real-time data transmission, wireless integration, and efficient processing, the ESP32 is the more suitable choice. With a dual-core 32-bit LX6 processor running at up to 240 MHz, the ESP32 provides ample computational power for managing the peripheral controls while enabling real-time responsiveness. Its built-in Wi-Fi and Bluetooth support align with the project's stretch goal of remote data logging and monitoring, offering seamless communication between the fire detection system and external interfaces. Unlike Arduino, the ESP32 also features a broader set of GPIOs, allowing for scalability and integration of additional sensors should the system expand.

While Arduino remains an excellent choice for simpler applications, its lack of built-in wireless capabilities and limited processing power make it less suitable for the FLAMES project. The ESP32's superior performance, integrated connectivity, and enhanced scalability make it the optimal choice for ensuring efficient and real-time fire detection system functionality while maintaining flexibility for future improvements.

STM32

In evaluating the suitability of the STM32 microcontroller series for managing the button, LED, and buzzer system within the FLAMES project, it is important to assess its advantages and limitations in the context of the project's specific requirements. STM32 microcontrollers, based on ARM Cortex cores, offer powerful processing capabilities and a wide range of built-in peripheral modules, including UART, SPI, I2C, USB, GPIO, and timers. These features make STM32 a strong choice for applications requiring substantial computational power and extensive hardware interfacing [51]. The STM32 series provides a large number of GPIO pins and supports multiple communication protocols, allowing for seamless integration with various sensors and actuators. This flexibility is beneficial for complex embedded systems requiring precise control and extensive peripheral connectivity [51].

However, for the button, LED, and buzzer system within the FLAMES project, which primarily involves basic digital input and output operations, STM32 presents several drawbacks. Most STM32 models lack built-in Wi-Fi or Bluetooth capabilities, necessitating additional modules for wireless communication. This increases design complexity, integration efforts, and overall costs [52]. Additionally, STM32's development environment, which often involves direct register programming or HAL-based abstraction layers, can be more challenging for teams unfamiliar with the platform, resulting in longer development times. Cost considerations further highlight STM32's limitations, as lower-end models start at approximately \$3-\$6, but high-performance variants such as the STM32H7 series can exceed \$20 per unit. In contrast, the ESP32, priced around \$6-\$8, includes both Wi-Fi and Bluetooth connectivity, making it a more cost-effective solution for applications requiring wireless communication [53].

While the STM32 series offers excellent performance and scalability, its advanced capabilities are excessive for the button, LED, and buzzer system in FLAMES. The system requires efficient peripheral management with minimal complexity, a task that the ESP32 handles with ease. With its built-in Wi-Fi/Bluetooth, accessible development environment,

and sufficient processing power, the ESP32 aligns more effectively with the project's needs. Its lower overall cost and integrated wireless functionality ensure a streamlined, efficient, and scalable solution, making it the optimal choice for the button, LED, and buzzer system within the FLAMES project.

Table 20. MCU Comparison

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)
Best Use Case in FLAMES	Best for wireless integration, real-time peripheral control	Overqualified for simple tasks, excessive power use	Lacks wireless connectivity, limited processing power	Overcomplex for simple digital I/O tasks

3.2.3 Motor

The motor within our system plays a critical role in providing complete environmental observation through 360-degree scanning of the detection area. By constantly rotating the optical sensor, the motor allows the system to sweep a wide field of view and offer a better

chance of early fire detection regardless of the site of ignition. Additionally, the motor must operate with high accuracy and efficiency because proper positioning is imperative in aligning optical sensors suitably to detect fire signatures properly without interference. Incorporating the motor into this system renders it more dependable, protected, and responsive, and its use as a necessary component is imperative for the installation of early and accurate fire detection.

We decided to implement a 180-degree scanning range for FLAMES instead of a full 360-degree rotation due to concerns about the motor and power supply wiring becoming tangled or wrapped around the system during continuous movement. By reducing the field of view to 180 degrees, we can strategically place the enclosed system against a wall or in the corner of a room or a CNC machine. This setup still allows FLAMES to effectively monitor fire within its designated area, while also minimizing interference with other ongoing industrial activities, such as welding or grinding, commonly present in active work environments.

Stepper Motor

A stepper motor moves in precise angular increments, typically in an open-loop control system, making it ideal for applications requiring accurate and repeatable positioning without the need for feedback [54]. In our fire detection system, a stepper motor would allow controlled stepwise scanning of the environment, ensuring thorough examination of each segment of the field of view. Since the stepper motors hold their position when powered, they would maintain scanning direction without drift.

However, there are certain limitations to the stepper motors: at higher speeds, they lose tremendous torque, and therefore, rapid repositioning may be challenging in case the system needs to re-scan an area [55]. Additionally, stepper motors consume their power continuously, even when holding one and the same position, which means higher dissipation of heat and thus more power consumed [55]. Moreover, since they work in an open-loop system, there is no feedback to correct missed steps; over time, the scanning system could lose alignment unless there is a secondary correction mechanism. Even with these disadvantages, stepper motors become a viable alternative if accurate incremental movement is to be achieved at the expense of speed and power efficiency.

Servo Motor

Servo motors utilize closed-loop feedback with an encoder, which creates their high degree of accuracy and adaptability for applications that require dynamic control [55]. The servo motor would make it possible for the fire detection system to scan with real-time adjustments so that, if the event that external factors such as vibrations or wind affect the position of the detector, it may self-adjust the motor's orientation. This is particularly helpful when one needs to stop immediately upon detection of a fire to avoid unnecessary overshooting or delays to halting of the rotation.

One of the key advantages of servo motors is that they are power-efficient; they draw power only proportionally to the load applied, while stepper motors constantly draw current. Another key benefit is that the servo motors can provide high torque at higher speeds, enabling faster repositioning if a more rapid scanning approach should be required [55]. However, servo motors are more expensive and require additional components like the

encoder. The servo motor would be the ideal option for our detection system because of its real-time positioning accuracy, smooth operation, and energy efficiency [55].

DC Motor

DC motors provide continuous rotation and can operate with simple control mechanisms making them a straightforward option for applications that do not require precise positioning. In our system, a DC motor could be used if smooth continuous scanning motion is preferred over stepwise movements. Additionally, DC motors tend to be cost-effective and consume power only as needed, improving energy efficiency [56].

The lack of precise positioning control is a significant drawback. Without an encoder, a DC motor would not be able to stop at an exact position when fire is detected, which can potentially cause a misalignment for data collection. Adding an encoder would present more accurate results but this again increases the cost and complexity making it similar to the servo motor in terms of requirements [57]. DC motors tend to overshoot their stop position, which is problematic in a fire detection scenario where stopping the motor is critical. Although for simple continuous scanning of a DC motor could be utilized, it is less suited for precise positioning unless combined with an encoder, in which the servo motor would be a better alternative.

Table 21. Motor Comparisons

Feature	Stepper	Servo Motor	DC motors
Precision Control	High	High	Low
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

Suitability for Fire Detection	Good for precise scanning	Best for dynamic control and efficiency	Requires encoder for accurate positioning
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The utilization of a stepper motor would be the best choice for our application primarily due to its cost-effectiveness compared to the other motor technologies. Although the stepper motors offer precise control and are more affordable, I am aware that they are generally less efficient in terms of power consumption, especially when holding position or remaining idle.

Unipolar Motors

Unipolar stepper motors are constructed to include windings with a center tap, which effectively divide each coil into two halves. Unipolar motor uses only one half of each coil is active at a time, which makes it easier to control since the direction of current does not have to be reversed-this makes driving unipolar motors simpler with accompanying driver circuits [58]. The integration of a unipolar motor would lower the cost and complication of the motor control circuit and allow a reduction in time spent on development, plus eased troubleshooting. However, this means a loss in torque won't be compensated for. The torque output will generally be less in unipolar motors compared to their bipolar counterparts because only half of the coil is energized per each phase of operation. This may limit performance in the system, where rotation of the scanning assembly and potential inertial loads is required.

Bipolar Motors

Bipolar stepper motors offer a more powerful alternative for use in applications requiring more torque and better efficiency. Bipolar stepper motors, as opposed to unipolar motors, do not use center taps and instead use the entire coil per phase operation. This configuration requires a more sophisticated driving circuit, typically realized as an H-bridge reversing the direction of current through the windings, but is repaid with optimal coil utilization, producing greater torque and more efficient energy [58]. In our fire detection system where the motor is employed for a constant scan and must stop precisely on fire detection, the higher torque and smoother operation of the bipolar motor ensure more stable and reliable performance. This is especially important considering the moving components in the scanning assembly, as a motor with insufficient torque could result in positional errors or failure to detect. Where the control circuitry is more complicated, the sacrifice is well justified in those applications where accuracy and reliability are necessary abilities that are essential in a fire alarm system. Furthermore, the increased efficiency of the bipolar motor benefits the aim of minimizing the use of power because it takes away unnecessary loss of energy.

Table 22. Unipolar Vs Bipolar Motor Technology

Feature	Unipolar	Bipolar
Wiring	Typically, 5 or 6 wires to account for the center taps.	4 wires
Torque Output	Small: 0.05-0.15 Nm	Small: 0.1-0.2 Nm

	Medium: 0.2-0.4 Nm Larger: 0.6-1.5 Nm	Medium: 0.3-0.6 Nm Larger: 1.2-3 Nm
Efficiency	Slightly less efficient as not all winding is used at once.	More efficient; full winding used for torque generation.
Complexity of Driver Circuit	Simpler driver circuits: less complex switching required.	Requires an H-bridge driver to reverse current; more complex circuitry.
Heat Generation	Can generate more heat due to partial coil energization.	Can operate cooler due to better energy utilization.
Cost	Small: \$10-\$20 Medium: \$15-\$30 Large: \$20-\$45	Small: \$12-\$25 Medium: \$20-\$40 Large: \$30-\$60

I have decided to select the bipolar configuration of the stepper motor. Bipolar stepper motors are known for delivering higher torque output compared to unipolar motors of the same size, which will ensure stronger and more consistent motor movement, especially during scanning operations where stability and precision are critical. This configuration uses the entire winding for each phase, increasing efficiency and allowing for smoother micro stepping. Additionally, bipolar motors generally have simpler construction without center taps, making them more robust and better suited for applications that require precise and controlled motion over extended use. The combination results in more precise control and superior performance which is critical for maintaining the accuracy and consistency.

Stepper Motor Technologies

Nema 17

In terms of size the Nema 17 stepper motor is the smallest, most compact with a frame size of 42mm x 42mm [59]. Nema 17 is highly efficient from a wattage perspective assuming operating currents of between 1.2A and 1.7A, hence generating less heat [59]. This makes it appropriate for battery-driven or low-energy designs. Its featherweight and smaller size make it best for jobs limited by space. However, it is less suited for movements of heavier scanning assemblies or precision systems under load due to the relatively lower torque it produces. Nema 17 would serve small-scale scanning systems or applications for which conservation of power is most crucial.

Nema 23

The Nema 23 possesses a frame size of 57mm x 57mm, it has enough power for moderate load handling with smooth and accurate scanning. It draws 2.8A per phase and thus provides significantly higher torque as compared to Nema 17 while being economical [59]. Though consuming greater power and generating more heat than Nema 17, this could be handled easily by low-power modes and optimized control methods. The Nema 23 is commonly used in CNC machines, 3D printers, and robotics, thus adding a balance in affordability and performance.

Nema 24

For applications that demand greater torque without jumping to industrial-level motors, the Nema 24 is the logical next step. With a slightly larger frame size 60mm x 60mm, it provides stronger holding power and smoother operation at higher speeds. This motor draws between 3.5A and 4.2A per phase so it will not be as energy efficient as Nema 23 but can better accommodate heavier scanning systems or larger fields of view [59]. The trade-off is bigger size and greater power consumption, which could require heavier-duty drivers and larger power supplies. This, however, makes it an ideal compromise between enhanced torque for applications requiring broader or more expansive scanning setups and just performance vs. power efficiency.

Nema 34

The industrial category contains among the most powerful and rugged stepper motors; the Nema 34. With a frame size of 86mm x 86mm, it is configured for heavy, demanding applications to move heavy equipment or loads. The motor consumes around 5.5A to 6.3A per phase and needs a high voltage power supply, typically from 36V to 80V which leads to very high-power consumption [59]. Although carrying large scale or industrial fire detection systems is easy on the Nema 34, its higher energy demand, larger size, and cost make it less suitable for projects where power efficiency and compactness are priorities.

Table 23. Stepper Motor Comparisons

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+

The Nema 23 was chosen for its excellent performance-to-cost ratio. It provides enough power to drive the scanning mechanism of the fire detection system without sacrificing stability and precision. One of the primary factors influencing my decision was the affordability of the Nema 23 compared to higher torque motors like the Nema 24 or Nema 34 which comes higher costs and greater energy demands. Its versatility, cost-effectiveness and ability to meet the mechanical demands of our system make the Nema 23 a strategic choice that supports both the technical requirements and efficiency goals.

Table 24. Nema 23 Model Comparison

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
Frame size	57 x 57 mm	57 x 57 mm	57 x 57 mm
Weight	0.69	0.7 kg	1.08 kg
Cost	\$15.65	\$10.59	\$54.95

The selection of the Nema 23HS22-1006S stepper motor is the most practical choice for our fire detection system in terms of cost-effectiveness, its attainable power needs, and assured torque output. The motor is the most cost-effective option among those being compared and can be achieved with a minimal cost in the project without any compromise on the required performance. Its 0.9 Nm holding torque is sufficient to smoothly rotate the optical sensor in our system with enough force to overcome mechanical resistance without compromising the precise scanning alignment. Its rated current of 1 A per phase is sufficient for application in more power-efficient motor drivers, reducing the system's overall power consumption. The moderate mass of 0.7 kg and nominal frame size of 57 x 57 mm of the motor permit easy installation and incorporation into the scanning mechanism without imposing undue mechanical load or requiring overly heavy-duty support structures. This balance between weight, torque, and current draw ensures that the system can perform continuous or on-demand scanning operations with smooth, efficient motion, and in accordance with the design requirements of low power usage and cost-effectiveness. Generally, the Nema 23HS22-1006S motor is a considerate choice that is supportive of both operational and cost aspects and is well-suited for this fire detection application.

3.2.4 Motor Driver

Within our fire detection system, the motor is responsible to rotate our detection system ensuring enough coverage within our field of view for sensing fire hazards. For accurate and proper control, it requires a compatible motor driver for controlling the step sequencing, current limiting, and voltage supply for smooth and precise operation. Unlike bipolar stepper motors, unipolar motors have center-tapped windings and, therefore, can be driven using simpler circuitry because the current does not need to be reversed in the coils. This makes unipolar drivers easier to implement while reducing the complexity of the control system.

By selecting an appropriate motor driver for the bipolar stepper motor, the system has simpler wiring, reduced control complexity, and reliable operation in continuous fire detection applications. It is important to consider factors such as power efficiency, current handling, micro stepping capability, and control interface compatibility. In doing so, the

scanning mechanism is guaranteed to operate smoothly with the overall system design still efficient and maintainable.

Motor Driver Technologies

Eason TB6600

Although the EASON TB6600 Stepper Motor Driver is a commonly used solution, it is not the most power-effective solution. Some users have stated that it does not consistently live up to its name when it comes to efficiency, particularly when handling micro stepping and current regulation, which will affect the smoothness and responsiveness of the motor. Although the TB6600 supports up to 4A of current and features several modes of micro stepping, its power dissipation and heat management can fall short for long-term usage in applications [60]. Since power efficiency and precise control are important considerations, this motor driver may not be ideal.

Pololu Tic T500

A power-effective alternative is the Pololu Tic T500 Stepper Motor Controller, which also has several communication interfaces such as USB, TTL serial, and I2C, making it highly compatible for integration with the FPGA [61]. This driver is unique because of its low power consumption, programmable current limiting, and smooth motion control, making it highly suitable for systems where power effectiveness and precision are of importance.

Pololu DRV8825

The Pololu DRV8825 Stepper Motor Driver is also a widely used driver for stepper motor applications where moderate power ratings are required. It can handle a maximum of 2.2A per coil, thus being suitable for use in Nema 23 motors in which lower levels of current are employed. This driver is particularly renowned for its current limiting and thermal protection features, thus being very reliable and reducing power loss [62]. But if the motor requires higher levels of current to produce the maximum performance, DRV8825 may not be able to provide your stepper motor with the full torque capability.

Leadshine DM542

The Leadshine DM542 has a high current capacity, supporting up to 4.2A peak current with a variety of micro stepping configurations for more precise motion control. It's accurate and dependable and would be an excellent choice for applications where smooth, consistent motion is critical. It also features built-in protection mechanisms against overvoltage, under-voltage, and overheating, improving its performance and longevity with continued use [54].

GeckoDrive G203V

For high-performance and durability, the GeckoDrive G203V Stepper Motor Driver is a top choice. It can drive up to 7A per phase, and it is one of the highest current drivers for Nema 23 stepper motors [63]. This driver is well-known for being very rugged, having low heat dissipation, and providing smooth micro stepping control so that the stepper motor can be driven efficiently with low vibration. Although more expensive than the other options, it provides long-term durability and excellent motor performance that benefits our

system in applications requiring precise and extended operation, such as the continuous scan motor of our system.

Table 25. Motor Driver Comparisons

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°	0.00703°	0.18°
Cost	\$10.89	\$29.85	\$12.95	\$46.23	\$155

I have selected the Pololu DRV8825 motor driver for due to its excellent balance of performance, efficiency, and control accuracy for the Nema 23 unipolar stepper motor. Micro stepping capability, which provides 1/32 micro stepping, is one of the primary strengths of the DRV8825, which allows for smooth and accurate motor control. This degree of accuracy is particularly important to my system as it ensures proper and controlled scanning of the area of fire detection to minimize any positioning errors that might impact the ability of the sensor to detect fires.

Lastly, the DRV8825 is affordable and easily accessible, so it is a practical but efficient choice for my application. Its compatibility with typical stepper motors and ease of integration with microcontrollers or control systems based on FPGAs make it straightforward for me to connect it directly to my existing design without significant reconfiguration. The blend of high precision, good performance, on-board safety features, and competitive pricing makes the DRV8825 motor driver the ideal solution for our fire detection system's motor control needs.

While the DRV8825 motor driver was ultimately able to drive our motor, we encountered several issues during testing—most notably, thermal failures where the IC would overheat and become non-functional. These issues were partly due to design flaws in the custom DRV8825 PCB, but they also revealed that the DRV8825 was not an ideal match for our motor. This driver is generally better suited for smaller stepper motors like the NEMA 17, whereas our system uses a larger NEMA 23 motor. If we were to revisit our motor driver selection, we would opt for the TB6600, which is specifically designed to handle larger motors like the NEMA 23 and above. It also provides adjustable current control and

microstepping capabilities, which offer greater flexibility and reliability. The main trade-off, however, would be increased power consumption compared to the DRV8825.

3.2.5 ADC

The Analog-to-Digital Converter (ADC) is also a crucial component of my fire detection system since it serves as the required link between the world of analog optical sensor signals and the digital domain of the FPGA. The optical sensors in the system generate analog signals relating to the sensed light intensity, which need to be correctly translated into digital information so that they can be processed, and decisions can be made based on them by the FPGA. Without the ADC, the system would be unable to process and understand the outputs of the sensors and would thus be impossible to detect fire. The purpose of the ADC is to enable the readings from the sensor to be sampled with high velocity, fidelity, and accuracy so that the system may even sense the slightest change in the optical signals that can indicate the preliminary presence of fire.

The importance of the ADC also lies in its impact on the response time and resolution of the system. A high-resolution ADC enables measurement of sensor output changes, which translates into greater accuracy and sensitivity in fire detection. Its support for SPI communication protocol allows for fast and reliable data transfer to the FPGA, causing the system to process information fast and react swiftly to fire incidents. Overall, the ADC is a key element in converting physical signals into usable digital data, and it is a key consideration in offering early detection, system reliability, and real-time responsiveness for our system.

Successive Approximation Register (SAR) ADC

The Successive Approximation Register (SAR) ADC is one of the most appropriate choices for our fire detection system because it has an optimal approach to balancing speed, resolution, and power efficiency. SAR ADCs work by implementing a binary search algorithm to determine the digital representation of an analog input, making them very appropriate for moderate-to-high-speed applications with adequate resolution (typically 8 to 18 bits) [64]. Because our system needs real-time conversion of optical signals, a SAR ADC can deliver rapid and precise data collection without drawing too much power. SAR ADCs also handle low-power situations well, which fits with my aim of reducing energy use within the fire detection unit.

Sigma Delta ADC

The Sigma-Delta ADC is appropriate for applications requiring very high resolution but at significantly lower speed than SAR ADCs. The application of oversampling and noise shaping yields high-resolution outputs (16 to 24+ bits) [65], and these ADCs are appropriate for slow, precise measurements such as temperature sensing or environmental monitoring. While this accuracy is worthwhile, it is unsuitable for real-time fire detection, where the immediate response is needed to detect flames. A Sigma-Delta ADC could be used for ambient tracking of conditions within the environment, such as air quality monitors, but might not be able to handle sudden fluctuations of the light signals from optical detectors.

Flash ADC (Parallel ADC)

For high-speed applications, a Flash ADC would be the fastest choice, as it performs instantaneous analog-to-digital conversions in a single clock cycle. Flash ADCs achieve speeds in the GSPS (giga samples per second) range, making them ideal for applications like radar systems, oscilloscopes, and RF communications. However, Flash ADCs typically offer low resolution (6 to 10 bits) and consume a large amount of power, which makes them impractical for our fire detection system [66]. Since our system does not require extreme-speed data processing but rather a balance of speed and accuracy, a Flash ADC would not be the most efficient choice.

Pipelined ADC

The Pipelined ADC offers a trade-off between high-speed conversion and resolution, and it is appropriate for applications demanding fast, real-time processing but also a higher degree of precision than Flash ADCs. This ADC type segments the conversion into several stages of processing, enabling it to offer 10 to 100 MSPS (million samples per second) speeds and 8 to 16-bit resolution [67]. If our fire detection system needed very high-speed data acquisition with high accuracy, a Pipelined ADC would be a good option. But pipelined ADCs consume more power compared to SAR ADCs and are thus less power-efficient.

Dual-Slope (Integrating) ADC

The Dual-Slope (Integrating) ADC is mainly used in applications where stability and accuracy are more necessary than speed. This ADC type integrates the analog signal over a period of time, and then slowly discharges it at a known rate to determine the digital output. It is common to find this ADC type in digital multimeters and sensor applications where stability and low noise is more necessary than response speed [60]. However, because it operates at incredibly sluggish speeds, a Dual-Slope ADC would not be appropriate for my fire detection system, which requires rapid signal processing to identify threats of fire as soon as possible.

Table 26. ADC Technology Comparisons

Feature	SAR	Sigma Delta	Flash	Pipelined	Dual Slope
Sampling Rates Ranges	Up to 10 MSPS	Only up to a few hundred kSPS	Hundreds of MSPS - several GSPS	Up to 100+ MSPS	100-100k SPS
Typical Resolution	8-16 bits	16-24 bits	8-10 bits	8-16 bits	10-18 bits
Power consumption	Low to Moderate	Generally higher	High	Moderate to high	Low
Common Applications	Precision measurement systems, industrial controls,	Audio processing, instrumentation, application	Ultra-fast applications: oscilloscopes,	Video processing, digital signal processing	Digital voltmeters, accurate measur-

	embedded sensors	requiring high accuracy	radar, high-speed data capture		ement devices
Cost	\$5-\$50+	\$10-\$80+	\$50-300+	\$30-\$200+	\$5-\$30

The best choice of ADC is a function of required speed, resolution, and power efficiency to be used for real-time processing of optical signals. The SAR ADC offers the best compromise of speed, resolution and effective samples of the optical sensor signals with low-power consumption.

ADS8319

The Texas Instruments ADS8319 is a 16-bit SAR ADC that provides a high-resolution digital output while maintaining a fast-sampling rate. This makes it a strong choice for this project, as it ensures precise signal conversion from the optical detector while being fast enough to process rapid fire detection responses. Since my system relies on accurate light intensity readings, having a 16-bit resolution allows for detailed signal differentiation, reducing false alarms or missed detections [68]. Additionally, its SPI interface ensures high-speed, reliable data transmission to the FPGA, preventing bottlenecks in the processing pipeline.

ADS7042

The Texas Instruments ADS7042, on the other hand, is a 12-bit, 1 MSPS ultra-low-power SAR ADC with an SPI interface. While it has a higher sampling rate than the ADS8319, its reduced resolution (12-bit) means that it may not capture as much fine detail in the optical signals from the optical detector [69]. But this compromise has the advantage of lower power consumption, and it's a good option if energy efficiency is a higher priority. Since my system is being supplied by an outlet, power consumption isn't a significant constraint, but if I wanted to reduce heat dissipation and increase efficiency, the ADS7042 could be a good option.

LTC2452

The Analog Devices LTC2452 is a low-power, ultra-compact ADC with a significantly lower sampling rate of 60 SPS. This model is designed for low-speed, high-precision applications, particularly where power efficiency is a priority [70]. Unlike the ADS8319, the LTC2452 features a fully differential input, allowing it to measure signals with higher accuracy while minimizing noise interference.

Table 27. ADC Comparison

Feature	ADS 8319	ADS 7042	LTC 2452
Resolution (bits)	16-bit	12-bit	16-bit
Sampling Rate (SPS)	500 kSPS	1MSPS	60 SPS
Input Type	Single-ended	Single-ended	Differential input
Input Voltage Range (V)	0 - 5.5	0 - 3.6	2.7 - 5.5
Interface	SPI	SPI	SPI

Cost	\$14.51	\$3.22	\$6
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ADS8319 is best suited for our system because of its high sampling rate, which enables fast conversion of sensor signals. In fire detection, photodiode signal speed and accuracy in handling are crucial since data capture delay can impact the detection response time. With a 16-bit resolution, it is precise enough to detect small variations in intensity in infrared or optical signals so that the system can distinguish between normal environmental fluctuations and actual fire events.

At one point, we successfully established SPI communication between the ADS8319 and the ESP32 MCU, and I was able to program the ESP32 to read accurate values from the ADC, which was receiving input from the transimpedance amplifier. However, the setup eventually stopped working, and we were no longer able to obtain reliable ADC readings. Suspecting a hardware failure, we replaced the ADS8319, but the issue persisted, indicating that the problem lay elsewhere. Due to time constraints, we decided to pivot and use the ESP32's internal 12-bit ADC instead. This alternative proved to be significantly simpler in terms of both wiring and programming, allowing us to move forward more efficiently.

3.2.6 LED

The selection of an LED is important in providing immediate visual indication on sensing fire. The LED is a simple but highly effective indicator that alerts users or operators of a potential fire occurrence, as additional feedback of the system. Choosing the right LED is crucial as it must balance high luminosity, power efficiency, and reliability to be easily seen under various light conditions without drawing too much energy from the system. Since our system aims to use the least amount of power, an LED with high luminosity at low currents preserves energy efficiency while still showing a clear visible indicator.

Additionally, the LED should be capable of supporting control schemes such as PWM of the FPGA or microcontroller to facilitate brightness adjustments or blink patterns that can enhance alert visibility and emphasis. An appropriately chosen LED not only adds to the functionality and safety of the system but also integrates well with the PCB design's electrical and power aspects. Therefore, the selection of a proper LED is not only an ancillary choice but a key step in making the fire detection system intuitive, effective, and reliable in offering visible indications to occupants when prompt attention is required.

Low-Power Indicator LEDs

Low-power indicator LEDs, consuming a current level up to 20 mA, are most energy-efficient and perfect for systems needing minimal power consumption [71]. However, their output brightness is low for larger areas, making them better employed in close-range indicator situations rather than large-scale alerts. The project envisions power efficiency as the primary goal above visibility, this option allows for a minimum power consumption on the constraint of maintaining an adequate alert [71].

High-Intensity LEDs

High-brightness LEDs consume higher power, drawing current within the 350-100 mA range, but offer significantly improved visibility, making them ideal for outdoor or larger area fire detection systems. These LEDs ensure that an alert can be seen from a distance,

which is crucial within emergency scenarios or for industrial environments. However, they require proper heat dissipation and power management, making them less ideal for ultra-low-power applications unless they are controlled using PWM to optimize energy usage [72].

Flashing/Strobe LEDs

Flashing or strobe LEDs become some of the best options for emergency warning systems, as these LEDs can grab attention better than a continuously lit LED. In practice, such LEDs generally get driven either from a built-in flasher circuit or, usually, via PWM control from a microcontroller [73]. As a result, LEDs are very efficient in that they light up in short bursts rather than a continuous operation. This would be an excellent choice if our main focus is the desire to reach out to people immediately about a dangerous situation from within extremely noisy environments where an LED on its own is not sufficient.

Addressable RGB LEDs

Addressable RGB LEDs allow for the building of a more customizable alert system with multi-color signaling, meaning your system could indicate the level of alert with a green, yellow, or red light. These LEDs require control via a microcontroller to give you more of a dynamic and programmable approach to fire alerts [74]. They are more power-hungry, consuming about 20 mA to 60 mA per LED, and they may require coding correctly to allow proper performance in the intended manner. They are more for the construction of a smart alarm system rather than a regular active/inactive warning for notifications. RGB LEDs could be included for more intuitive feedback.

Table 28. LED Comparisons

LED Type	Impact on Fire Detection	Current drawn	Luminous Intensity	Cost Ranges
Low-Power Indicator LEDs	Energy-efficient, simple alerts	Very Low (20mA max)	10 mcd-200 mcd	\$0.05-\$0.5 per unit
High-Brightness LEDs	Highly visible in large areas	Moderate (350-1000mA)	5000mcd-12000mcd	\$0.5-\$2.5 per unit
Flashing/Strobe LEDs	Strong attention-grabbing alert	Moderate (60-550mA)	100000mcd-300000mcd	\$1.5-\$5 per unit
Addressable RGB LEDs	Multi-color dynamic alerts	Moderate (20-60mA)	500mcd-2500mcd	\$0.2-\$1 per unit

To maintain low power consumption within the entire system, the low-power indicator LED is most attractive, thus making it an ideal choice for an energy-efficient system. Unlike high-brightness or strobe LEDs, that demand more power, a low-power LED ensures that my system remains sustainable and optimized for a long-term operation. By integrating this LED with PWM control, I can further reduce energy usage by adjusting brightness dynamically, ensuring that power is only used when necessary. While the brightness of a low-power LED may not be as intense as other options, it is sufficient for close-range status indication, ensuring that the fire detection system provides a clear visual alert without excessive energy drain.

Low Power Indicator LED Technologies

Würth Elektronik 151051RS11000

The Würth Elektronik 151051RS11000 is an indicator LED with low power consumption. It can operate 20 mA and has a forward voltage of 2.1V. It's not very bright nor too dim. The luminous intensity of 30 millicandela (mcd) allows its use in simple indicator applications where visibility is required, but power constraints are not extremely tight [75]. It is more efficient than super-bright LEDs; however, it is still substantially more consuming when compared with ultra-low power indicator LEDs, making it an inappropriate use in battery-powered or energy-conscious applications.

Kingbright L-934SRD

The Kingbright L-934SRD is one of the most efficient minimal power consumption devices in the low power consumption category, drawing 20mA at 1.8V [76]. It provides us a good balance between power efficiency and sufficient luminous intensity. Hence, it is well suitable for close-range or indoor indicators; however, it can be effective for long-distance visibility. Its main feature is that it extends battery life in energy-sensitive applications; thus, perfect for applications requiring continuous operation from limited power sources.

Osram LS L296

The Osram LS L296 is powerful and efficient LED that draws 20 mA at a minimum of 1.8 volts forward voltage and features a good compromise between power saving and brightness. In terms of luminous intensity, it can go up to a brightness of 112 mcd, while still maintaining low power consumption [77]. The LED also maintains a great balance between visibility and maintaining good energy economy while working very well with PWM dimming for dynamic brightness control.

Everlight 204-10SURD

The Everlight 204-10SURD is one of the best-balanced options for low-power applications. With current drawn at 20mA a forward voltage of 2.0V exists and can achieve high brightness at typically 80mcd [78]. The LED also provides PWM control, which can adjust the brightness dynamically, this allowing further energy savings.

Table 29. Low Power Red LED Comparisons

LED Model	Forward Voltage (V)	Current Drawn (mA)	Brightness (mcd) at 20mA	Cost
Würth 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

The rationale for selecting the Kingbright L-934SRD LED for my fire alarm system is its optimal compromise between low current draw and high brightness, making it a functional yet effective choice for visual warning function. The L-934SRD is a low forward current type, which allows it to contribute minimally to the system's overall power consumption — a very crucial factor considering my project's energy efficiency agenda. Although it has low power requirements, it has high luminous intensity so that warnings are conveniently observed under varying light conditions.

Additionally, its durability and reliability also ensure that it will continue operating through the entirety of the system's life with no replacements or normal maintenance. The PWM controllability of the L-934SRD makes it possible to modulate brightness and blink patterns, which can easily be integrated into the FPGA for indicating different system states. Overall, the Kingbright L-934SRD is a great selection for a system requiring reliable, bright, and power-efficient visual indication.

3.2.7 Buzzer

The buzzer is a critical component for providing immediate sound feedback to notify users in case of fire detection. While visual indicators like LEDs are critical, a sound alarm ensures attention is drawn with urgency even when the user's vision is not directly on the system. Selecting the right buzzer is critical in achieving a balance of sound output, power consumption, and reliability. The buzzer should emit a clear and audible sound that is audible throughout a room or noisy setting so that the warning is clear and imperative. Choosing the right buzzer also affects the system's ability to deliver stable, consistent alerts without failure through prolonged use.

Regardless of using an active or passive buzzer, the device should be able to operate well with the control circuitry to allow the production of simple or complex alert patterns via direct voltage control or PWM signals. The buzzer supplements the visual warning system with a redundant and highly effective warning system. This requires the precise selection of the buzzer to guarantee that the fire alarm system not only senses danger but transmit it clearly and effectively to anyone within the surrounding area.

Piezoelectric Buzzers

Piezoelectric buzzers are widely used in low-power applications, often less than 10 mA and can usually operate in the range of 3V to 250V and offer the best choice for energy-conscious implementations [79]. They consist of piezoelectric element which vibrates when a particular electrical voltage is applied producing sound waves. Despite their energy efficiency, the sound from the piezoelectric buzzers is ordinarily quite loud, usually within the vicinity of 70-90 dB and especially at their resonant frequency range of 2kHz - 6kHz that aligns with the human ear peak sensitivity [79]. This makes them suited for use in quiet indoor environments such as offices, residences, or small commercial venues [96]. However, regarding very noisy or industrial environments, the sound output from piezoelectric buzzers may not be sufficiently loud to notify any individual in the case of a fire.

Magnetic Buzzers

Magnetic buzzers provide a good compromise between sound intensity and power efficiency, with an output of 70-95 dB and an operational frequency of 1-3 kHz. They draw more power than piezo buzzers, at 20-60mA, but are energy-efficient enough to be usable in situations where moderate volume is needed in moderately noisy surroundings [79]. Thus, magnetic buzzers would suit fire-alarm systems installed in office blocks, schools, or apartment complexes where background noise may be present to an extent but not overly so. Another advantage of magnetic buzzers is clearer and deeper tone, usually interpreted as a signal for urgency, and this means they would work more effectively in grabbing the attention of people. However, they might be more prone to magnetic interference and not the best choice in environments with huge electromagnetic activity. While not as power conscious as piezo buzzers, magnetic buzzers strike a balance between volume and energy use, making them a versatile choice for many fire detection scenarios.

Table 30. Buzzer Comparisons

Buzzer Type	Piezoelectric	Magnetic
Operating Voltage	3 – 250V	1.5-12V
Current Drawn	Max 10 mA	20-60mA
Resonant Frequency	2-6kHz	1-3kHz
Sound Level	85-120dB	70-95dB
Cost Range	\$0.1-\$5 per unit	\$0.8-\$3.5 per unit
Best Usage	Low Power Systems	Moderate noise environments

I selected the piezoelectric buzzer as my fire alarm system component due to its impeccable low-power consumption and high-sound output balance, which is ideal for delivering efficient audible notification without exhausting the power budget of the system. Piezoelectric buzzers, unlike magnetic buzzers, can produce higher, more piercing sounds at reduced currents, which renders them extremely economical for constant or repetitive operation in an alerting system. This causes the buzzer to emit an acoustically perceivable sound through the noise of the environment, making sure that warning notices for fire are audible and prompt.

Furthermore, piezoelectric buzzers are extremely reliable and long-lasting, having no moving parts, which eliminates the possibility of mechanical wear or breakdown over time. Having such a broad frequency range also enables me to make the sound as attention-grabbing as possible. With this synergy of good acoustic presence, low energy requirement, and durability, the piezoelectric buzzer emerges as the best option to provide ongoing and effective audio feedback for this project.

Piezoelectric Buzzer Technologies

Murata PKM13EPYH4000-A0

Murata PKM13EPYH4000-A0 is a small and effective speaker that produces a sound pressure level of around 78 dB when driven from a wide voltage range of 3 to 15 V. It is highly appropriate for space-constrained systems where low-power operation is critical, though its sound output is modest compared to others [80].

TDK PS1240P02CT

The TDK PS1240P02CT steps down the sound level to 70 dB output at 10 cm and operates at a maximum of 15V[81]. Its solid build and stable frequency output make it particularly appropriate for industrial and embedded applications where reliability is paramount.

CUI Audio CPT-1495C

For applications requiring more audio presence, the CUI Audio CPT-1495C generates a massive 84 dB at 10 cm with a resonant frequency of 4.25 kHz [82]. This makes it highly efficient in larger environments where higher volumes are required for instant identification, although it does mean slightly more power usage.

Mallory Sonalert PS-12

The Mallory Sonalert PS-12 is an industrial-service piezo buzzer that can support a broad operating voltage range of 5 to 15 V with a satisfactory 85-100dB at a 100cm distance and is suitable for long-range alarm usage or harsh industrial application where broad operating conditions are crucial [83].

Kingstate KPEG158

The Kingstate KPEG158 provides a decent 70-85 dB at 10 cm, and it is a decent all-around buzzer for overall fire alarm or warning applications [84]. Its compact PCB mounting and balance between power efficiency and audible presence make it an appropriate mid-range choice for decent, reliable alarms without excessive power consumption.

Table 31. Piezoelectric Buzzer Comparisons

Features	Murata PKM13EPYH4000- A0	TDK PS1240P02 CT	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

I selected the Mallory Sonalert PS-12 due to its ideal combination of loud sound output at a significant distance and efficiency in power, thus proving to be a reliable and effective choice for an audible fire alarm. It can provide up from 85 to 100dB at the rated voltage of 12V within 100cm of the buzzer which is farther than the other buzzer models that were considered. With its ability to project at longer range, it makes sure that occupants receive instant notice and unambiguously, thus making the system more secure and responsive.

Also, the PS-12 is an active buzzer, which means it has an internal oscillator. Once a DC voltage of operating range is applied it outputs sound, and we have been able to control that sound via PWM. While possessing higher output sound, it is still power saving, which makes it quite suitable for this project's objective of low energy consumption without performance compromise. Its durable industrial-grade design also ensures long-term reliability and durability, critical factors for a system that's designed to be constantly on standby. The PS-12 is a sturdy, dependable choice that compromises on audibility, simplicity, and power efficiency.

3.2.8 Button

Selecting the right switch or button is important to provide manual control and user input to the system. The button activates or deactivates the motor scanning function, offering users a convenient and simple way of activating or halting the detection process. Choosing an appropriate button technology ensures the user interface is resilient, responsive, and durable, especially in an application where frequent manual use may be required. The button has to offer a suitable balance of tactile feel, useability, and mechanical lifetime so that the user can utilize the motor with confidence without accidental use or mechanical failure after a long time.

Furthermore, the button should comfortably fit within the physical limits of the PCB and enclosure as well as be electrically compatible with the control electronics. In an application like fire detection where the system is safety-critical, responsiveness and dependability are all-important — an ill-chosen button could cause lost commands or delayed system response. Whatever it is that is applied to initiate scanning, system reset, or manual override initiation, selecting the right button technology is essential to the delivery of smooth user control, system dependability, and system overall performance.

Tactile Switches

Tactile switches, a form of mechanical switch, offer an even more compact design-or simply to reduce the physical size of the control interface, tactile switch is light in weight and has a low profile [85]. While these switches offer less tactile feedback than other heavy weight mechanical push-buttons, they still provide enough displacement when operated to confirm that the motor control has been energized [85]. They are a good candidate for compact control panels or embedded systems in an enclosure because of their small size and low power needs. Still, for critical functions such as the start/stop switch of the motor, the tact switch chosen has enough actuation force to prevent accidental presses. When coupled with an LED indicator or buzzer acting as a confirmation of the state of the motor, tact switches form a worthy space-saving solution.

Capacitive Touch Buttons

For a more modern or sealed interface, a capacitive touch button could be an innovative alternative, one that is perfect for situations where dust, moisture, or dirt threaten to weather the system. A capacitive button operates through the evolutionary process of the human body, and no physical force is required to operate it [86]. Thus, they are fully sealed and exceedingly durable over time. A capacitive touch button would facilitate toggling the motor between active scanning and idle modes with a simple touch and provide an aesthetically pleasing interface, very easy to clean within the fire detection system. However, given that capacitive buttons do not furnish tactile feedback, integrating visual cues, like an LED indicator changing depending on the motor's status, or an audible indicator, essentially confirm user actions [86]. They consume slightly more power than mechanical switches and require more complicated control circuits, but their durability and sleek design fill a niche for applications where appearance and environmental sealing matter.

Membrane Switches

For ultra-thin, fully sealed interfaces—such as for a control panel mounted onto the system—then membrane switches might also suffice. Membrane switches are made of flexible layers of printed circuits and provide an interface that is flat and weatherproof. They are excellent to be used in external and rugged environments in which the system could encounter dust, water, or debris [87]. Within our system, a membrane switch could have simple labels such as "START" and "STOP," indicating to engage and disengage the engine. Similar to capacitive touch buttons membrane switches typically provide a softer touch than mechanical push buttons, they can be used with visible indicators, such as an LED, to further demonstrate the state of the motor. Again, they can be integrated into small control panels because they are very thin, although they might not be as resilient under heavy or repeated use situations as mechanical buttons.

Piezoelectric Buttons

For situations where durability and environmental resistance are key—such as outdoor installations or high-use areas—piezoelectric buttons may be perfect. Packed with no moving parts, the piezoelectric buttons are solid-state [88]. When pressure is applied to the surface, a voltage spike is generated, triggering the motor controller. Within our system, a piezoelectric button may serve as the rugged start/stop control for the scanning motor, able to withstand harsh weather, dust, or even moisture [88]. While piezo buttons do not offer tactile feedback, they can be coupled with visual or auditory indicators to confirm that they activate or deactivate the motor. Their very long life and withstanding high impact make them ideal for public areas or industrial applications, thereby keeping the system functional even in harsh conditions [88].

Optical Touch Buttons

When vulnerable to infection from touch or if hygiene might be a concern, the optical touch buttons permit total contactless usage [89]. By way of infrared sensor, it allows sensing hand proximity, permitting the operator to start or stop the motor without having to physically touch the surface of the button. Reduced wear and contamination work in conjunction with the use of an optical touch button for the purpose of controlling the motors

of our system, especially when it is affixed in an accessible position for utilization. Optical touch buttons are more expensive and sensitive to ambient light but offer a hygienic solution that requires low maintenance in an application where user health or long-term durability is important.

Table 32. Button Comparisons

Feature	Tactile Switch	Capacitive Touch	Membrane Switch	Piezoelectric Button	Optical Touch Button
Activation Mechanism	Dome-shape actuator providing feedback	Senses electrical capacitance change	Pressure applied to conductive layers	Pressure generates an electrical charge	Infrared or optical sensor detects touch
Power Consumption	Low	Moderate	Low	Low	Moderate
Tactile Feedback	Moderate	Low	Low	Low	Low
Durability	High	High	Low	Very High	High
Size Ranges	3x3 - 12x12	10x10 - custom panel sizes	50x50-full keypad panels	12x12-22x22	20x20-30x30 with embedded IR sensors
Cost	\$0.05-\$0.5 per unit	\$1.5-\$8 per unit	\$3-\$15 per unit	\$10-\$30 per unit	\$10-\$25 per unit

I have decided to select tactile switch push button. Tactile switches present a compact and efficient solution suitable for limited or space-constrained scenarios while integrating their very usage into projects. Their small footprint allows them to be mounted directly on a PCB, thereby reducing the need for additional mounting hardware, which simplifies the overall assembly. The integration of these tactile switches allows for an improvement in production efficiency and reliability due to a reduction in external connections liable to subject to wear or failure. In addition, tactile switches are designed to provide solid and consistent tactile feedback so that every user action is picked up correctly, especially important in safety-related applications. Owing to their sturdy construction and high mechanical life, tactile switches contribute to long-term durability.

Tactile Switch Technologies

Omron B3F Series

The Omron B3F Series is known for its superior durability and crisp tactile feedback, making it one of the most widely used designs that integrate switches directly into PCBs [90]. The switches come in a few actuation force variances that let the designer precisely customize the switch to his project requirements. Its small footprint (6mm x 6mm) makes it ideal for applications with space constraints, allowing them to easily fit into the overall

design [90]. When you put these specifications together, a proven track record in both consumer and industrial applications makes the Omron B3F Series a versatile and dependable solution.

C&K PTS Series

The C&K PTS series places itself in sharp contrast with ultra-low-profile constructions, apt in situations where PCB layouts are space- and size-constrained. Models like the PTS645 and PTS526 are purposefully designed not to increase the total height of the switch, keeping it thin for use in sleek modern devices still requiring low-profile components [91]. Besides their compactness, these switches provide the user with reliable tactile feedback and consistent performance to ensure user input is accurately registered even under conditions where space constraint might pose a challenge. Their suitability to address diverse design specifications, backed by different available height profiles, further strengthens the PTS series for a wide range of applications [91].

E-Switch TL1105 Series

The TL1105 series E-Switches are designed with high robustness and long life so that they fit very well into a high-usage application. The series is designed with an emphasis on durability and stable performance, thus featuring reliable tactile feedback for a high number of cycles, which is a critical requirement in safety-critical and high-usage environments. The design of these buttons allows for a variety of actuation forces, fine-tunable according to user preferences and application needs [92]. The TL1105 series is really built tough and durable, such that it does maintain performance integrity under demanding situations.

ALPS SKRP Series

The ALPS SKRP Series is characterized by the blend of a soft click tactile response and again, super-low profile design, making this series perfect for interfaces where subtle and precise feedback is critical [93]. Constructed to provide a gentle yet discernible click upon actuation, thus enhancing user experience in applications that prioritize a more refined tactile feel. The form factor is low enough to allow integration onto very compact PCBs, not taking up any extra space, which is particularly useful for devices where each millimeter of space counts [93]. The SKRP Series is, in other words, well suited for designs where aesthetic integration and nuanced tactile response are both central.

Panasonic EVQ-P Series

The Panasonic EVQ-P Series stands out with its ultra-compact dimensions, making it an excellent choice for designs that demand minimal space usage with PCB integration. These switches not only offer a very small footprint but are also designed for a high operating life, ensuring longevity even in applications that require frequent actuation [94]. The series provides multiple height profile options, giving designers the flexibility to optimize the switch integration based on the specific constraints and needs of the project. This combination of compact size, durability, and versatility makes the EVQ-P Series particularly attractive for modern, space-sensitive electronic designs [94].

TS02 Series

The TS02 Series has been purpose-designed with a focus on PCB integration. Compact yet notably keeping switch bounce to a minimum, it offers consistent actuation performance. There are several variants, such as the TS02-66-130 and TS02-66-153, with variations in serrations such as actuation force and mechanical life to allow performance that can be tailored toward application requirements [95]. Emphasis is laid on reliability and durability of design, enabling the switch to act without fail in safety-critical systems such as fire detection or alarm panels. Overall, the TS02 Series combines a compact design with precise tactile feedback and solid construction; an attractive combination indeed for applications where performance and ease of integration are both called for.

Table 33. Button Model Comparison

Feature	Omron B3F Series	C&K PTS Series	E-Switch TL1105 Series	ALPS SKRP Series	Panasonic EVQ-P Series	TS02 Series
Actuation Force	100-260 gf	100-300 gf	160-260 gf	100-260 gf	100-350 gf	160-300 gf
Lifespan (cycles)	300k – 10 million	Up to 500k	100k-500k	Up to 500k	1 million	100k
Size Range (mm)	6x6-12x12 (various sizes)	4.2x3.2-6x6	Typically 6x6	Typically around 4x4	Typically 6x6	Typically 6x6
Tactile Feedback	Strong, crisp tactile click	Moderate to strong tactile feel	Moderate tactile click	Soft but noticeable	Strong tactile click	Strong tactile click
Typical Application	Industrial controls, keypads, reliable switches	Consumer electronics, automotive	General purpose consumer and industrial products	Mobile devices, consumer electronics	Remote controls, wearable devices	Cost-effective simple button use
Cost Range	\$0.30-\$1.20 per unit	\$0.20-\$0.80 per unit	\$0.15-\$0.60 per unit	\$0.20-\$1 per unit	\$0.25-\$0.90 per unit	\$0.10-\$0.30 per unit

I have decided to make the choice of selecting the TS02 especially because of reliability, performance, affordability, and ease of integration. The TS02 is primarily designed for PCB integration, making it ideal for compact projects where space is an issue. It has a small form factor, allowing a clean fit onto cramped circuit boards without compromising performance. Also, tactile feedback is both clear and consistent, which is in high demand due to its necessity in safety-critical applications such as fire detection systems-it ensures that a user input is taken into consideration. One benefit to this switch series is that the switch bounce is low and thus it allows the entire system to be reliable by preventing false

activations or missed inputs. The availability of numerous variants with different actuation forces and mechanical live spans will help customize the TS02 according to specific project needs- user comfort or high-frequency actuation. It has a robust construction and thus can withstand heavy use for a very long time; therefore, it is a very good option for projects that require switches capable of performing reliably for quite a long period. All these benefits incorporated-small in design, well-directed feedback, durability, and form customization-make it an exceptional solution for both performance and ease of integration.

We ultimately selected a different button to enhance the overall aesthetic of our design. The PR144C1900 E-Switch, a larger red push button, was chosen over our initial selection purely for its visual appeal. As we progressed to the final stages of the project, creating a clean and polished appearance became a priority, and this switch better aligned with our desired design aesthetic.

3.2.9 External Memory

Memory Types (Volatile vs Non-Volatile)

In FLAMES, we were originally selecting the right external memory for our Artix-7 FPGA PCB and was essential for balancing performance, power efficiency, and data retention. Memory falls into two categories: volatile and non-volatile, each with its own advantages and trade-offs. Volatile memory, such as SRAM (Static RAM) and DRAM (Dynamic RAM), provides fast access speeds and low latency, making it ideal for real-time processing and frequent data updates. However, volatile memory loses all stored data when power is removed, making it unsuitable for long-term storage [96].

Non-volatile memory retains data even without power, ensuring persistence and reliability. Flash memory and EEPROM (Electrically Erasable Programmable Read-Only Memory) are common non-volatile options, with flash memory being widely used for its high storage density and low power consumption. The downside is that non-volatile memory typically has slower write speeds and limited endurance, which can be a disadvantage for applications that require frequent memory updates. In FLAMES, the choice between volatile and non-volatile memory depends on the specific system requirements [97]. Volatile memory is better suited for real-time computations, while non-volatile memory ensures long-term data storage and integrity.

For FLAMES, selecting the right mix of SRAM, DRAM, and Flash memory if using an FPGA PCB was critical. Since this type of system requires real-time processing and efficient data storage, SRAM or DRAM could be used for high-speed temporary data, while Flash memory would be considered only for storing essential long-term data. The table below summarizes the key characteristics of these memory types.

Table 34. Volatile vs Non-Volatile Memory Types Comparison

Memory Type	Volatile/Non-Volatile	Advantages	Disadvantages
SRAM (Static RAM)	Volatile	Fast access, low latency, no refresh needed	Expensive, low density

DRAM (Dynamic RAM)	Volatile	High density, cost-effective	Requires constant refreshing, loses data without power
Flash Memory	Non-Volatile	Retains data after power loss, high density	Slower write speeds, limited write cycles

DRAM

Selecting the right external DRAM (Dynamic Random Access Memory) could have been essential for FLAMES to efficiently handle real-time data processing and high-speed memory access. DRAM acts as the primary working memory, temporarily storing data for quick retrieval and modification before it is overwritten. Unlike SRAM, which has lower latency but a significantly higher cost per bit, DRAM provides a high-density and cost-effective solution, allowing for larger storage capacity while maintaining fast read and write speeds. Since FLAMES continuously recalibrates its environmental baseline, the choice of DRAM needs to balance latency, power consumption, bandwidth, and cost to support real-time photodiode data processing. Three DRAM types were considered: DDR3, DDR4, and LPDDR (Low-Power DDR).

DDR3 DRAM is a widely used memory standard known for its cost-effectiveness, stable performance, and broad compatibility. Operating at 1.5V (or 1.35V for DDR3L variants), [98] DDR3 offers data transfer rates up to 2133 MT/s, making it a solid balance of performance and power efficiency for applications that do not require extremely high memory bandwidth [99]. While DDR3 does not match DDR4's speed and efficiency, its lower cost and reliability make it the better choice for systems that prioritize consistent and predictable performance over peak efficiency. [96].

DDR4 DRAM is the successor to DDR3, offering higher bandwidth (up to 3200 MT/s) and lower operating voltage (1.2V) [100]. DDR4 features improved power efficiency and higher density, making it better suited for modern computing applications with heavy multitasking and data-intensive operations. However, DDR4 introduces increased latency in row activation time (tRCD, tRP, and CAS latency) due to its higher prefetch size, which can slightly impact real-time processing tasks that require rapid memory access. Additionally, DDR4 requires a more complex memory controller, which increases overall system cost and power overhead. Given that FLAMES is not operating under extreme memory bandwidth constraints, DDR4's additional speed does not provide a significant advantage over DDR3 for this application [101].

Lastly, LPDDR (Low-Power DDR) is designed primarily for mobile and embedded applications, LPDDR operates at significantly lower voltages (1.2V or 1.8V for LPDDR3 and as low as 0.5V for LPDDR5) [102] and features advanced power management techniques such as deep power-down modes and per-bank refresh. While LPDDR is ideal for battery-powered devices due to its efficiency, it trades off some performance for power savings and is typically used in smartphones, IoT devices, and ultra-low-power embedded systems. Given that FLAMES does not operate on battery power, the advantages of LPDDR are not significant enough to justify its higher cost and lower bandwidth compared to standard DDR memory.

After comparing these options, DDR3 DRAM (MT41K64M16TW-107 IT) would have been chosen as the best fit for FLAMES. Its cost, performance, and system compatibility make it ideal for real-time environmental baseline recalibration. Since the system does not require extremely high memory bandwidth or ultra-low power consumption, DDR4 and LPDDR were unnecessary for this implementation. DDR3 strikes the right balance between speed, reliability, and affordability, keeping system complexity and power requirements at a manageable level while ensuring efficient operation.

Table 35. DRAM Type Comparison

DRAM Type	Voltage	Bandwidth (MT/s)	Latency Considerations	Power Efficiency	Suitability for FLAMES
DDR3	1.5V (1.35V for DDR3L)	Up to 2133	Moderate	Moderate	Best choice due to cost-performance balance
DDR4	1.2V	Up to 3200	Higher row activation latency	High	Unnecessary for FLAMES; increased cost and latency
LPDDR	1.2V-1.8V (LPDDR3) to 0.5V (LPDDR5)	Varies	Low	Very High	Not needed as FLAMES is not power-constrained

SRAM

For real-time data processing, selecting the right external Static Random-Access Memory (SRAM) could have been essential for low-latency, high-speed performance in FLAMES. Unlike DRAM, which requires constant refreshing, SRAM retains stored data as long as power is supplied, making it ideal for applications that demand fast, predictable memory access. Since FLAMES continuously processes real-time sensor data, SRAM is used to store immediate sensor readings, intermediate calculations, and system control variables, where quick retrieval and minimal access time are critical. Different SRAM types were evaluated based on latency, power consumption, and suitability for high-speed embedded applications.

Asynchronous SRAM (Async SRAM) is a traditional SRAM type where memory access is independent of a clock signal. Since data access is controlled by address and control signals alone, Async SRAM provides simpler system integration but generally slower performance compared to synchronous alternatives. This memory type is best suited for low-power, low-speed applications but is not ideal for real-time processing in FLAMES due to its higher access times [103].

Unlike Async SRAM, Sync SRAM is clock-driven, meaning that memory operations are synchronized with the system clock. This reduces access latency and improves data throughput, making it better suited for high-speed applications. Sync SRAM is particularly useful in real-time systems where timing consistency is crucial. Variants such as pipeline-burst SRAM (PB-SRAM) and flow-through SRAM further optimize performance for applications that require continuous data access with minimal delay [104].

Non-Volatile SRAM (nvSRAM) retains stored data even when power is lost by incorporating a non-volatile storage element. While nvSRAM is beneficial for systems that require persistent memory storage, it introduces additional complexity and cost, which is unnecessary for FLAMES, since the system does not require data retention between power cycles [105].

Given the system's need for fast real-time processing without requiring data persistence, Synchronous SRAM (CY7C1061G) could have been selected as the best option. Since Sync SRAM operates with the system clock, memory access remains predictable and efficient, minimizing bottlenecks when processing photodiode sensor data. Unlike Async SRAM, which can introduce delays due to variable access times, Sync SRAM ensures consistent read and write operations that align with FLAMES's processing requirements. Because FLAMES demands immediate response times for environmental baseline analysis and anomaly detection, the system must have fast, reliable access to frequently used sensor data without delays. The use of Sync SRAM guarantees this accessibility, preventing interruptions in data retrieval and processing. Additionally, since FLAMES recalibrates its baseline with each activation, the data retention feature of nvSRAM is unnecessary, making Sync SRAM the most cost-effective and efficient choice for this application.

Table 36. SRAM Type Comparison

SRAM Type	Clock Dependency	Latency	Data Persistence	Suitability for FLAMES
Asynchronous SRAM	No	Higher	No	Not suitable due to slower performance.
Synchronous SRAM	Yes	Low	No	Best choice due to high-speed access and real-time compatibility
Non-Volatile SRAM	Yes	Low	Yes	Unnecessary; FLAMES does not require persistent data

Flash Memory

Flash memory is a type of non-volatile storage that retains data even after power loss, making it an essential component in many embedded systems for firmware storage,

configuration retention, and long-term data logging. However, in FLAMES, external flash memory was not considered due to its high write latency, limited endurance, and lack of necessity for real-time operations. The system does not require persistent storage across power cycles, eliminating the need for a memory solution that prioritizes long-term data retention over speed.

Several types of flash memory were considered for FLAMES, including NOR Flash and NAND Flash, each with distinct characteristics. NOR flash is known for its fast read speeds and byte-addressable memory structure, NOR flash is commonly used for code storage in embedded systems. While it allows for random access, its write and erase speeds are significantly slower compared to SRAM and DRAM. Furthermore, NOR flash has a limited number of write cycles (typically 10,000 to 100,000 cycles per block [106]), which could become a bottleneck in applications requiring frequent memory updates. Given that FLAMES recalibrates its environmental baseline upon each activation, there is no need for long-term data retention, making NOR flash unnecessary.

Unlike NOR flash, NAND flash is optimized for high-density storage and sequential data access, making it well-suited for mass storage applications such as SSD drives and data logging systems. While NAND flash provides a higher storage capacity per dollar compared to NOR flash, it suffers from even higher write and erase latencies and is not designed for frequent random-access operations. In FLAMES, where fast, real-time data processing is required, the slow write speeds of NAND flash would introduce unacceptable delays and unnecessary complexity

After evaluating the trade-offs of flash memory, it was determined that it was not necessary for FLAMES, as the system does not require persistent storage across power cycles. The main reasons for excluding flash memory include several reasons. Since FLAMES recalibrates the environmental baseline upon each activation, retaining previous data is not needed. Flash memory has slower write speeds and limited write/erase cycles, making it unsuitable for real-time memory updates. Flash memory requires higher power to erase and write data, while DRAM provides faster, temporary data storage without these constraints.

Instead of flash memory, a combination of DRAM and SRAM was chosen to ensure fast processing speeds, low-latency memory access, and efficient real-time computation. Flash storage would have introduced unnecessary complexity without offering meaningful benefits, making DRAM and SRAM the more efficient and practical choices for the system.

Table 37. Flash Memory Types Comparison

Flash Memory Type	Advantages	Disadvantages	Suitability for FLAMES
NOR Flash	Fast read speeds, ideal for firmware storage	Slow write speeds, limited write cycles	Not needed; system does not require persistent storage
NAND Flash	High storage density, cost-effective for bulk storage	Poor random access, high latency for writes	Not suitable for real-time processing

No Flash Memory	Eliminates unnecessary complexity, lower latency	No long-term storage capability	Best choice for real-time, volatile processing
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3.3 Power Management

3.3.1 Power Delivery

Several key elements, shown in Table 38 require power delivered directly through carefully designed voltage regulation circuits. These components all have specific voltage levels and power ranges, and to enable them to run safely through stable operation. The system must be equipped with mechanisms that reduce the voltage from the main power source and limit current to protect each component. Starting from a more elevated input voltage provided by the power adapter, buck converters and linear regulators have been implemented to bring down the voltage to the requisite levels, namely 5V and 3.3V, efficiently and with little ripple.

In addition to voltage regulation, current-limiting techniques are also essential. The ADC and photodiode are susceptible to oscillation and must be protected against high current by filtering capacitors and current-limiting resistors. High but stable current supply is necessary for FPGA and Raspberry Pi 5, which necessitates the utilization of high-current buck converters with overcurrent protection and thermal shutdown features. Collectively, these voltage regulation and current limiting techniques form the foundation of powering the system's key components reliably and safely.

Table 38. Power Management

Component	Power Consumption	Operating Voltage
Si Photodiode (FDS1010)	3uW (5V bias), 250mW (25V max bias)	5V - 25V (reverse bias)
Basys 3 Artix 7 FPGA Board	5W	5V
Microcontroller (ESP32)	231mW	3.3V
Raspberry pi 5	3-5W (idle), 7-10W (moderate load), 20-25 (heavy load)	5V
ADC (ADS 8319)	0.25uW (power-down mode), 18 mW (typical) at 5V	2.25V-5.5V
Motor Driver (DRV8825)	12.3-67.5W	8.2V - 45V

In addition to the components that receive regulated power directly, several other components (specifically stepper motor, buzzer, and LED indicator) have been powered via Pulse Width Modulation (PWM) signals. PWM control allows for selective modulation of the delivery of power by rapidly switching the signal on and off at a controlled duty

cycle and frequency. In the case of the stepper motor, the PWM outputs by the motor driver offer control on motor steps and speed to provide accurate scanning of the surroundings without power wastage. The buzzer has further been driven with PWM control to output audible fire detection signals, the tone and the duration of the sound being settable for generating signals for attentions without permanent current draw. The LED indicator, used for visual status feedback, have been modulated via PWM to adjust brightness levels and flashing patterns, helping signal system status or fire detection events clearly while minimizing power consumption. Integrating PWM control for these components allows for greater efficiency and flexibility, enabling dynamic response behaviors and controlled power usage that align with the low-power, precision-driven design goals.

3.3.2 Adapter

Selecting the proper power adapter is a crucial decision that directly affects the overall performance, stability, and reliability of the entire system. The adapter is the primary source of power, delivering the correct voltage and current to all the essential components. Without a proper adapter, the system is prone to erratic power supply, voltage sag, or insufficiency insufficient current capability, thus giving rise to abrupt resets, reduction in lifespan of components, and spurious fire detection reaction. Therefore, not only does the adapter need to provide a suitable output voltage, but also a sufficient level of current, protected by attributes of overcurrent protection and short-circuit protection for dynamic demands of the system.

Particularly, since this project has components with varying power demands, it is essential to select an adapter with a high enough current margin. A high-power, stable adapter ensures that all subsystems are operating within their rated parameters, even during maximum operation when all devices are activated simultaneously. This guarantees the fire detection system can run efficiently, safely, and uninterruptedly without degradation in performance or interruption in the system. Basically, the power adapter offers the backbone of our power management system, maintaining both the functionality and lifespan of all the components incorporated into it.

Adapter Models

Table 39. Adapter Model Comparisons

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
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I have selected the LXLQZXW Adapter for our system due to its balance of cost-effectiveness, high current capacity, stability, and reliability required to supply power to all the components in my design. With a constant supply of 12V at 10A, the adapter delivers a total output of 120W [107], giving me more than sufficient power headroom to run heavy loads such as the Raspberry Pi 5, FPGA, microcontroller, motor driver, ADC, and photodiode without risking voltage drops or system instability. This high current capacity is especially useful when multiple high-power components, like the stepper motor and Raspberry Pi, are active simultaneously. This adapter also incorporates overcurrent, overvoltage, and short-circuit protection within it, adding an additional layer of safety and protecting the system under varying load conditions.

Moreover, the 12V supply allows for an easy handling of power, which allows me to step down voltage efficiently to power lower-voltage components. The build quality, durability, and reliability of the adapter make it an excellent long-term power solution, which keeps the system operating perfectly and continuously through long scanning and monitoring sessions. Overall, the LXLQZXW Adapter is a well-matched product that ensures the power requirements of our system with efficiency, safety, and flexibility.

3.3.3 Power Jack

The selection of the power jack is a critical decision that directly affects the reliability, safety, and long-term functionality of the system. The power jack creates the primary interface between the external power adapter and the general power management system of the PCB. The power jack is needed to handle the total current load supplied by the adapter while maintaining a secure mechanical and electrical connection. A poorly chosen jack with a low voltage or current rating can lead to system failure, overheating, or power instability — any one of which may compromise the system's ability to detect and respond to fire outbreaks in real time. Therefore, the power jack must not only physically fit the plug size of the power adapter but also be rated for continuous high current to provide power-hungry loads such as the Raspberry Pi 5, stepper motor driver, and other significant components.

The power jack must be capable of handling the level of current without degradation or failure. Its role is more than that of a connector — it is the gateway that ensures stable power supply to voltage regulators, microcontrollers, FPGA, and motor systems. A proven, industry-grade jack with appropriate barrel size and available current capacity provides safe operation, reduces disconnection hazards, and can withstand mechanical forces in long-term operating conditions. The power jack, therefore, is a vital piece of equipment that improves the reliability and continuous operation of the entire fire alarm system.

Power Jack Models

Table 40. Power Jack Comparisons

Model	Current Rating	Voltage Rating	Barrel Size	Cost
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PJ-080BH	10A	36V	5.5x2.5mm	\$1.83
KLDHCX-8-0202-B	8A	24V	6.5x2.5mm	\$2
PJ-082BH	10A	24V	5.5x2.5mm	\$1.78

I have chosen the PJ-082BH power jack because it has an ideal fit with the specifications of my power adapter, ensuring both mechanical and electrical compatibility. The adapter plug's outer diameter is 5.5mm and inner diameter is 2.5mm, and the PJ-082BH is designed specifically for that plug dimension, so it can be fitted securely and tightly, preventing intermittent power drop or disconnection during operation [108]. Additionally, the voltage and current levels of the PJ-082BH are safely inside the parameters for enabling the adapter's 12V, 8A output, ensuring consistent power delivery to critical system elements like the Raspberry Pi 5, FPGA, stepper motor driver, ADC, sensors, and visual/audio feedback components.

This model is a good choice not only due to its electrical efficiency but also due to its mechanical durability and long life. The PJ-082BH is constructed for high-current use and possesses rugged construction that endured repeated insertion and mechanical stress without compromise in performance. This jack ensures that the power interface is safe, stable, and strong in the years to come. Choosing the PJ-082BH reduces the risk of overheating, voltage sag, or accidental disconnection, ultimately leading to the long-term operational reliability and safety of the whole fire detection system.

3.3.4 Energy Sources

3.3.4.1 Wall Outlet

One of the simplest and most reliable sources of power is a wall outlet, which gives a steady and uninterrupted supply of power. In our system, by using an adapter plugged into an outlet to convert the energy guarantees that the system is always powered without fear of energy exhaustion. This is especially critical in a fire detection system, where the system must run 24/7 without the possibility of downtime. Having an outlet as the energy source, you eliminate the hardship of voltage drop or loss of power in conjunction with the limitation of small-scale energy storage. You also have the capacity with an outlet to include voltage regulators to change the voltage levels to accommodate the specific needs of all the different components from the FPGA and photodiodes to the stepper motor and visual/auditory feedback units. This technique allows continuous scanning and live fire detection without the need for periodic maintenance or battery replacement.

3.3.4.2 Batteries

As a power source, batteries impose significant limitations on a system whose functionality must be uninterrupted. While batteries have the benefit of mobility and can be utilized in remote or transient applications, they are limited in energy storage and will eventually drain as time goes by, needing constant recharging or replacement. This is certain to impact the reliability of a fire detection system, especially if battery condition isn't watched over with care. In addition, while discharging batteries, they experience voltage drops, which may influence sensitive components like the ADC or photodiode arrays and introduce potential errors in fire detection. Even rechargeable high-capacity batteries have the limitation of

limited cycle life, which means that they deteriorate with each use and decrease the overall lifespan and reliability of the system.

3.3.4.3 Power Banks

Power banks, while seeming to be a compromise solution, suffer from the same problems. Designed for portable use, power banks have higher capacities than regular batteries but are still not capable of providing the constant, long-term power that an outlet can. They are capacity-constrained and must be recharged frequently, introducing a maintenance element that is not suitable for a system that needs to operate continuously. Power banks usually carry more heat-related problems as well when being used continuously, especially with high-current loads of high-current appliances like the Nema 23 stepper motor. Although these could be good back-up sources of power in instances of short-duration disruption, relying on them as the normal power source would cause intrinsic vulnerabilities within the fire detection system.

With a wall outlet selected as the source of power, our fire detection system would benefit from constant power supply, consistent voltage supply, and absence of downtime with battery replacement or recharging power banks. We have harnessed this power with an adapter that steps down the voltage and converts it into a DC signal so we can further implement within our PCB. This selection is the best fit with the system requirement for continuous observation so that detection functionality is always on and ready, and the system is still responsive when most needed. Whereas power banks and batteries make portability possible, their in-built limitations make them less suited for an application in which there is the need for uninterrupted power for safety and functionality purposes.

One feature I hadn't considered until after completing the design was the inclusion of a dedicated power switch. Currently, our system powers on automatically as soon as the adapter is plugged into the wall outlet. In hindsight, I would have preferred to implement a switch that allows the user to manually turn the system on or off. This would provide greater control and safety, ensuring the system remains off until the switch is intentionally toggled to the 'on' position.

3.3.5 Voltage Regulation

Selecting the right voltage regulator is an extremely critical aspect of my fire detection system design, as it ensures that all components operate at their particular voltage and current ratings. The system power is provided by a high-current adapter, but every device requires regulated and stable voltages to function optimally. Voltage regulators play a crucial role of bringing the voltage from the main supply down to levels required with low noise and ripple, which is required for sensitive parts like the FPGA and ADC. Without proper voltage regulation components could experience voltage fluctuations, leading to improper processing of data, random operation, or even permanent damage.

Linear Regulator

Linear regulators are simple devices that maintain a constant output voltage by dissipating the excess voltage as heat. It employs a pass transistor operating in its linear region to drop the voltage difference between the input voltage and output voltage [109]. It has very low output noise and excellent transient response and is well suited for use in noise-sensitive

applications, such as audio or precision analog circuits. However, because any voltage difference must be dissipated in the form of heat, linear regulators tend to be less efficient in cases where there is a big difference between input and output voltage [109]. Their ease of use, along with very few external components, makes linear regulators great for low-current applications whereby efficiency isn't so much of a concern. Linear voltage regulators may enhance the system by supplying filtered, stable power to sensitive analog or low-current digital circuits [109]. This combination allows balancing between efficiency and signal integrity. The fire detection system is allowed to operate correctly while keeping general power management in check.

Switching Regulator

A switching regulator converts one voltage level into another with high efficiency using inductors, capacitors, and sometimes transformers, through high-frequency switching. Instead of dissipating the excess voltage as heat, it rapidly turns the input voltage on and off, storing energy in the inductor or capacitor, and then releases that energy to maintain a stable output voltage [110]. This method increases efficiency, especially in high-current or high-voltage-drop applications, which makes switching regulators suitable for battery-powered devices and systems where power loss must be minimal. On the downside, switching regulators are a bit more complicated, can introduce high-frequency noise and electromagnetic interference, and require special attention to the design of the circuit and filtering. Different types of switching regulators include a buck and a boost regulator [110]. The system is powered through an adapter sourced from a standard outlet, the use of both buck and boost regulators plays a crucial role in efficiently managing the voltage levels required by various components on the PCB.

Buck Regulator

A buck regulator is a step-down converter that lowers the input voltage to a reduced stable output voltage [111]. In our system, the buck regulator is an essential component, supplying power for the microcontrollers, sensors, or LEDs that require voltages lower than the supply, typically operating in a range of 3.3V to 5V. The buck regulator achieves this high efficiency very well, minimizing power loss by switching instead of linear dissipation, which is highly beneficial for any system which is targeting power optimization [111].

Boost Regulator

On the other hand, a boost regulator, or step-up converter, has an inverse function and raises the input voltage to the required value for any component that must operate at a higher voltage than the adapter supplies [112]. A boost regulator in our fire detection system might be able to power devices or any other high-demand components exceeding the input level from the adapter. It assures that these components get power without using several external adapters for clean and modular power architecture.

Voltage Regulator Models

LM2576

The LM2576 is a good candidate because it is a simple and reliable step-down (buck) converter that provides up to 3A of current with a suitable output voltage range for the

hardware that are in our system. Additionally, it features current limit and thermal shutdown protection, protecting the system from going out of control and being damaged under a variety of load conditions [113]. Since our fire detection system consists of various components such as the ADC, FPGA, motor driver, and feedback systems, the LM2576's ability to supply up to 3A output current ensures power demands are met efficiently.

LMR51430

A more modern option is the LMR51430, operating from 500-1100 MHz, significantly higher than the LM2576 [114]. It is also designed for low ESR capacitors, enhancing stability and filtering performance. With my intention to maintain power consumption at low levels, this regulator provides an energy-efficient solution that reduces overall heat generation and thus is an appropriate selection for our system.

LM2596

The LM2596 is another option, which also has a higher switching frequency (110 kHz) than the LM2576. Still maintaining 3A output current, it provides some improvement on efficiency and component size [115]. Since our fire detection system is operating with various voltage levels, both fixed and adjustable output voltage features make the LM2596 a viable option, with versatility to supply various subsystems of my PCB.

LM2679

Where an application of a higher power is required, the LM2679 provides a 5A output current at a higher switching frequency of 260 kHz [116]. This is ideal if our system requires more loads, such as when supplying power to devices requiring more power such as the motor driver. The higher frequency also enables me to employ less size-intensive passive components, which makes the overall PCB design more efficient. If this system requires a more robust power supply that can handle greater peak currents, the LM2679 would be ideal.

Table 41. Voltage Regulator Comparison

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

I have decided to use the LM2679 voltage regulator in my fire detection system because it offers a reliable, efficient, and easy-to-implement power regulation solution. Its compatibility with supporting 5 A of current is particularly attractive because it is needed to support the Raspberry Pi 5 safely and reliably. We need to decrease the amount of current using different techniques with the implementation of resistors to ensure that the amount of current distributed to the other components do not over exceed their capacity. Since our system operates on an adapter, the voltage stepping-down capability of LM2679 ensures that all devices receive the correct power level without wasting excess energy or overheating.

3.4 Communication Protocol

The communication protocol defines how signals are exchanged, the speed of data transmission, and the complexity of wiring and interfacing. Given the variety of components working together to detect fire signals, process optical data, and trigger visual and audio feedback, having a robust and reliable communication protocol ensures that information flows quickly and accurately without errors or delays. Any miscommunication between the ADC and FPGA, or between the FPGA and control systems, could result in missed detection signals or false alarms, potentially compromising the system's safety and effectiveness.

3.4.1 UART

The UART (Universal Asynchronous Receiver/Transmitter) protocol is a popular, simple, and efficient method of serial communication among digital devices. It utilizes asynchronous transmission, wherein it does not utilize a clock signal to synchronize data between devices [117]. Instead, UART relies on baud rate agreements (the transmission rate of data) and utilizes start bits, stop bits, and parity bits (optional) to structure the data being transmitted. It speaks on just two primary lines: TX (transmit) and RX (receive), with the provision to add additional lines for handshaking if needed [117]. This is what makes UART particularly valuable in embedded systems where low pin count and easy implementation are preferred.

Within our fire detection system, UART can be included to handle point-to-point communication between critical components, particularly in the case of transmitting data between the FPGA and other peripherals like an external microcontroller, computer interface, or even for debug purposes. UART offers unique advantages for external communication or scenarios where high-speed, reliable data streaming is necessary. For example, UART can be used to transmit system logs, diagnostic data, or fire alarm signals to an external monitoring device or interface with a PC while testing and developing the system.

UART can be easily implemented within our fire detection system. The microcontroller or FPGA can be coded with UART ports, and if we set a standard baud rate (e.g., 9600, 115200, or higher depending on the data rate need), we can have a reliable communication link [117]. In a real fire detection scenario, UART can be used as an interface between the fire detection system and an alarm control panel, sending plain ASCII commands or binary data packets to trigger external alarms or send status reports. Because UART supports full-

duplex communication—where data can be sent and received simultaneously—it gives real-time feedback and control, which is critical in safety applications like fire detection.

UART can be better suited for longer-distance or direct device-to-device communication without the complexities of addressing multiple devices on a bus [117]. It also offers robust error-checking capabilities through optional parity bits, ensuring that data integrity is maintained during transmission—an essential feature in fire detection systems where data accuracy is critical.

3.4.2 SPI

The SPI (Serial Peripheral Interface) is a synchronous full-duplex high speed communication protocol that is widely used in embedded systems to communicate data at high speeds with reliability between digital devices. SPI contrasts with UART, an asynchronous mode and I2C, a slower multi-device mode, since it transfers data synchronously via a clock signal (SCK) for synchronizing the data transfer. It is a master-slave architecture, where a master unit (e.g., microcontroller) controls communication, and one or more slave units (e.g., sensors, ADCs, or display modules) respond accordingly. The primary signals of SPI communication are MOSI (Master Out, Slave In), MISO (Master In Slave Out), SCK (Serial Clock), and SS (Slave Select), which enables the master to choose which device to talk to at any given time [118].

Within our fire detection system, integrating SPI could be beneficial for components that require high-speed data transfer, such as high-resolution ADCs used for converting the optical signals from the detector [118]. Since fire detection relies on precise and timely data acquisition, SPI's ability to handle higher data rates compared to I2C makes it a strong choice for real-time signal processing. For instance, having the ADC is SPI-compatible, it can efficiently pass continuous analog-to-digital conversion data to the ESP32 so that the system processes optical signals with reduced delay, which translates to faster fire detection response times.

Another key advantage of SPI is its reduced communication overhead compared to I2C. While I2C uses addressing schemes to communicate with multiple devices on a shared bus, SPI's direct select line (SS) allows faster point-to-point communication between the master and a specific slave [118]. This is particularly useful for our fire detection system since it involves high-speed units like real-time monitoring components, since SPI ensures that lots of data may be transmitted at high speed without bus blocking.

Whereas I2C is better suited to manage multiple low-speed devices on the PCB, SPI is better suited where low latency and data speed are a priority. The only drawback of SPI is that it requires additional wiring (dedicated SS lines for each slave device), increasing the complexity of the PCB if multiple SPI devices are employed. If reducing wiring complexity is critical, I2C is nevertheless the better option for general communication between multiple components.

3.4.3 I2C

Introducing the Inter-Integrated Circuit (I2C) communication protocol into the fire detection system makes transmission of data between various components on the PCB extremely efficient and neat. I2C is by far the best choice for this project: it controls many

devices that operate on two communication branches, SCL or serial clock line and SDA or serial data line [119]. Not only does it minimize pins on the microcontroller or FPGA, but it also simplifies overall wiring and PCB layout-an added advantage, due to the complexity in integrating sensors, ADCs, and feedback devices like the buzzer and LEDs.

When implementing I2C, precaution must be taken with the addressing scheme, as each device on the bus must have a unique 7-bit or 10-bit address. Other considerations are proper pull-up resistors on the SCL and SDA lines for reliable signal integrity, particularly in case of long bus distances spreading across the PCB. With I2C standard speed (100 kHz), fast mode (400 kHz), and even high-speed mode (to 3.4 MHz), under real-time requirements, we have to select the right data rate. For instance, simpler devices like status LEDs can operate at lower speeds [119].

The integration of I2C into the fire detection system allows for higher scalability, reduced complexity in wiring, and efficient communication between components. Due to its two-wire implementational fashion and multi-device operation on a single bus, integration of an I2C protocol fits well with the design objectives given by the project, thereby allowing seamless data exchange between sensors, controller, and user interfaces towards a merely responsive and effective fire detection system.

Table 42. Communication Protocol Comparisons

Feature	UART	I2C	SPI
Communication Type	Asynchronous	Synchronous	Synchronous
Number of wires	2 (TX, RX)	2 (SCL, SDA)	4 (MOSI, MISO, SCK, SS)
Speed	Moderate (115200 – 1 Mbps typical)	Low to Moderate (100kHz, 400 kHz, up to 3.4 MHz)	High (1 – 50+ MHz)
Number of devices	1-to-1(Point-to-point)	Multi-Master, Multi-Slave	Single Master, Multiple Slave
Data Transmission	Full-Duplex	Half-Duplex	Full-Duplex
Error Checking	Parity bit (optional)	Acknowledgement (ACK/NACK)	No built-in error checking
Best Use Case	Serial communication between two devices	Multi-device communication within the PCB	High-speed data for real-time processing

A proper communication architecture is highly essential for ensuring effective data transfer and system operation. In this regard, I2C will be utilized as a communication protocol within the PCB to allow simple integration of different peripherals, and SPI was also utilized for more heavy data transportation communication such as the interaction between ESP32 and ADC for high-speed data acquisition.

Where low-latency, high-speed data transport between FPGA and ADC is needed, SPI is the protocol to be used. The ADC digitizes the optical signal from the photodiode into digital data, which must be processed quickly so the fire can be detected accurately and in time. SPI has greater data transport rates than I2C, as it operates in synchronous full-duplex mode, allowing for simultaneous reception and transmission of data. With its own SCK and independent MOSI and MISO, SPI minimizes delays to almost zero and ensures that critical fire detection data is communicated to the FPGA with zero latency. This is especially crucial in high-resolution ADC processing where responsiveness in real-time is crucial.

Through this hybrid communication architecture, the system can achieve speed and scalability effectively. With I2C employed to the TSL2591 for sensor reading. Since we have pivoted to the internal ADC within the ESP32, we have not utilized SPI communication protocol within our system. This configuration optimizes wiring simplicity and performance while maintaining the fire detection system efficient, responsive, and capable of handling real-time optical signals without excessive complexity.

3.5 Software

3.5.1 Development Languages

HDL (Verilog/VHDL)

When working with FPGAs, the use of Hardware Description Language (HDL) is fundamental. Unlike traditional programming languages that execute sequential instructions, HDL defines hardware circuits at a low level, allowing for precise control of digital logic and real-time processing. This capability makes it essential for applications requiring high-speed signal processing, real-time control, and hardware acceleration, such as fire detection in the FLAMES project. Within this project, HDL plays a crucial role in FPGA-based fire detection by enabling sensor interfacing, data acquisition, and motor control, ensuring accurate and efficient hazard identification. The Artix-7 FPGA used in FLAMES is designed with four conceptual core processing modules, each implemented in HDL: Environmental Baseline, Temporal Stability Detection, Color Extraction Detection, and Flag Detection.

The Environmental Baseline Module is responsible for collecting real-time sensor data and converting it into a format usable by the ESP32 by the TSL2591 light sensor and FDS1010 photodiode. Since the FDS1010 photodiode array outputs analog signals, an Analog-to-Digital Converter (ADC) is required to digitize this data before it is transmitted to the ESP32. To facilitate fast and reliable communication, the Serial Peripheral Interface (SPI) is used to connect the ADC to the ESP32-WROOM-32D, allowing for efficient transfer of visual data. A strong example of SPI implementation between an ADC and an Artix-7 FPGA is found in a GitHub repository [120], where a VHDL-based SPI master module (ADC controller.vhd) is used to manage high-speed data acquisition and conversion. This real-world application closely aligns with FLAMES by ensuring that sensor data is accurately transmitted for further processing and analysis. We will also be collecting LUX data from the TSL2591 light sensor to fully implement the environmental baseline portion of the project, where it will determine if an abnormal light source is detected by it.

Once the data is received, the Threshold Stability Detection Module applies comparator logic to determine whether sensor readings exceed predefined fire detection limits. This module filters out insignificant variations, ensuring that only meaningful changes trigger further action. A commonly used example is a thermistor-based circuit, where the thermistor's resistance decreases as temperature rises. This change affects the voltage across the thermistor, which is then compared to a predefined reference voltage using an operational amplifier (op-amp) configured as a comparator. When the sensed voltage surpasses the reference, indicating a potential fire due to elevated temperature, the comparator outputs a signal to activate an alarm [121]. The module then evaluates whether a fire condition persists in the frequency and infrared light of a typical fire. This step is essential for reducing false positives caused by brief or fluctuating signals. For instance, a study on smoke detection using spatial and temporal analyses emphasizes the importance of evaluating motion patterns over consecutive frames to accurately identify smoke, reducing false positives caused by short-term disturbances [121]. While smoke detection is not a primary focus of FLAMES, this method highlights the flexibility of temporal analysis techniques in fire detection.

The Color Extraction Detection module utilizes input from the Raspberry Pi 5 in order to later synchronize the flag detection with the FDS1010 photodiode. This module is programmed in Python using OpenCV and performs image-based flame analysis in the YCbCr color space, which is particularly effective in low-light conditions common in enclosed environments. The system initiates this module only after the TSL2591 sensor detects an abnormal lux spike, prompting the Raspberry Pi to begin capturing and analyzing video frames. Within each frame, the module extracts chrominance information (Cb and Cr channels) to differentiate flame-specific hues from other bright light sources such as sparks or reflections. The brightness and temporal consistency of the identified color region are also considered, as flames exhibit both sustained motion and warm chromatic signatures. If these color characteristics align with a flame profile, a flag is asserted and transmitted to the FPGA for final decision-making. This color-based validation provides a crucial third layer of redundancy, ensuring high accuracy in rejecting false positives and enabling FLAMES to function reliably in visually dynamic environments.

The final component, the Flag Detection Module, utilizes the FPGA's ability to perform fast, deterministic logic to synchronize detection inputs from both the ESP32 and the Raspberry Pi 5. Implemented in Verilog, this module ensures that both the frequency-domain detection from the photodiode (via FFT analysis on the ESP32) and the YCbCr color analysis from the Raspberry Pi 5 are confirmed before issuing a final fire alert. The module checks for simultaneous assertion of both flags, using synchronized signal handling to mitigate timing mismatches and false positives. Only when both flags are received does the system activate the final alert signal, which triggers the ESP32 to initiate user notification protocols including LED and buzzer activation. By consolidating the four conceptual detection layers into a single fire_alert logic module, the FLAMES system preserves modular clarity while optimizing for timing accuracy, system stability, and scalability. Through this architecture, HDL empowers real-time environmental monitoring that is robust, synchronized, and highly responsive to nuanced fire behavior in enclosed, spark-prone settings.

Beyond development, HDLs play a crucial role in verifying the hardware implementation of FPGA-based fire detection systems. Test benches, specialized simulation environments written in HDL, enable designers to validate and optimize their hardware before deployment. Test benches allow engineers to apply a set of stimuli to the design under test (DUT) and observe its responses, ensuring the system behaves as intended under various conditions. In the context of FLAMES, HDL test benches support the simulation of fire detection algorithms, sensor interfacing, and motor control mechanisms, ensuring the system's reliability and accuracy prior to real-world implementation [123].

Several advantages come from using HDL test benches in FPGA design. One key benefit is the early detection of design flaws. By simulating HDL code, designers can identify and rectify logical or functional errors early in the development process, reducing the need for costly revisions later. Another advantage is performance evaluation; test benches facilitate the assessment of system performance under various scenarios, ensuring that the fire detection process meets required speed and accuracy standards. Furthermore, simulation enables students and developers to analyze FPGA resource utilization, allowing for design optimization to fit within hardware constraints.

A practical example of HDL test bench usage in fire detection is demonstrated in the design of a forest fire detection system using color models [124]. In this project, a fire detection algorithm was developed in Verilog HDL, and a test bench was created to simulate and verify system functionality. The test bench applied various test vectors to the DUT and captured output responses, ensuring that the design met the specified requirements before actual hardware implementation [125].

By incorporating HDL-based design, verification, and optimization techniques, FLAMES achieves a robust and efficient FPGA-based fire detection system. HDL test benches not only validate system accuracy but also provide students with valuable experience in digital design, fostering deeper understanding and practical skills in hardware development. The structured approach of using HDL in both implementation and simulation ensures that FLAMES remains an effective, high-performance solution for fire detection and monitoring.

MATLAB

MATLAB plays a pivotal role in the FLAMES project, primarily due to the team's familiarity with the platform and its robust simulation capabilities. A significant advantage of MATLAB is its ability to facilitate the conversion of high-level algorithms into Hardware Description Language (HDL) code, streamlining the development process and minimizing the need for manual coding in Verilog.

MATLAB serves as a powerful tool in the FLAMES project, enabling the design and simulation of complex fire detection algorithms within a high-level programming environment. This capability simplifies the conceptualization and validation of detection processes before they are implemented in hardware. One of MATLAB's key advantages is its integration with HDL Coder [126], which allows for the automatic generation of synthesizable Verilog or VHDL code from MATLAB functions or Simulink models. This automation significantly reduces the likelihood of human error and expedites the

development cycle by streamlining the transition from software-based design to hardware deployment.

Additionally, MATLAB's robust simulation environment ensures that algorithms meet design specifications and perform reliably under various scenarios. This verification step is critical for validating the effectiveness of fire detection algorithms prior to implementation on an FPGA. Furthermore, MATLAB provides advanced tools for analyzing and optimizing resource utilization, allowing designers to make data-driven decisions that ensure the system meets specific speed and area constraints in FPGA implementations [127].

By leveraging MATLAB's capabilities, the FLAMES project can efficiently transition from algorithm development to hardware implementation, ensuring a reliable and effective fire detection system.

C

In the FLAMES project, programming the ESP32 microcontroller using the C language provided several advantages that align with the system's requirements for efficiency, performance, and control. C is a widely used language in embedded systems due to its low-level hardware access, efficient memory management, portability, real-time performance, and extensive community support. These characteristics make it an ideal choice for handling the ESP32's peripheral control functions, such as monitoring buttons and managing LEDs and buzzers.

One of the key benefits of using C is its ability to provide direct interaction with hardware registers and memory, enabling precise control over the ESP32's GPIOs, timers, and communication interfaces. This level of access ensures that the system operates efficiently and responds quickly to user inputs, a crucial feature in safety-critical applications like fire detection [128]. Additionally, C's efficient memory management is particularly important in embedded systems with limited resources, ensuring that the ESP32 runs optimally without unnecessary overhead.

C is also highly portable, allowing for minimal modifications when transitioning between different microcontroller platforms. This flexibility is beneficial for potential future iterations of the FLAMES project that may involve upgrading hardware or integrating additional functionalities. Furthermore, its deterministic execution ensures predictable response times, making it suitable for real-time applications that demand quick and reliable processing [128].

The ESP32 microcontroller is compatible with multiple programming environments, including the Arduino IDE, which uses a C/C++-based language, and the Espressif IoT Development Framework (ESP-IDF), which fully supports C programming. These platforms provide robust libraries and development tools that streamline the coding process and facilitate efficient debugging [129]. With an extensive developer community and abundant resources available, programming in C ensures that the ESP32 operates reliably while remaining accessible for future modifications and optimizations.

By leveraging C for microcontroller programming, the FLAMES project could have benefitted from a well-established, efficient, and scalable approach to embedded system

development. The language's strengths in performance, control, and reliability make it a close choice for managing the ESP32's peripheral controls, allowing the FPGA to focus on complex real-time data processing and analysis.

Java

In the context of the FLAMES project, utilizing Java for programming the ESP32 microcontroller presents several challenges that make it less suitable compared to languages like C or C++. Java typically requires a Java Virtual Machine (JVM) to execute code, which demands additional system resources such as memory and processing power, resources that are often limited in microcontroller environments like the ESP32. This added overhead can lead to inefficiencies and increased power consumption, which are critical considerations in embedded systems.

Moreover, the support for Java on platforms like the ESP32 is relatively limited. While there are solutions such as MicroEJ that enable Java development on the ESP32, they may not be as mature or widely adopted as traditional C/C++ toolchains [130]. This can result in a steeper learning curve and potential integration issues. Discussions among developers highlight these challenges, with some suggesting that learning C or Python might be more practical than attempting to implement Java on unsupported platforms.

However, Java has found success in embedded systems with more substantial resources. For instance, Java is utilized in in-car infotainment systems, home automation, and edge gateways, where the hardware can support the JVM's requirements [131]. Additionally, educational case studies have explored Java's application in embedded systems, demonstrating its potential in specific scenarios [132].

In summary, while Java offers benefits such as portability and a rich set of libraries, its implementation on resource-constrained microcontrollers like the ESP32 is not ideal due to the lack of native support and the additional overhead of running a JVM. Therefore, languages like C or C++ remain the preferred choices for programming the ESP32 in the FLAMES project [133].

C++

In the context of the FLAMES project, selecting C++ as the programming language for the ESP32 microcontroller offers distinct advantages that align with both the system's modularity needs and the development team's long-term growth. While embedded systems have traditionally favored C for its simplicity and minimal overhead, modern microcontrollers like the ESP32 support C++ efficiently, making it a practical and powerful option for development. C++ extends C with object-oriented programming, encapsulation, and abstraction—features that enhance code organization, scalability, and reuse, particularly beneficial in complex, multi-component systems like FLAMES.

The ESP32's relatively generous memory and processing capabilities, compared to older microcontrollers, make it well-suited to handle the added overhead of C++ features. Leveraging classes and modular design in C++ allows for cleaner task separation—for example, isolating motor control, sensor interfacing, and FFT-based detection—leading to easier debugging and future scalability. Additionally, using C++ promotes better alignment with industry-standard tools and practices. Many widely adopted computer architecture

frameworks, such as gem5, are built in C++ due to its strong support for hardware modeling and simulation, reflecting its relevance beyond embedded systems.

For students, developing in C++ also builds transferable skills applicable to both embedded and high-level software design. While C remains foundational, C++ offers a modernized toolkit without compromising the low-level access needed for direct hardware interaction. By adopting C++ for the ESP32 in the FLAMES project, the team benefits from a structured, maintainable, and extensible codebase which is crucial for collaborative development and long-term system evolution.

Table 43. Programming Languages Comparison

Feature	HDL	MATLAB	C	Java	C++
Primary Use	FPGA-based hardware implementation	Algorithm development & simulation	ESP32 microcontroller programming	Not suitable for microcontrollers	Object-oriented alternative to C
Key Functionality	Defines hardware circuits for real-time fire detection, sensor interfacing, and motor control	Converts high-level algorithms to HDL, aiding FPGA development	Provides low-level hardware control for ESP32	Requires JVM, leading to inefficiencies on ESP32	Adds OOP features but with added overhead
Advantages	Enables real-time parallel processing, FPGA resource optimization	High-level modeling, automatic HDL code generation, efficient debugging	Direct hardware access, efficient memory management, low overhead	Portability and rich libraries (but unsuitable for ESP32)	Useful for architecture modeling, supports complex system simulation
Challenges	Requires hardware-specific knowledge, debugging can be complex	Transitioning to FPGA requires validation, may introduce computational overhead	Requires manual memory management, no high-level abstractions	JVM increases memory and power requirements, limited microcontroller support	Increased memory and processing overhead, may not be ideal for embedded systems
Example Usage in FLAMES	Implements modules like Data Acquisition, Threshold Detection, Temporal Stability, and Motor Control	Simulates fire detection algorithms, verifies performance before FPGA deployment	Controls ESP32 peripherals like buttons, LEDs, and alarms	Not used due to inefficiency on ESP32	Used in architecture-related projects, easy to adapt to Arduino-IDE libraries

3.5.2 Algorithms

Environmental Baseline Analysis

When looking at environmental baseline analysis for FLAMES, there are a lot of options to choose from, and the best choices depend on factors like low latency, high accuracy, and long-term stability. Here, environmental baseline analysis refers to establishing the initial reference point for further analysis, specifically based on lighting data collected from the photodiode. The incident radiation that the photodiode captures will enable the team to take an initial reading of the ambient light. A better measure of the ambient light is the lux. The lux is a measure of lumen per square meter. In a bright room, there would be an increased amount of lux compared to a dark room. Establishing a lux value would enable the motor to trigger a stop of the motor once a specific threshold is detected. For example, in our ideal demonstration setting, a fire will be lit in a dark environment. The lux sensor that is being utilized has a large dynamic range which is suitable for low light conditions. The baseline of the environment will read as a relatively low lux value. When the fire or spark is detected, we shall observe a spike in the lux indicative of a fire or spark.

For lighting analysis with a photodiode, we can apply different software methods. For signal processing and noise reduction, potential approaches include the moving average filter, exponential moving average, Kalman filter, and wavelet transform techniques. For baseline calibration and adjustment, options like adaptive thresholding, polynomial regression, and principal component analysis can be used to ensure long-term accuracy. Finally, for detecting changes in environmental conditions, we can consider z-score anomaly detection, cumulative sum control charts, and hidden Markov models.

We will first discuss signal processing and noise reduction techniques to determine which provide the lowest latency, highest accuracy, and longest stability. While it would be ideal to optimize all three factors, tradeoffs are inevitable. Given that our project is short-term by nature, we will prioritize low latency and high accuracy, though improvements in stability can be considered for future iterations.

The Moving Average Filter (MAF) is a widely used and straightforward filtering technique that smooths data by averaging a set number of consecutive samples, making it highly effective at reducing random noise. The Scientist and Engineer's Guide to Digital Signal Processing explains its implementation and effects, highlighting its low latency and high stability over time [135]. However, despite its consistency, MAF introduces lag when detecting sudden changes, as its smoothing operation can delay real-time responsiveness. Research from the University of Southern California further analyzes the amplitude and phase response of the Moving Average Filter, demonstrating its effectiveness for gradual trends rather than immediate fluctuations [136].

The Exponential Moving Average (EMA) enhances MAF by assigning exponentially greater weight to recent observations, allowing it to react more quickly to environmental changes. This characteristic makes EMA particularly useful for dynamic lighting conditions. A study comparing EMA with the Kalman Filter concluded that EMA achieves a strong balance between speed and accuracy, making it a viable alternative in situations where computational resources are constrained [137].

For more advanced filtering, the Kalman Filter (KF) is regarded as one of the most accurate techniques for real-time photodiode data processing. Unlike MAF and EMA, which rely solely on past data, KF incorporates predictive modeling to estimate the true signal while filtering out noise and adapting to variations in environmental conditions. This makes it particularly useful for long-term monitoring, where gradual shifts must be accounted for. While KF offers the highest accuracy among these methods, it requires significantly more computational power due to its recursive updates and matrix operations. Despite its ability to maintain long-term stability, its complexity and higher latency make it less ideal for rapid, real-time filtering.

The Wavelet Transform, unlike the previous methods, analyzes signals in both time and frequency domains, making it highly effective for detecting non-stationary variations in photodiode data. It provides exceptional accuracy when identifying transient events, such as sudden illumination changes, while maintaining stability over time. However, due to its high computational complexity, it suffers from significant latency, making it unsuitable for real-time applications.

When comparing Kalman Filter (KF) and Exponential Moving Average (EMA) in terms of accuracy and latency, KF clearly provides superior accuracy, as it integrates both past measurements and predictive modeling to estimate the most probable signal value. This makes it highly resistant to noise and dynamic variations. However, this comes at the cost of higher latency, as KF requires intensive matrix operations and recursive updates, increasing computational demand. On the other hand, EMA is optimized for low-latency applications, as it prioritizes recent data points and adjusts rapidly to changes, making it more responsive but less precise. Given that stability is only a short-term concern, our main tradeoff shifts toward simplicity in implementation.

From an implementation perspective, EMA has a clear advantage. While KF requires careful tuning of noise covariance matrices and system states, which can be complex and computationally expensive, EMA operates as a simple single-equation filter, requiring minimal processing resources. This makes it significantly easier to integrate into real-time photodiode-based environmental baseline analysis while still achieving an acceptable level of accuracy. Considering the need for low-latency, high accuracy, and ease of implementation, EMA was the best choice for this project.

A summary of all this information can be found in Table 44 below.

Table 44. Filtering Techniques Summary

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	Low	Moderate to High	Moderate	Low	Simple

Average (EMA)					
Kalman Filter (KF)	Moderate	High	High	High	Complex (Tuning Required)
Wavelet Transform	High	Very High	High	Very High	Very Complex

After processing the raw sensor data using signal processing and noise reduction techniques, baseline calibration and adjustment methods ensure long-term accuracy by accounting for drift, environmental changes, and sensor inconsistencies. Several approaches can be applied, including adaptive thresholding, polynomial regression, and principal component analysis (PCA). Each method provides different benefits in terms of latency, accuracy, and computational complexity.

One of the simplest and most effective methods for baseline calibration in a dynamic lighting environment is adaptive thresholding. Unlike static thresholding, which applies a fixed value, adaptive thresholding continuously adjusts the baseline based on previous sensor readings. This allows the system to respond to gradual shifts in illumination while maintaining sensitivity to sudden changes. Adaptive thresholding is particularly well-suited for real-time applications, as it requires minimal computational resources and has low latency [138]. It is still widely used in sensor networks for its ability to dynamically calibrate baseline readings while keeping computational costs low [139]. Given our project's need for low-latency processing, adaptive thresholding is a strong candidate for baseline calibration.

For environments where baseline drift follows a predictable pattern, polynomial regression provides a more robust calibration technique. Instead of dynamically adjusting based on recent data, polynomial regression models the long-term trend of the baseline shifts, allowing it to correct for non-linear changes in illumination or sensor readings. This technique is more accurate than adaptive thresholding but requires historical data to train an appropriate model.

While polynomial regression is well-suited for baseline drift correction, its higher computational complexity and reliance on past data make it less ideal for real-time calibration. Additionally, if environmental changes do not follow a consistent pattern, polynomial regression can overfit to the data and become less effective. Given that our project is short-term and prioritizes low-latency over long-term stability, polynomial regression may not be the best fit unless we anticipate gradual, non-random baseline drift in lighting conditions.

For applications involving multi-sensor integration or large datasets, Principal Component Analysis (PCA) is a powerful baseline adjustment method. PCA is a dimensionality reduction technique that identifies the most significant trends in sensor readings while filtering out noise. It is particularly useful when multiple environmental variables (e.g., light intensity, temperature, and humidity) must be analyzed together to determine a stable baseline.

Although PCA provides exceptional accuracy, its computational complexity is high, making it unsuitable for real-time baseline adjustments. The technique requires large datasets to train the model effectively and is not responsive to immediate changes, making it less practical for our low-latency application [140]. While PCA can be highly effective in smart building systems or multi-variable sensor networks, its use in real-time single-sensor calibration is limited.

Given our project's need for quick responsiveness and minimal computational overhead, adaptive thresholding was the optimal choice for baseline calibration. If we observed consistent drift in the sensor's baseline, polynomial regression could've be introduced to further refine the calibration.

A summary of all this information can be found in Table 45 below.

Table 45. Baseline Calibration and Adjustment Techniques Summary

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

After signal processing, noise reduction, and baseline calibration, detecting significant changes in environmental conditions is crucial for identifying anomalies, fluctuations, or transitions in light intensity. Three key techniques can be applied for change detection: Z-score anomaly detection, cumulative sum (CUSUM) control charts, and hidden Markov models (HMMs). Each method varies in latency, accuracy, and computational complexity, making their selection dependent on the specific application requirements.

One of the simplest and most commonly used statistical methods for anomaly detection is Z-score anomaly detection. This technique determines whether a data point significantly deviates from the mean by calculating how many standard deviations it is away from the expected value. By setting a Z-score threshold, such as ± 3 standard deviations, this method effectively flags abrupt changes in light intensity. Z-score detection is particularly useful in real-time applications due to its low latency and minimal computational requirements. It excels in environments where anomalies are distinct and infrequent, such as sudden light fluctuations, flickering, or unexpected obstructions. However, Z-score analysis struggles with gradual shifts that occur over time, as it primarily identifies immediate deviations rather than cumulative trends [141].

For detecting gradual changes in environmental lighting conditions, CUSUM (Cumulative Sum) control charts offer a more robust alternative. Unlike Z-score detection, which focuses on sudden anomalies, CUSUM accumulates small deviations from the expected baseline over time. When these deviations exceed a predefined threshold, a change is flagged, allowing the system to detect long-term variations that may otherwise go unnoticed. This method is particularly valuable in scenarios where lighting conditions slowly drift, such as dimming trends, gradual sensor degradation, or seasonal lighting shifts. However, CUSUM requires multiple sensor readings to accumulate deviations before detecting a change, making it less responsive to sudden fluctuations compared to Z-score analysis. Despite this moderate latency, its ability to identify small but persistent changes makes it well-suited for long-term monitoring applications.

For more advanced detection of pattern-based anomalies, Hidden Markov Models (HMMs) provide a sophisticated approach to change detection. Unlike Z-score and CUSUM, which rely on statistical thresholds, HMMs utilize probabilistic models to classify sequences of sensor readings into different states. This makes them particularly effective at recognizing patterns in lighting transitions, such as automated lighting schedules, periodic flickering, or distinguishing between natural and artificial light sources. HMMs excel at analyzing time-series data, allowing the system to not only detect anomalies but also predict potential changes before they occur. However, this high accuracy comes at the cost of significant computational complexity, as HMMs require extensive training data and high processing power to operate effectively. Additionally, HMMs may introduce higher latency due to the need for probabilistic state estimation, making them less suitable for real-time detection but highly effective for structured event classification.

Given our project's focus on fast, accurate, and computationally efficient detection, Z-score anomaly detection was the best primary approach, while CUSUM could have served as a secondary method for monitoring long-term baseline drift. If pattern recognition is needed in later iterations, HMMs can be considered for more advanced anomaly classification.

A summary of all this information can be found in Table 46 below.

Table 46. Change Detection Techniques Summary

Change Detection Techniques	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

Temporal Fluctuations Analysis

Temporal fluctuation analysis is essential for distinguishing fire from artificial light sources because fire exhibits a unique, non-static intensity pattern. Unlike a light switch, which produces an instantaneous and stable change, firelight flickers over time due to air currents, fuel consumption, and combustion dynamics. To detect this behavior, several signal processing and machine learning algorithms can be used to analyze intensity fluctuations over time including Fast Fourier Transform, Wavelet Transform (Time-Frequency Analysis), and Autoregressive (AR) Modeling.

One of the most effective approaches for fire flicker detection is the Fast Fourier Transform (FFT), a signal processing technique that converts time-domain data into frequency components. Fire flickering typically falls within the 1–10 Hz frequency range, while artificial light sources, such as fluorescent or LED lighting, have much higher or more stable frequency signatures. By analyzing the dominant frequency components of the intensity signal, FFT can detect fire based on its unique oscillation pattern. Studies have shown that FFT-based fire detection improves accuracy by filtering out static light sources and enhancing the reliability of fire detection systems. However, FFT assumes a stationary signal, meaning it does not handle sudden, short-duration fluctuations well, making it less effective for fires that exhibit highly irregular flickering behavior.

To overcome FFT's limitation of stationary signal assumption, the Wavelet Transform is another effective method for detecting transient intensity variations. Unlike FFT, which analyzes the entire signal at once, wavelet transform allows for time-frequency decomposition, making it highly effective for identifying short-term flickering patterns of fire. Wavelet-based detection has been widely used in fire monitoring systems due to its ability to capture localized fluctuations, providing a more accurate and responsive way to identify fire signals. However, wavelet transform is computationally more expensive than FFT, which can increase latency and require greater processing power for real-time applications.

Another useful approach for analyzing fire fluctuations is Autoregressive (AR) Modeling, which predicts expected light intensity values based on past observations and flags any deviations that match fire-like behavior. Instead of relying purely on frequency characteristics, AR models attempt to predict the next intensity value and measure the error between prediction and reality. A rapidly fluctuating light source that does not conform to a stable prediction model can be classified as a possible fire event. This technique is particularly useful for environments where light intensity changes are complex, such as areas with reflections, moving shadows, or intermittent artificial light sources. AR modeling is computationally less expensive than wavelet transforms but requires historical data to generate effective predictions, which may introduce slight delays in real-time fire detection systems.

After evaluating various algorithms for flicker-based fire detection, the Fast Fourier Transform (FFT) was chosen due to its balance of accuracy, computational efficiency, and real-time applicability. Fire exhibits a distinct flicker frequency range (1–10 Hz), and FFT effectively decomposes time-domain intensity data into frequency components, allowing the system to identify fire-like fluctuations while filtering out steady artificial light sources.

Although Autoregressive (AR) Modeling appears to be the better option based on computational efficiency and real-time responsiveness, Fast Fourier Transform (FFT) was ultimately the better choice for our fire detection system. While AR modeling excels at detecting unpredictable fluctuations, it does not explicitly analyze fire's characteristic flicker frequency (1–10 Hz), which is a key distinguishing factor from artificial light sources. Despite FFT's higher computational cost, its ability to filter out steady artificial lights and identify fire's unique frequency signature makes it the more reliable option for detection. While Table 47 suggests AR modeling might be the more practical choice, our specific needs prioritize flicker frequency detection, making FFT the most effective approach despite its complexity.

Table 47. Algorithms for Temporal Fluctuation Analysis Summary

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

Color Feature Extraction Analysis

Fire detection in FLAMES requires a precise and computationally efficient color analysis method that enables real-time processing while minimizing false detections. The Raspberry Pi 5 camera, in combination with OpenCV, provides a viable platform for extracting fire-colored regions, but selecting the most suitable algorithm is critical for maintaining low latency and high accuracy. Three leading approaches, HSV color thresholding, YCbCr fire region extraction, and Gaussian Mixture Models (GMM), offer different trade-offs in accuracy, adaptability, and computational efficiency. A comparison of these methods helps determine the best fit for FLAMES based on its performance requirements.

HSV color thresholding is a widely used method for detecting fire-colored pixels due to its simplicity and computational efficiency. The Hue, Saturation, and Value (HSV) color space separates color from brightness, making it more robust than RGB in dynamic lighting conditions. Since fire typically falls within a specific hue range (0–60), an HSV thresholding approach can quickly segment fire regions using OpenCV's `cv2.inRange()` function. However, HSV thresholding has limited adaptability, as it relies on predefined color thresholds. This makes it prone to false positives in the presence of warm-colored objects like indoor lighting, reflections, or high-temperature surfaces. Additionally, it may struggle in varying environmental conditions, where fire's color signature could shift due to factors like smoke density, distance, and camera exposure settings. Despite its limitations, HSV thresholding remains an efficient and easily implementable method, making it a strong candidate for low-latency fire detection in FLAMES.

YCbCr fire region extraction improves on HSV by separating luminance (Y) from chrominance (Cb and Cr), allowing for better differentiation between fire and non-fire warm-colored objects. Fire exhibits high red chrominance (Cr) values and low blue chrominance (Cb) values, which can be leveraged to reduce false detections caused by artificial lighting. OpenCV allows for easy conversion to the YCbCr color space, after which thresholding on the Cr and Cb channels can isolate fire regions with greater accuracy than HSV. While this method is more effective at filtering out non-fire heat sources, it introduces a slightly higher computational cost, as it requires additional color space conversion and thresholding operations. Additionally, YCbCr-based detection still relies on static thresholds, meaning it may not fully adapt to changing fire conditions. While YCbCr provides higher accuracy than HSV, its increased processing cost and continued reliance on thresholding make it only a moderate improvement over HSV for FLAMES.

Gaussian Mixture Models (GMM) offer a more adaptive, data-driven approach to fire detection, moving away from fixed thresholding methods in favor of probabilistic classification. Instead of defining hardcoded fire color ranges, GMM models the distribution of fire colors based on training data, allowing it to adapt to various fire conditions. OpenCV's `cv2.ml.EM()` function provides built-in support for training and applying GMM classifiers, making it a feasible option for FLAMES. By classifying pixels based on probability density functions, GMM can reduce false positives more effectively than either HSV or YCbCr. However, this approach comes at the cost of higher computational complexity, GMM requires model training, continuous probability estimations, and higher memory usage compared to basic thresholding methods. GMM still, however, introduces greater latency compared to HSV and YCbCr, making it less suitable for real-time fire detection. The need for training data and parameter tuning also makes it harder to implement and adjust compared to the simpler, threshold-based methods.

YCbCr Fire Region Extraction was the best choice for FLAMES because it provided the highest balance of accuracy and efficiency while remaining feasible for FPGA implementation. While HSV Thresholding is the simplest and has the lowest latency, it suffers from high false positives due to its dependence on static thresholds. On the other hand, Gaussian Mixture Model (GMM) offers the highest accuracy but is too computationally complex for real-time FPGA execution.

A summary of all this information can be found in Table 48 below.

Table 48. Color Feature Extraction Algorithm Summary

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	High	Very High	Very High	Complex	Moderate

Model (GMM)					
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Chapter 4 – Standards and Design Constraints

4.1 Industrial Standards

4.1.1 Fire Safety Standards

National Fire Protection Association (NFPA) 72

The NFPA 72 is a comprehensive fire safety standard developed by the National Fire Protection Association to establish minimum requirements for the design, installation, performance, and maintenance of fire detection, alarm, and emergency communication systems. This standard provides guidelines for fire detection technology, alarm signals, notification systems, monitoring processes, and emergency evacuation protocols to ensure reliable and effective fire safety measures in various settings, including residential, commercial, and industrial buildings.

Some of the key aspects of the NFPA 72 include the following:

Fire Detection and Alarm Requirements

NFPA 72 defines stringent performance specifications for different fire detection technologies so that fire alarm systems can detect fire hazards promptly and with high accuracy while reducing the risk of false alarms. NFPA 72 specifies smoke detectors, heat detectors, flame detectors, and manual pull stations and defines their sensitivity levels, triggering thresholds, and installation requirements. The standard is critical in ensuring early detection of fires to prevent disastrous damage and to ensure safety of occupants. NFPA 72 requires fire detection systems to be capable of differentiating between actual fire hazards and environmental factors that could cause false alarms, such as steam, dust, or electrical noise [142]. This functionality is necessary in my fire detection system, where photodiodes have been utilized to detect fire through optical signal processing, enabling timely and accurate detection without generating false alarms.

Sensor Placement and Coverage

Effective placement and coverage of fire detection sensors are crucial to the system's effectiveness. The NFPA 72 provides recommendations for sensor locations relative to room size, ceiling height, airflow, and potential fire hazards. For instance, heat rises so heat detectors would be located near ceilings whereas smoke detectors are located where smoke will naturally accumulate. In addition, NFPA 72 also provides detailed requirements for space coverage so that no part of a building is left uncovered [142]. In our fire detection system, in which a scanning system is to be used, these standards have been crucial to ensure that sensor placement is optimally located to give complete coverage with no blind spots. The motor-driven scanning mechanism has allowed the system to continuously monitor its surroundings, following NFPA 72 principles to maximize detection accuracy.

Alarm Notification System

NFPA 72 sets clear specific standards for alarm notification systems, which ensures that occupants receive immediate alerts instantly in case of a fire. These notification systems include audible alarms, visual strobe lights, and text alerts to cater to different environments and accessibility needs. The standard enforces minimum levels of sound intensity to ensure that alarms are heard in noisy environments and flashing levels of intensity to be visible in low-light environments [142]. This characteristic is relevant to my project because our system gives visual and audio feedback by using an LED indicator and magnetic buzzer to signal fire detection. Following NFPA 72, we ensured that the alarm device is both audible and visible enough to notify individuals effectively without triggering false alarms that could lead to alarm desensitization.

Emergency Communication Systems

Along with alarms and alerts, NFPA 72 also covers emergency communication systems that facilitate real-time coordination in the event of a fire emergency. Some of these are public address systems, voice evacuation systems, and two-way emergency communication to evacuate occupants safely from dangerous areas. For larger buildings, mass notification systems (MNS) are required to provide automated voice announcements or text-based instructions in a fire scenario [142]. Even though my fire alarm project is not currently configured to handle large-scale emergency alerts, incorporating an expandable system to notify external monitoring stations would provide it with additional potential for usage in commercial and industrial settings.

Testing, Inspection, and Maintenance

NFPA 72 emphasizes the regular testing, inspection, and maintenance necessary to ensure that fire detection and alarm systems will continue to operate over an extended period. The standard provides for periodic regular testing of diverse fire detection equipment like sensor calibration checks, tests of battery life, and tests of circuit integrity. It also needs backup power sources, such as uninterruptible power supplies (UPS) or backup batteries, to ensure fire detection systems will continue to function when there is a power failure. In our fire detection system, proper calibration of the photodiodes and ADC are necessary to ensure proper signal processing and reliable fire detection. Also, motor control and scanning mechanisms should periodically be kept in good condition so that movement becomes smooth and uninterrupted, as NFPA 72 requires long-term system reliability.

By following the key provisions of NFPA 72, our FLAMES is designed to meet fire safety codes, deliver accurate detection, proper installation of sensors, effective alarms, and prolonged reliability. Applying these industry standards in my design will not only enhance the system's strength but also scale it up for bigger applications, thereby making it a feasible and compliant fire detection system.

International Electrotechnical Commission (IEC) 61508

IEC 61508 is a well-known international standard containing the requirements of electrical, electronic, and programmable electronic systems for the safety-related application to detect and react to hazards. It specifies the hardware and software safety measures to ensure the reliability of critical systems, even if a fault were to occur. It is particularly applicable to life-safety uses such as fire detection and extinguishing, in which system malfunction could have very serious consequences.

Key aspects of IEC 61508 are shown in the following:

Functional Safety and Risk Management

IEC 61508 is mostly concerned with functional safety, so that electronic systems utilized in hazard detection and response applications should function appropriately, even in the presence of faults. It proposes the notion of Safety Integrity Levels (SIL), which categorizes systems into varying reliability levels in accordance with the risks' severity and failure probability. Increased SIL levels necessitate more stringent design, testing, and redundancy precautions to provide high system failure minimization [143]. Functional safety is an important concern for my fire detection system since the system needs to constantly monitor its surroundings and identify fires at high precision without generating false alarms. In case of a failure within the detection of the optical sensor, ADC, or FPGA processor unit, the system should either recover rapidly or go into a safe mode without shutting down entirely. The inclusion of watchdog timers, self-test mechanisms, and redundancy mechanisms can enhance system reliability so that the fire detection unit can fulfill functional safety standards and be used in sensitive applications where reliability is crucial.

Hardware Design and Reliability

One of the fundamentals of IEC 61508 is making sure hardware components are designed to have high reliability and fault tolerance. In safety-critical systems such as fire detection, hardware failure may result in delayed or missed fire detection that may cause serious damage or loss of life [6]. To avert such failures, all electronic parts must be scrupulously chosen for their ruggedness, accuracy, and stability during operating conditions. In our system, the ADC must ensure reliable multi-channel signal conversion, providing fast and accurate optical data processing for fire detection. Additionally, the voltage regulator must ensure a stable power supply, preventing voltage fluctuations that could affect sensor readings or FPGA performance. Another key hardware consideration is electromagnetic interference (EMI) protection, as external electrical noise could distort sensor data, leading to false positives or incorrect readings [143]. With the use of shielding, grounding, and filtering methods, this fire detection system can be immune to electrical noise, with correct and stable performance in industrial or high-noise environments.

Software Safety and Error Handling

IEC 61508 is also placing very much emphasis on software safety, with the embedded systems and firmware being structured to not add fault that will compromise safety [143]. In application in fire detection, signal processing and decision-making algorithms must be in such a form that they immediately and accurately recognize the occurrence of a fire. The system needs to detect the fault or pipeline error automatically if a software glitch or processing pipeline error occurs. In our design, this requires that the signal processing system implemented using the FPGA must incorporate mechanisms for detecting errors and faults and recovering from faults, for example, using parity checks, duplicate processing units, and watchdog timers that cause a system reset when a fault is detected. Apart from this, our fire detection logic must also be tested in varied conditions of the environment, e.g., changes in ambient light, reflections, and interference from smoke, to ensure that the fire detection logic is correct and consistent in all situations.

Environmental and Operational Resilience

Since fire detection systems are typically installed in harsh environments, IEC 61508 requires that components be rugged, durable, and resistant to external environmental factors [144]. My fire detection system may be exposed to heat, dust, humidity, and continuous vibrations from mechanical movement, making hardware durability a key concern. The optical sensors and ADC components must be able to operate within high-temperature environments without signal degradation or performance loss. Furthermore, designs for long-term durability for the stepper motor and scanning mechanism must be realized; continuous rotation may eventually lead to mechanical wear and tear. For reliability, high thermal resistance components, dustproof enclosures, and vibration-resistant designs should be used. With environmental protections in line with IEC 61508, my system can be reliably used in industries or hazardous environments wherever precision and robustness are at a premium.

Testing, Validation, and Maintenance Requirements

Adherence to IEC 61508 can only be accomplished with comprehensive testing, verification, and regular upholding at the whole life span of the system. Fire protection systems must extensively test before using to ensure correct functionality in any condition. That entails stress test on sensors at different types of fire conditions, power stability test for emulating voltage instability, and system checks to validate correctness in conjunction amongst all components of the system. Also, there needs to be periodic calibration and maintenance schedules to prevent sensor drift and ensure long-term accuracy [144]. Within our system, periodic self-diagnostic tests within the FPGA firmware has allowed the system to detect faults automatically and reset the faulty components or alert. In accordance with IEC 61508 maintenance standards, our fire alarm system can function safely for extended periods without the risk of unexpected breakdowns and sustained adherence to fire safety standards.

By integrating the principles of IEC 61508, our fire detection system is designed to operate safely within safety-critical environments so that hardware and software modules are fully compliant with functional safety requirements necessary. Through robust design of hardware, fault-tolerant software, environmental robustness, and rigorous testing regimes, the system have been able to effectively detect fires, minimize false alarms, and offer long-term reliability. Compliance with this standard not only enhances system safety but also ensures that the fire detection unit is dependable for utilization in real applications, where failure is not permissible.

4.1.2 PCB Design Standards

IPC-2221

The IPC-2221 standard is a comprehensive guide for the design of PCBs with important information regarding trace width, spacing, via design, conductor thickness, thermal issues, and material selection. The standard provides the basis for designing boards that are both manufacturable and dependable with guaranteed long-term performance in many electronic applications, thus including:

Conductor Sizing

IPC-2221 specifies how to calculate the proper trace width based on the current a conductor carries and the acceptable temperature rise. This is crucial for power delivery traces for this project, especially those powering the motor driver and voltage regulator, which consume relatively high current. Under-sized traces can overheat and cause damage, intermittent failure, or reduced system reliability. As per the conductor sizing guideline, all power traces must be sized to accommodate continuous current loads without heat build-up, protecting components and the PCB for long-term operation.

Clearance and Spacing

IPC-2221 defines minimum conductor spacing based on operating voltage. This is to prevent shorting, arcing, and signal interference, especially in circuits that mix both low-voltage control signals (I2C, SPI) and higher-voltage power rails [145]. In our detection system, where reliable communication between the FPGA and ADC is so critical, these spacing recommendations maintains clean secure signals which renders the PCB design immune to normal and transient voltage conditions without compromising detection accuracy.

Thermal Management

The standard also requires proper thermal management by suggesting adequate copper areas, heat dissipation structures, and component spacing guidelines since the voltage regulator and motor driver produced heat during operation. The IPC-2221 provide recommendations for heat dissipation techniques, such as copper plane sizing and thermal reliefs. This is critical so that these components can operate within safe temperatures [145]. This reduces the chances of thermal stress and increases the life of crucial parts of the system.

Material Selection

IPC-2221 also provides guidelines for the selection of PCB base materials and solder mask specifications that can withstand thermal stress, humidity, and shock. Under a fire detection system, all environmental conditions are significant. Using flame-retardant materials (UL 94V-0 rated) and high-quality laminates makes sure that the PCB is not only capable of withstanding normal operating conditions but even adverse conditions [145]. Proper material selection prevents warping, delamination, and heat failure, all of which are paramount in a safety-critical device like a fire alarm system.

By maintaining my PCB design consistent with the standards in IPC-2221, I can ensure that everything — from trace size and clearance to thermal issues and material selection — is optimized for maximum long-term reliability, safety, and performance of the fire detection system in real-world environments.

4.1.3 Communication Protocol Standards

I2C Protocol Standards

The Inter-Integrated Circuit (I2C) protocol is a widely utilized serial communication standard designed for data exchange between integrated circuits, particularly in embedded systems [146]. I2C operates on two bidirectional lines: the Serial Data Line (SDA),

responsible for transmitting data between devices, and the Serial Clock Line (SCL), which synchronizes data transmission. Both lines are typically pulled up to a positive voltage supply, commonly +5V or +3.3V, using pull-up resistors to ensure proper signal integrity.

I2C supports multiple operational modes, each with distinct maximum data transfer rates:

- Standard Mode (Sm): Up to 100 kbit/s.
- Fast Mode (Fm): Up to 400 kbit/s.
- Fast Mode Plus (Fm+): Up to 1 Mbit/s.
- High-Speed Mode (Hs-mode): Up to 3.4 Mbit/s.
- Ultra-Fast Mode (UFm): Up to 5 Mbit/s (unidirectional).

These speed classifications enable designers to optimize communication performance based on specific application requirements and bus capacitance constraints [147].

Addressing in I2C follows a 7-bit scheme, allowing up to 128 unique device addresses (0–127). However, certain addresses are reserved for specific functions, reducing the available space for general device communication. To accommodate a larger number of devices, a 10-bit addressing mode was introduced, significantly expanding the addressable range.

As a multi-master bus, I2C allows multiple master devices to initiate communication. To prevent collisions, the protocol implements an arbitration mechanism, where masters monitor the bus and withdraw if another transmission is detected. Additionally, I2C supports clock stretching, a feature that permits slave devices to hold the clock line low to signal the master to pause, thereby enabling more flexible data handling.

The I2C protocol has undergone several revisions to enhance its functionality and adaptability:

- Version 1.0 (1992): Introduced Fast Mode and 10-bit addressing.
- Version 2.0 (1998): Added High-Speed Mode (3.4 Mbit/s).
- Version 3.0 (2007): Introduced Fast Mode Plus (1 Mbit/s) and a device ID mechanism.
- Version 4.0 (2012): Added Ultra-Fast Mode (5 Mbit/s) with push-pull logic.
- Version 7.0 (2021): Updated terminology and aligned with the I3C bus specification.

These advancements reflect the protocol's continuous adaptation to meet the increasing demands of modern electronic systems.

I2C is extensively applied in various domains, including sensor interfacing, display communication, and memory device integration within embedded systems. It is also employed in managing system configurations in servers and personal computers, as well as facilitating communication between components in consumer electronics. Due to its

simplicity and efficiency, I2C remains a preferred choice for short-distance, intra-board communication [147].

SPI Protocol Standards

The Serial Peripheral Interface (SPI) is a synchronous serial communication protocol originally developed by Motorola in the 1980s. It facilitates high-speed, full-duplex data exchange between a master device and one or more slave devices, making it widely used in embedded systems for short-distance communication. Unlike other serial communication protocols such as I2C, SPI offers higher data rates and does not require addressing, allowing for more efficient and direct communication between components. Despite its widespread adoption, SPI lacks a formal standard maintained by an international organization such as IEEE; instead, various semiconductor manufacturers, including Motorola, Texas Instruments, and STMicroelectronics, define their own SPI implementations in datasheets and application notes. Variants such as Dual SPI and Quad SPI (QSPI) have been introduced to improve data throughput by enabling multiple data lines, enhancing its capabilities for applications like high-speed memory access.

SPI operates using a four-wire interface consisting of a serial clock (SCLK), master out slave in (MOSI), master in slave out (MISO), and slave select (SS). The master generates SCLK to synchronize data transmission. MOSI carries data from the master to the slave, while MISO allows the slave to transmit data back to the master. The SS line, controlled by the master, determines which slave is active during communication. Unlike I2C, which utilizes a shared data line and an address-based arbitration system, SPI requires a separate SS line for each slave device, increasing pin usage in multi-slave configurations. To accommodate multiple slaves efficiently, some implementations use a daisy-chain architecture or additional control logic such as demultiplexers.

Data transmission in SPI is highly flexible, as the protocol does not enforce a fixed frame size. Instead, it typically operates in multiples of 8 bits, allowing designers to optimize communication for their specific applications. Clock synchronization is defined by two parameters: clock polarity (CPOL) and clock phase (CPHA), which determine when data is sampled and shifted relative to the clock signal. These settings allow SPI to support different timing requirements depending on the connected devices. Electrical characteristics such as voltage levels, impedance, and pull-up resistors are typically defined by the hardware manufacturer, with common voltage levels being 5V, 3.3V, or even 1.8V in low-power applications. Manufacturers such as NXP and Analog Devices provide detailed timing diagrams in their datasheets, outlining required setup and hold times for reliable data transfer.

SPI is widely implemented in applications that require high-speed communication and deterministic timing. It is frequently used in sensor interfacing, such as connecting temperature sensors, pressure sensors, and accelerometers to microcontrollers. It is also common in memory communication, where it enables access to flash memory and EEPROMs. In display control, SPI facilitates communication with LCDs, OLEDs, and touchscreen controllers, making it a crucial interface in embedded graphical applications. Additionally, it plays a significant role in peripheral integration, providing connectivity for Ethernet controllers, RF transceivers, ADCs, and DACs.

One of the primary advantages of SPI is its simplicity and efficiency. The protocol requires minimal control logic, making it easy to implement in hardware. Its high data transfer rates allow for rapid communication, making it suitable for real-time applications. Unlike protocols with shared bus architectures, SPI does not require complex arbitration mechanisms, as the master directly controls data flow. However, SPI also presents several challenges. The lack of a built-in acknowledgment mechanism means that there is no native error detection, which can lead to data integrity issues if signal integrity is compromised. To mitigate this, designers often implement error detection techniques such as cyclic redundancy checks (CRC) at the application level. Additionally, the requirement for separate SS lines increases pin usage in multi-slave configurations, making scalability a concern in systems with numerous connected devices. While SPI can technically support multi-master setups, implementation is complex and not commonly used due to the lack of a defined arbitration scheme [148].

Despite these challenges, SPI remains a preferred communication protocol in applications requiring high-speed, low-latency data exchange. Its continued evolution, including the introduction of Quad SPI and serial memory interfaces like Octal SPI, reflects its importance in modern embedded systems. As technology advances, semiconductor manufacturers continue to refine SPI implementations, incorporating higher-speed variants and additional features to address the growing demand for efficient, high-bandwidth serial communication. Research into enhancing SPI's reliability, security, and multi-master capabilities continues, ensuring its relevance in future embedded and industrial applications. For detailed specifications, designers rely on semiconductor manufacturers' documentation, such as NXP's SPI application notes [149], STMicroelectronics' protocol reference guides, and Texas Instruments' interface design manuals, which outline best practices and recommended electrical characteristics for robust SPI communication.

4.1.4 Motor Control Standard

IEC 61800

IEC 61800 standard specifies extensive specifications for the design, performance, and safety of electrical motor drive systems like stepper motor controls, DC drives, and variable-speed systems. The standard sets out principal design requirements so that drive systems is be safe, predictable, and efficient under a broad variety of conditions. It emphasizes fundamental safeguards such as overcurrent protection, immunity to short circuits, dependable braking capability, and safe start/stop patterns, all of which are crucial in use where motors perform subtle motions — such as the scanning movement of our system. The standard includes electromagnetic compatibility (EMC) guidelines as well, which will stop motor running and driver switching from generating noise that could cause interference to other sensitive components, such as the ADC or FPGA communication lines [150].

Overcurrent Protection is a crucial aspect of the IEC 61800 standard that ensures motor drive systems are protected from overcurrent draw [151]. This translates in our system analogy to the motor driver limiting current delivered to the stepper motor to prevent the driver and motor from being damaged by excessive heat or electrical stress under sustained or unexpected load conditions. Overcurrent protection helps to extend the life of the motor as well as protect the system from failure and scanning disruption.

Safe Start/Stop Control requirements ensure that motors initiate and terminate motion in a controlled, repeatable manner. This eliminates jerks or mechanical shocks at starting or stopping the scanning rotation to maintain sensor alignment and precision. Smooth start/stop motion also reduces mechanical stress on the motor and supporting structures, enhancing reliability and safety for extended use [150].

Braking and Deceleration mechanisms are detailed in the standard so that motors may be stopped under control without overshooting or losing position accuracy [150]. This is an important aspect in our detection system since the motor need to stop scanning once fire is detected. Controlled braking comes to a precise stop, preventing misalignment of optical sensors and enabling consistent detection across the full scanning area.

Current Limiting is another key point, where the standard requires drive systems to place stringent current limits to protecting the motor and circuitry [150]. This serves our system directly by allowing the motor driver to dynamically limit current depending on the needs of the load, preventing power wastage and thermal stress. It also prevents the compromise between efficiency and torque, allowing our system to operate without wastage of energy.

Thermal Protection Needs require motor drives and drive systems to have the ability to sense overheating and automatically shut down or reduce power if necessary [150]. In relation to our system, this provides protection to the motor driver and associated components during prolonged scanning operations or unexpected load conditions. By preventing thermal overload, you guarantee system lifespan and consistent performance.

Electromagnetic Compatibility (EMC) standards address reducing electrical noise caused by switching motors and control signals [150]. EMC is essential to ensure within our fire detection system, as interference from noise might affect sensitive signals between FPGA and ADC or between sensors and processors. Following these standards reduces the likelihood of spurious detection or misreading caused by electrical interference.

System Safety Integration is emphasized in the standard, encouraging the use of fault detection, redundancy, and emergency stop functions [150]. For our system, this means that if any abnormality in motor behavior or electrical behavior is detected, the system can immediately stop or adjust operation to avoid mechanical destruction or data corruption. Such integrated safety features ensure the motor control system operates with confidence and reliability, essential for a high-risk application like fire detection.

Conformance to IEC 61800 ensures that motor driver and motor is operating safely and effectively without room for uncontrolled motion. The standard ensures smooth acceleration and deceleration curves as well as operating within safe currents, preventing the motor from draining too much energy or heating. This is vital in guaranteeing both power efficiency and system dependability, especially regarding the continuous nature of scanning operations [150]. Additionally, by following these guidelines, our motor control system behaves uniformly, reducing the risk of mechanical stress, sensor misalignment, or erratic behavior during fire detection criticality. Lastly, IEC 61800 guarantees that the motor is running as part of an interference-free, integrated, and safe system that increases the overall efficiency and lifespan of FLAMES

4.1.5 Optical Hardware Standards

Photodiode Standards

International and national organizations such as IEC, JEDC, ANSI, and MIL-STD create standards to ensure proper performance, safety, interoperability, and reliability of photodiodes across various applications and environments.

IEC 60747-5-5: Optoelectronic Devices – Photodetectors

This specification covers the terminology, definitions, and measuring methods for photodiodes. It outlines performance characteristics such as spectral response, dark current, responsivity. The metric also focuses on testing methods, and terminology to characterize the performance of the photodiodes. By standardizing how photodiodes are measured and specified, IEC 60747-5-5 ensures that the manufacturers and designers can compare devices fairly and reliably. This standard is widely adopted in commercial and industrial applications [152]. The standard also handles representation for limiting values such as operation above temperature range. This specification is very valuable to the project. In our demonstration, we utilized fire, a substantial source of heat. The temperature standard highlighted will enable engineers to make an informed decision on whether the photodiode can operate and produce meaningful values under the constraints we have established. When a diode experiences an increase in temperature, the holes experience a thermal imbalance, leading to electron-hole exchange and, consequently, current generation. If operated at a temperature higher than the standard rated by IEC-60747-5-5, the current reading cannot be considered accurate. The IEC-60747-5-5 standards sheet ([153]) clearly defines the cutoff frequency and input-to-output capacitance. When manufacturers or retailers emphasize these specifications, it allows the end user to clearly assess the extent of usage before potentially damaging the product. In our specific case, the cutoff frequency limits the frequency of signals that can be detected before a 3 dB signal loss occurs.

JEDC JESD22 Series – Environmental and Reliability test

JEDEC standards, such as JESD22-A101 and JESD22-A108, meticulously test semiconductor devices, including photodiodes, for environmental and reliability. JESD22-A101 specifically focuses on steady-state temperature and humidity bias life testing, evaluating a device's ability to operate under prolonged exposure to high humidity and temperature—a critical concern for photodiodes utilized in outdoor or high-moisture environments. JESD22-A108 addresses temperature cycling, assessing a device's robustness to extreme thermal fluctuations. These tests assist manufacturers in identifying potential failure modes and guaranteeing that photodiodes perform reliably over extended operational lifetimes, particularly in automotive, aerospace, and industrial settings.

MIL-STD-750- Test Methods for Semiconductor Devices

MIL-STD-750 is a comprehensive set of test methods developed by the U.S. Department of Defense for evaluating the performance and reliability of semiconductor devices, including photodiodes. It is particularly critical for military and aerospace applications where components are exposed to extreme conditions and must meet stringent reliability

requirements. The standard includes detailed procedures for measuring key photodiode characteristics such as leakage current, reverse breakdown voltage, response time, and radiation hardness. Devices tested under MIL-STD-750 protocols are often qualified for use in satellites, aircraft, and defense systems, where performance and durability are paramount [153].

lens Standards

ISO 10110 – Optical Drawing Standards

In optical system design, standardized documentation such as ISO 10110 is essential for clearly communicating the specifications of lenses and optical components, especially in precision applications like flame and spark detection. ISO 10110 allows engineers to define critical optical parameters in a structured way on technical drawings, including surface quality, curvature, material type, and manufacturing tolerances. In my senior design project, where I'm using a lens system to focus light from a flame or spark located about two meters away onto a photodiode, adhering to these standards is especially important. One of the key factors in my setup is the diameter of the lens, which directly affects the light collection efficiency. Since flame and spark signals are often low in intensity, a larger lens diameter is crucial to maximizing the amount of light directed onto the detector, thereby improving sensitivity and reducing the chance of false negatives.

Additionally, effective focal length (EFL) is a core parameter that determines how well the lens system can focus light onto a small photodiode area. In ISO 10110-compliant drawings, the EFL can be clearly documented, allowing for consistent interpretation by lens suppliers or manufacturing partners. Similarly, lens coatings—which play a role in minimizing reflection losses and improving transmission—can also be specified within the standard, ensuring that the lens performs optimally in the visible range used in my system. Though my system doesn't include filters, it's still critical that the lens surface specifications, centering tolerances, and possible coatings are all carefully defined to avoid unintended aberrations or misalignment in the focused image. By integrating ISO 10110 into the design process, I ensure that the optical components in my flame detection system meet the necessary standards for performance, durability, and compatibility, ultimately leading to more reliable detection and easier collaboration with manufacturers or optical engineers.

4.2 Design Constraints

4.2.1 Power Constraints

Our fire detection system is powered from an adapter, with the switching regulator handling the stepping down of the voltage as needed to supply different components. Ensuring efficient power distribution is an important design consideration, considering that the system contains many power-consuming components, including the FPGA, ADC, motor driver, sensors, and buzzer. When power is not effectively managed, the system may experience voltage fluctuations, heat generation, and potential instability, which compromise fire detection precision and system long-term reliability.

This system also has a highly important power drain: the Nema 23 stepper motor, which sweeps over the whole area of fire detection within our field of view. Present in the stepper

motor nature is the fact that they draw current even when standing still, hence wasting power consumption unless regulated effectively. The motor driver, although effective in managing motor movement, still needs a constant and adequate power supply to guarantee that the scanning mechanism is smooth and uninterrupted. To counteract excessive power consumption, the system needs to have low-power modes when the motor is not scanning. Through the reduction of motor holding current or the use of periodic shutdowns, the system can reduce overall energy consumption without compromising functionality.

Moreover, SPI data transfer from the ADC demands a steady source of power so as not to cause signal integrity problems. SPI is a high-speed data protocol, and therefore, any variation in power would inject noise or inaccuracies in the digitized readings from the sensors, resulting in spurious fire detections or loss of events. Epic voltage regulation and power filtering measures, including utilizing low-equivalent series resistance (ESR) capacitors and shielding practices, need to be employed for the purpose of sustaining clean, stable power distribution to the FPGA processing unit as well as ADC.

Managing power consumption, stability, and efficiency is essential for ensuring the reliable operation of our fire detection system. Implementing low-power motor control strategies, and employing proper voltage regulation and thermal management techniques contributes to a system that is energy-efficient, stable, and capable of long-term operation without failure.

4.2.2 Optical Constraints

In designing an optical system for flame and spark detection, several key optical Constraints must be carefully considered to ensure accurate and reliable signal acquisition. One of the primary constraints is light collection efficiency. The system requires detecting low-intensity, rapidly fluctuating light from flames or sparks at approximately 0-2 meters. Therefore, it is crucial to maximize the amount of light entering the system. This necessitates selecting lenses with a large diameter and high numerical aperture (NA), which allow more light to be collected and directed towards the detector. However, this must be balanced with physical size limitations, as the optical components are mounted on a rotating platform and require compactness for system mobility and integration.

Another significant constraint is the effective focal length (EFL) of the lens system. The focused light must precisely land on a small-area photodiode so the optics must be able to demagnify the incoming light into a smaller spot size. A short focal length helps minimize the total track length of the system, but it also necessitates careful spacing and alignment. This leads to another constraint: alignment and centration. Any deviation in lens alignment or detector positioning can result in optical power loss or complete miss of the detector. Tight mechanical tolerances and precision mounts are essential to maintain the optical axis and ensure consistent performance. Additionally, optical aberrations such as spherical aberration, coma, and chromatic distortion can further degrade the focused spot and reduce signal intensity. To mitigate these, the use of aspheric or achromatic lens elements may be necessary, particularly when dealing with a wide range of angles or broadband light emissions from combustion events.

Material and coating selection are also influenced by spectral transmission limitations. The lens material must transmit effectively in the visible to near-infrared region, where flames

and sparks emit the majority of their light. Common materials such as BK7 or fused silica are typically employed. Anti-reflective coatings, for instance, minimize signal loss caused by reflections and enhance transmission through the lens. Furthermore, environmental conditions, such as exposure to heat, dust, and smoke, introduce additional optical and mechanical considerations. Lenses may necessitate protective housing or sealing, and surface durability becomes a significant factor. Lastly, the detector itself presents constraints. The photodiode's smaller active area and fixed spectral responsivity range necessitate that the focused light be tightly confined in both spatial and spectral domains. Collectively, these constraints guide the design choices in optics, mechanics, and materials, ensuring that the system can accurately detect, analyze, and classify flame or spark events in real time.

4.3 Practical Constraints

4.3.1 Time

One of the main constraints in this project is the strict time limitation imposed by the senior design course. With only two semesters to design, develop, and test our system, we must carefully balance the scope of our work with the available time. This constraint significantly influences our decision-making, as we must prioritize meeting deadlines over making incremental improvements that could lead to a more refined final product.

A unique challenge for our project is that our second semester takes place during the summer, which is only 12 weeks long instead of the usual 16 weeks. This compressed schedule further limits the time available for debugging, optimization, and finalizing our system. Anticipating this challenge, we proactively began working on the project early, dedicating time in the previous semester to group formation, brainstorming, and initial research. By doing so, we aimed to mitigate some of the time pressures that would arise later in the project.

Another significant issue stemming from time constraints is the need for extensive testing, debugging, and iteration within this short timeframe. Unexpected errors in system design, software integration, or hardware functionality are inevitable, and each issue requires time to diagnose and resolve. With limited flexibility in our schedule, these setbacks could disrupt our progress and jeopardize our ability to meet milestones.

Beyond academic deadlines set by the course and our advisors, external factors also contribute to time limitations. Shipping delays can significantly impact our workflow, especially for essential components such as sensors, circuit boards, and specialized hardware. Planning and communication delays can also slow progress, particularly when coordinating with vendors, advisors, and among team members. Additionally, this phase of the project coincides with a period where many team members are traveling for job interviews and graduate school visits, making scheduling more difficult and reducing availability for in-person collaboration.

The cumulative effect of these constraints could lead to a rushed final product if not managed properly. To mitigate this, we emphasize early procurement of materials, structured planning, and effective communication to keep the project on track. By

anticipating potential roadblocks and addressing them proactively, we aim to maximize efficiency and ensure that our system is fully functional within the given time constraints.

4.3.2 Economic

One of the significant constraints in our project is the economic limitation. Unlike many senior design teams that consist of four or five members, our team is composed of only three members, meaning we have fewer people contributing financially. Additionally, our project is not sponsored, so the entire budget comes directly from our own pockets. Without external funding, we must carefully allocate our resources to ensure that we can afford the necessary components while staying within a reasonable personal budget.

One of the biggest financial considerations in our project was the purchase of an FPGA prototype board, which became our most expensive item. While this board was not a required component for the final design, it was a necessary investment to verify and debug our FPGA code before implementing it directly onto our PCB. This additional hardware served as an error-checking mechanism to prevent costly mistakes in the later stages of development, reducing the risk of failures once the design was finalized.

The second most expensive components in our project are the photodiode and Raspberry Pi 5 board, which serve as the primary input sources for our fire detection system. These components are essential to the functionality of our project, as they handle data acquisition and processing. Because these parts are vital, we had no choice but to allocate a significant portion of our budget to ensure that we acquired high-quality and reliable components.

Beyond the cost of core components, we also had to consider potential unexpected expenses. Shipping costs and availability of components can fluctuate, and delays in receiving parts could require expedited shipping, which adds to our expenses. Additionally, if any components fail during testing, we may need to repurchase them, further stretching our budget. Since our team is already working with a limited financial pool, we must be strategic in how we plan and manage our purchases to prevent unnecessary costs.

Despite these economic constraints, we aim to mitigate their impact by thoroughly researching cost-effective alternatives and ensuring that every purchase is justified. By carefully planning our budget, prioritizing essential components, and making informed decisions about where to allocate funds, we can successfully complete our project without compromising its functionality.

4.3.3 Environmental

One of the most significant design constraints for this project is the environmental constraint. Since FLAMES is designed to analyze and detect fire events based on lighting conditions, its functionality is directly influenced by the environment in which it operates. Unlike systems that rely on fixed thresholds or controlled settings, our system requires an adaptive environmental baseline, meaning that changes in natural or artificial lighting can impact its accuracy and reliability. As a result, environmental factors must be carefully considered throughout the design, calibration, and implementation process.

The first major environmental constraint is lighting variability. Since our system relies on a photodiode to measure light intensity, natural changes in ambient light, such as sunrise,

sunset, or cloud cover can affect the baseline readings. Indoor environments introduce additional challenges, as artificial lighting can turn on or off suddenly, creating abrupt changes that might be misinterpreted as a fire event. To account for these fluctuations, our system must implement robust baseline correction methods to distinguish between normal lighting changes and actual fire hazards. However, continuously adapting the baseline presents another challenge: if the system adjusts too frequently, it risks normalizing real fire events as part of the baseline, leading to missed detections.

Another environmental constraint is unwanted optical interference, which includes glare, reflections, and sudden bright flashes. In settings where reflective surfaces are present, light from external sources can bounce unpredictably, causing inconsistent sensor readings. Additionally, bright but harmless events, such as camera flashes or headlights in an indoor parking garage, could momentarily spike intensity levels, creating false positives. While software filtering techniques such as moving averages and threshold adjustments can help mitigate these issues, excessive filtering may also delay response time, which is a critical factor for emergency situations.

The third major environmental constraint is long-term drift in lighting conditions. Over time, bulbs may dim, windows may accumulate dust, and environmental conditions may shift in ways that subtly affect light measurements. If our system does not periodically recalibrate, these gradual changes could result in detection errors. However, frequent recalibration can introduce latency and computational overhead, creating a tradeoff between long-term stability and real-time responsiveness.

The physical environment also presents challenges, as factors like smoke, dust, or humidity could interfere with sensor readings. In high-dust environments, particles may scatter light in unpredictable ways, while high humidity levels could alter the way light interacts with the air, slightly modifying the readings. While these effects are generally small, they accumulate over time and may introduce minor inaccuracies if not accounted for.

Addressing these environmental constraints requires a balance between adaptability and stability. Our system must be sensitive enough to detect real fire hazards while being robust against routine environmental changes. By implementing dynamic baseline calibration, filtering techniques, and anomaly detection algorithms, we aim to mitigate the impact of these environmental factors. However, despite these precautions, it is important to recognize that no fire detection system can operate with absolute accuracy in all environments, and external conditions will always play a role in influencing performance. Understanding these constraints allows us to design FLAMES with realistic expectations while ensuring it remains as reliable and adaptable as possible within its operating conditions.

4.3.4 Manufacturability

Manufacturability is a key constraint in the design and implementation of FLAMES, as our project is a prototype rather than a mass-produced product. While we are focused on functionality and proof of concept, real-world manufacturability would require consideration of factors such as cost-effective assembly, component sourcing, scalability, and ease of replication. Several key manufacturability constraints affect our design.

One of the primary manufacturability challenges is custom PCB fabrication. Our design includes an FPGA-based system that requires precise hardware integration, and developing a printed circuit board (PCB) for this system involves sourcing components, ensuring proper layout design, and accounting for potential manufacturing tolerances. Small errors in PCB design, such as incorrect trace widths or poor power distribution, could lead to issues in large-scale manufacturing. Additionally, ordering and assembling PCBs involves lead times and costs that can delay our progress, particularly if revisions are needed due to design errors or component incompatibilities.

Another constraint is component availability and sourcing. Many of the components in our system, including the FPGA, Raspberry Pi 5, photodiode, and motor driver, are subject to supply chain fluctuations. Certain high-demand components, particularly microcontrollers and FPGAs, often face shortages, which can impact manufacturability if an alternative part with different specifications is not readily available.

Additionally, manufacturability is constrained by durability and reliability considerations. A fire detection system must operate reliably over extended periods, meaning that components need to withstand environmental stresses such as heat, dust, and electrical noise. In a production setting, the enclosure, wiring, and PCB design would need to meet industry safety and reliability standards to ensure long-term performance. While our prototype is focused on validating functionality, a manufacturable version would require further testing for compliance with fire safety regulations, electrical safety certifications, and robustness standards.

To address these manufacturability challenges, we focus on modular design principles, careful component selection, and optimizing our PCB layout for potential future scalability. While our current design is not optimized for large-scale manufacturing, understanding these constraints allows us to make design choices that could be adapted for future production if needed.

4.4 Other Constraints

4.4.1 Sustainability

Sustainability plays a role in the design of FLAMES, particularly in terms of energy consumption, component longevity, and material usage. While the primary focus is functionality, certain design choices impact the environmental footprint of the system.

One major sustainability consideration is energy consumption, as FLAMES operates on AC power from a wall outlet. Unlike battery-powered systems that require careful power management, our system has continuous power access, allowing for uninterrupted operation. However, components such as the FPGA, Raspberry Pi 5, and stepper motor contribute to overall power demand, particularly during scanning operations. While power efficiency is not a key focus, a more sustainable design could include optimized motor control and power-efficient hardware to minimize unnecessary energy usage.

Another sustainability constraint is electronic waste and component lifespan. The system incorporates specialized components, including the FPGA, Raspberry Pi 5, and photodiode, which may have limited recyclability or become obsolete as technology advances. If

replacements are needed, sourcing compatible components in the future could be a challenge. Designing the system with modularity in mind, allowing individual components to be replaced or upgraded, would improve long-term sustainability and reduce unnecessary waste.

Additionally, PCB fabrication presents environmental concerns due to the chemical processes and material waste involved. While our project is developed on a small scale, PCB manufacturing typically requires hazardous chemicals and non-biodegradable materials. If large-scale production were considered, sustainable design practices such as lead-free solder and material-efficient layouts would be necessary.

By considering energy efficiency, component lifespan, and material usage, we acknowledge the sustainability constraints of our project and recognize areas where improvements could be made in future iterations.

4.4.2 Political

Political factors impact the development and implementation of FLAMES, particularly in areas related to fire safety regulations, supply chain limitations, and compliance requirements.

A primary constraint is fire safety regulations and compliance standards. Fire detection systems must adhere to strict guidelines set by organizations such as NFPA 72 and IEC 61508, which establish the requirements for sensor placement, alarm signaling, and system reliability. These regulations ensure that fire detection systems function effectively in emergency situations, but they can also impose design constraints, limiting flexibility in component selection and system configuration.

Another key political constraint is supply chain and trade regulations that affect the availability of essential components. Many critical parts used in the project, such as the FPGA and Raspberry Pi 5, are sourced from global manufacturers and may be subject to import/export restrictions, tariffs, or supply shortages. Any disruption in the supply chain could lead to delays or increased costs, affecting the timeline and feasibility of implementation.

These political constraints influence system design, component sourcing, and regulatory compliance, all of which must be considered when developing a fire detection system that aligns with industry standards and practical implementation requirements.

4.4.3 Ethical

Ethical considerations in FLAMES primarily relate to reliability, false alarms, and system safety. Since fire detection is a critical application, the system must function accurately to avoid both missed detections and false alarms, which could lead to serious consequences.

One ethical concern is false positives, where the system incorrectly detects a fire due to environmental lighting changes or sensor noise. Frequent false alarms could lead to desensitization, where users begin to ignore warnings, potentially putting lives at risk in an actual fire event. To address this, we implement adaptive baseline calibration and filtering techniques to minimize unnecessary alerts while maintaining sensitivity to real fire events.

Conversely, false negatives, where a fire occurs but is not detected, pose an even greater ethical risk. If the system fails to recognize a fire due to environmental conditions or baseline drift, it could delay emergency response. Ensuring that FLAMES consistently identifies actual fire hazards while avoiding missed detections is critical to maintaining trust and effectiveness in fire detection systems.

Additionally, the system must be designed with safety and reliability in mind. Components should be properly tested and calibrated to ensure they operate as expected in real-world conditions. Ethical responsibility in this project includes thorough testing and validation to ensure the system does not introduce unintended risks.

By addressing false alarms, missed detections, and system reliability, we aim to uphold ethical standards in fire detection technology, ensuring that FLAMES prioritizes safety and accuracy in its operation.

4.4.4 Health and Safety

Health and safety constraints for FLAMES primarily focus on system reliability, false alarms, and proper functionality, ensuring that the system does not pose risks to users or fail in critical situations. While these considerations overlap with ethical constraints, the key difference is that health and safety constraints emphasize physical and operational safety, rather than ethical responsibility.

Electrical safety must be considered, as the system operates on AC power from a wall outlet. Ensuring that all wiring, power components, and PCB connections meet safety standards is essential to prevent hazards such as short circuits, overheating, or electrical failures that could compromise the system's operation.

4.4.5 Scalability

Scalability is a key consideration in the design of FLAMES, as expanding the system beyond its current implementation presents several technical and logistical challenges. While the system is designed for a single-unit prototype, scaling it for larger environments, multi-sensor networks, or commercial deployment would require significant modifications.

One major scalability constraint is system adaptability to different environments. FLAMES currently establishes an environmental baseline for fire detection based on a single photodiode sensor, which is calibrated for its specific surroundings. Expanding this system to cover larger areas or multiple rooms would require additional sensors and a more complex data fusion algorithm to handle multiple inputs while maintaining accuracy and reducing false positives.

Another limitation is processing power and data handling. The system currently relies on a Raspberry Pi 5 and FPGA, which are suitable for a single-unit setup. However, if the system were to be expanded into a networked fire detection system with multiple units communicating in real-time, it would require higher processing capabilities, cloud-based data management, or distributed computing to efficiently analyze and process fire detection data.

Integration with existing fire safety systems is another factor in scalability. Expanding the system to work with centralized fire alarm systems, emergency response networks, or smart

building infrastructure would require standardized communication protocols (e.g., Modbus, MQTT, or BACnet). While the current design does not include networking capabilities, future iterations would need to address compatibility with broader fire safety frameworks.

Scalability is ultimately constrained by sensor coverage, processing limitations, hardware adaptability, and system integration. While FLAMES functions effectively within its current scope, significant modifications would be necessary to expand its capabilities for larger-scale fire detection applications.

Chapter 5 – Comparison of ChatGPT with other Similar Platforms

ChatGPT has evolved immensely since the time of its release in November of 2022. With the introduction of GPT 4.0, advanced reasoning and logic capabilities have been included in the paid version. Initially, going into the beginning of senior design one, I believed that this would be one of my most used tools for conducting research and doing specification specific product comparisons. Unfortunately, this was not the experience I had in using a large language model such as ChatGPT. When conducting research with ChatGPT, I would often preface the prompt line with what my goal was and what outcome I wanted. Examples of potential outcomes that I was expecting were generative charts with part specific information and ask for a returned table highlighting key characteristics. In general, our use case between members of the team varied heavily. In the following case studies, we aim to highlight and showcase how each member of the project utilized the large language model to extract information and use it towards their advantage. ChatGPT is one of the many large language models that have been implemented in the past few years from the date of this extract.

In general, our use case between members of the team varied, but we all made an effort to explore how large language models could assist us throughout the design process. Each team member interacted with ChatGPT for different tasks, ranging from drafting documentation to clarifying technical concepts and identifying suitable hardware components. To evaluate ChatGPT's performance and consistency, we also tested two other large language models: Google AI and Deepseek. Google AI, known for its integration with Google's search capabilities, often provided more up-to-date information but was less structured in its formatting. Deepseek, on the other hand, focused more on technical accuracy and code generation, sometimes offering deeper insight for engineering-related prompts. By using the same set of prompts across all three models, we compared their responses in terms of completeness, accuracy, and usefulness. In the following case studies, we highlight how each member leveraged these tools and how their outputs influenced different stages of our project.

5.1 Case Study 1

Please refer to Appendix E, [1a], [1b] and [1c] for the Case Study 1 given prompt and outcomes from ChatGPT and Deepseek.

ChatGPT [1b] [154] did an excellent job of explaining how a Galilean demagnification system operates at a high-level overview. I also appreciate that it uses examples to support its equations. The equations that are provided are factual and are in fact how one would go about the designing the Galilean style telescope system. The large language model in this example also excelled at providing broad feedback of all prompts that were asked. One of the most important considerations to be considered is the distance between the lenses. This is a project specific limitation that ChatGPT has no way of being aware of. For example, if I aim to design a 50x demagnification system, I will need to compute the ratio of focal lengths of the negative lens and positive lens such that there is a 50 times demagnification factor. The large language model fails to provide insight into the practicality and feasibility of the system. To achieve this type of demagnification factor, a negative lens with a focal length of -500mm will need to be placed an approximate distance of 490 mm away from a positive focusing lens of 10mm. The model assumes that I am using a simple 2 lens system. Sourcing lenses with the exact focal lengths and matching diameters is not a feasible task. The Galilean system is also known for being a more compact system relative to the Keplerian style telescope. The optical engineer in this case must intervene and realize that the same task can be accomplished by using a three-lens system, where the positive lens can be a combination of lenses with an effective focal length of 10mm. As far as material selection, I believe that the information is factual and commensurate with industry standards. Although the LLM offers suggest that using a plano convex / concave or equiconvex / Equi concave solution, it does not consider the diameter of the lens. This is arguably a higher priority specification to maximize light collection efficiency of the system. I believe that ChatGPT has done exactly what I have prompted it to do. Had I prompted with part specific information, I have limited doubt that the LLM would struggle to provide relevant information pertaining to my part specific prompt line.

The same question has been analyzed by the Deepseek large language model. Deepseek / perplexity AI [1C] provided similar information to ChatGPT however, the AI model included a design example, advantages of system, challenges, and suggestions for my application section. This is an abundant amount of information compared to ChatGPT. While the information in both large language models is consistent with optical theory, the Deepseek AI model provided more tangible feedback given a singular prompt. This model also suggested using achromatization techniques, in the demagnification system which would be beneficial however it is out of context for my actual application [155].

5.2 Case Study 2

Please refer to Appendix E, [2a], [2b] and [2c] for the Case Study 2 given prompt and outcomes from ChatGPT and Google AI.

ChatGPT [2b] did a solid job of pulling relevant sources for high-performance MCUs, giving users a way to dive deeper if they need more details. It also breaks down why each MCU is powerful, rather than just listing names. Since “high-performance” can mean different things depending on the use case, ChatGPT seemed to prioritize processing power, RAM, and extra features like Wi-Fi and Bluetooth in its response.

However, a downside to ChatGPT’s response is it’s source-citing, as many of it’s sources, due to ongoing Copyright issues, are limited to unknown websites and LinkedIn posts. This

means that the answers are subjective to LinkedIn and article posts, which may have its benefits since there is a human-touch to the answers, but Google AI has access to all websites, which provides multiple sources and comparison of such. This can be seen next.

However, a downside to ChatGPT's response is its source-citing. Due to ongoing copyright restrictions, many of its sources are limited to lesser-known websites and LinkedIn posts. This means the answers are somewhat subjective, relying on opinions from professionals and tech enthusiasts rather than a broad range of official manufacturer sources. While this can be beneficial in providing a more human-touch perspective, it may lack the comprehensive, multi-source comparisons that Google AI can access.

Google AI [2c], on the other hand, has access to a wider range of sources, including official manufacturer websites, product datasheets, and review aggregators. This allows it to present a broader comparison of MCUs, pulling from multiple perspectives rather than relying heavily on individual articles or posts. This difference in source access is something to consider when evaluating the reliability and depth of information provided by each AI [156].

Interestingly, when I tried the same prompt on Google, its AI assumed I meant the Marvel Cinematic Universe instead of microcontrollers. I had to explicitly type out "microprocessor" to get the right results. The results can be seen in [2c].

Google AI, as shown in Appendix E, provided completely different answers compared to ChatGPT. Google AI seemed to focus mainly on technical specifications like core size and thread size, but it didn't go much beyond that in terms of practical applications or additional context.

On the other hand, ChatGPT not only listed high-performance MCUs but also explained why they are powerful, highlighting key features such as processing power, RAM, and connectivity options like Wi-Fi and Bluetooth. This approach helps users understand which MCU might be best suited for their specific needs rather than just comparing raw specs.

5.3 Case Study 3

Please refer to Appendix E, [3a], [3b] and [3c] for the Case Study 3 given prompt and outcomes from ChatGPT and Google AI.

The utilization of ChatGPT [3b] for specific hardware selections, such as the buzzer example, seemed to be extremely useful as it generates ideas that I can consider, along with extended parameters of the hardware that I need to be aware of. I simply asked just for buzzer technologies and ChatGPT indeed answered my question by providing me with different buzzer technologies, but it also provided "How it works" or "Power consumption" which I did not include in my question. By doing so, ChatGPT allows for me to expand my thinking giving more ideas to add within the hardware section.

Although it is helpful that ChatGPT goes beyond the limitation of my question to provide me with information, the accuracy of its information provided to me can be questionable. For example, within this case study, ChatGPT provided me with a frequency range of the piezoelectric buzzer which it stated to be "2-4kHz", but since I already extended my research utilizing external sources, I know that this measurement is slightly wrong as it is

2-6kHz. Although this is a slight misinformation that may not seem like a huge deal, I want to accurately present information by using correct values. Utilizing values generated by ChatGPT may not be ideal. There are other cases when I would have to fact check ChatGPT on values, and some of the values are entirely incorrect, in comparison with measurements from specific datasheets that I have referenced. Now by asking Google AI please refer to [3c]. It is similar to ChatGPT where it provides me with extra parameters and characteristics of each buzzer technology mentioned. It also provides all the sources that it utilizes to answer my question that I can click and analyze. Unlike ChatGPT it did not provide me with any measurements unless I specifically ask it to. Now when doing so it provides me with more accurate information regarding my question, and added more parameters along with the frequency range with the source that it was able to reference linked right next to it. Users need to be careful with the utilization of ChatGPT cause presented information, generated by ChatGPT, especially with specific values are shown to not always be accurate.

5.4 Case Study 4

Please refer to Appendix E, [4a], [4b] and [4c] for the Case Study 4 given prompt and outcomes from ChatGPT and Deepseek.

The solutions offered by ChatGPT [4b] are very feasible solutions. In the following critique, I am to identify the pros and cons and considerations that the LLM has missed. I will begin with the achromatic doublet paired with a field flattener lens solution. This is my design of choice, as it is relatively simple and results in an achromatic system which is highly beneficial to imaging in lowlight conditions. The LLM did an excellent job of listing out the information in a digestible manner however, it failed to explain the benefits of achromatization. As we will find with all of the imaging systems listed, there is no consideration mentioned of imaging with respect to a format size. In the case of our project, we will need to use quite a few preliminary calculations to determine how far the actual scene is from our sensor. I found it very impressive that the LLM was able to recognize the drawbacks of using solely an achromatic lens as their will be field distortion effects present in the final image. The term field flattener lens is very broad, as it can be numerous types of lens geometries. I would have liked for ChatGPT to list out why the specific geometry was chosen to get better insight into the level of imaging performance. Next is the analysis of a single lens imaging system. While this can theoretically be done, using spherical lenses can introduce immense amounts of aberrations. Sourcing a singular lens that can provide diffraction limited imaging performance is not very reasonable. Again, there is no mention of optical format size. The Galilean telescoping system would be an excellent candidate for a magnification imaging system. Because the AI does not know the optical format of the sensor, using a Galilean style system is unreasonable. The distances in-between the lenses needed for imaging far exceeds the physical size of the end system. I agree that using a Galilean system is useful, however it is not practical in regards to ease of implementation and optical alignment. Last, is the Cooke triplet lens. The Cooke Triplet is a classical imaging system that is cost effective and provides decent aberration control over the optical system. While the AI model recommends different geometries, it is not sufficient to be convincing to an optical designer. One of the two main drawbacks to the Cooke triplet system is its limited FOV. For our projects application, a large horizontal field of view is

required for best performance and image quality. The other main drawback to using a Cooke triplet imaging system is the manufacturing needed to induce power into the overall optical system. A total of 3 lenses and 6 surfaces will need to be aligned and tolerance properly. Once again, the LLM fails to consider the optical format size. Using off the shelf lenses creates a design constraint meaning that we can no longer use larger lenses. We will need to stick to lenses that are relatively small (roughly 6mm or less).

Deepseek [4c] is a relatively new large language model that was launched in earlier 2025. When asking Deepseek the same exact question, I got the same response. The key difference that I observed between the responses from Deepseek and ChatGPT lies in its suggestion of alternative methods. For example, the Deepseek AI suggested that I use the Cooke Triplet or Achromatic doublet and field flattener combination if field of view is not a priority. This shows that this AI model is considering the design constraints of the lens therefore it can make a suggestive and informative design choice. In the earlier ChatGPT case, the model was not taking into account design considerations and predicting points of design constraint [155].

5.5 Case Study 5

Please refer to Appendix E, [5a], [5b] and [5c] for the Case Study 5 given prompt and outcomes from ChatGPT and Google AI.

This question was meant to test ChatGPT's ability to handle software-related problems. It did a great job of shifting the focus away from quick sort, since it's not really suited for optimizing thresholds, and instead provided solid alternatives that actually make sense for threshold-based systems.

However, it does give a lot of information at once including not just solid alternatives, but also their best-use cases to help the user decide what fits their system. While I never specifically mentioned FLAMES, I bet if I had, it could've narrowed the list even more, making it even easier to choose the best option.

When asking Google AI the same question the following response was provided as seen in [5c].

As shown in Appendix E, Google AI also provides a vast amount of information, but unlike hardware, it dives deeper into the intricate details of software compared to ChatGPT. It also discusses how each one compares to thresholds, similar to ChatGPT. Google AI did well in keeping it connected to my original question by suggesting alternatives similar to quick sort, though they may not align with threshold optimization as effectively as ChatGPT's responses.

5.6 Case Study 6

Please refer to Appendix E, [6a], [6b] and [6c] for the Case Study 6 given prompt and outcomes from ChatGPT and Google AI.

Now when asking ChatGPT [6b] about a topic, such as the topic on I2C, where I want to learn the basics about a topic, ChatGPT is a great source to utilize because it not only explains the topic well but it also it explains it with such accuracy. I would still advise users

to fact check the information provided by ChatGPT especially for the specific values stated (such as the data speed in this case), but it gives you such a great structure in terms of providing functionality, key features, pros/cons and examples of the topic that is being researched. It is a great start off point when beginning to do research. Now comparing it to Google AI please refer to [6c].

Google AI [6c] does a great job in providing information such as listing its functionality along with its purpose, characteristic and extended parameters. But ChatGPT goes beyond that, in providing examples, key features and being articulate and specific when explaining its functionality. ChatGPT is a great tool for research purposes. It provides users a baseline when researching a topic along with multiple extended parameters to ponder on and to eventually consider within your research.

Chapter 6 – System Optical Design

6.1 Flame Imaging System Precursor Calculations

Our project highlights an integrated imaging system that enables imaging up to 5 meters away with a customized lens design. To establish a suitable lens design, we must first consider the fundamental parameters of our imaging system. These parameters will serve as critical limits that must not be exceeded. For instance, we will consider the sensor format size, the desired imaging distance, and the dimensions of the object. The imaging style specified in Chapter 3 is the aspheric doublet paired with a field flattener lens (plano convex or bi-convex lens). This system has been selected due to its simplicity and robust image quality with minimal aberrations. When bending light rays, it is essential to consider the number of surfaces present in the system. The more surfaces there are, the greater the designer's control over the light. As we will demonstrate in the subsequent sections of Chapter 6, a single doublet is insufficient to correct severe aberrations.

It is important to note that the primary objective of the imaging system is to capture an image at 5 meters with minimal blur or distortion. The analysis presented here will not utilize a circular aperture pinhole. The pinhole would increase the depth of focus, thereby maximizing the tolerable blur.

To commence, we will make the following assumptions:

- The diagonal of the Sony IMX 296 sensor is 6.3 mm.
- The object distance is 5 meters away.
- The pixel size is 3.45 microns.

Using Equation 12, we can obtain information regarding the half field of view of the system.

$$HFOV = 2 \cdot \tan^{-1} \left(\frac{\text{Scene Height}}{2 \cdot \text{Obj Distance}} \right) \quad (12)$$

For this analysis, we will assume that the scene height is ½ a meter in height and width. Using equation 12, we gather that the half field of view is 33.0127 degrees, or 66.025 degrees at the full field of view. The effective focal length of the system is found by

computation of equation 13. The effective focal length will be the distance in millimeters from the last surface to the imaging cmos sensor.

$$EFL = \frac{\text{Diagonal of Sensor}}{2 \cdot \tan\left(\frac{FOV}{2}\right)} \quad (13)$$

Computing equation 13, gives an effective focal length of 4.85 mm. This value will be important for Optimization of the system.

6.2 Zemax Optimization of Ideal lens System

For the purposes of this project and given that the effective focal length of the system is significantly shorter than the object distance, we will assume the object distance to be an infinite image. In Zemax, the fields of the system has been set to record ray traces at three distinct fields of 0-, 11-, and 33-degree fields. Because we are imaging the visible part of fire, we would like to use the C, D, and F sodium wavelength lines. In Zemax, we have used an image space f# of 10 which is a relatively small aperture. We begin with entering the first surface as a lens with a calculated radius given by equation 14.

$$\frac{1}{f} = (1.5168 - 1) \cdot \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (14)$$

Given that the focal length is 4.84mm, and assuming a plano convex lens, we have calculated the radius of surface one to be 2.506mm. It is imperative to note that the glass type used is N-NBK7 out of the Schott glass catalog. The resulting image of the lens with its prescription is shown below in Figure 11.

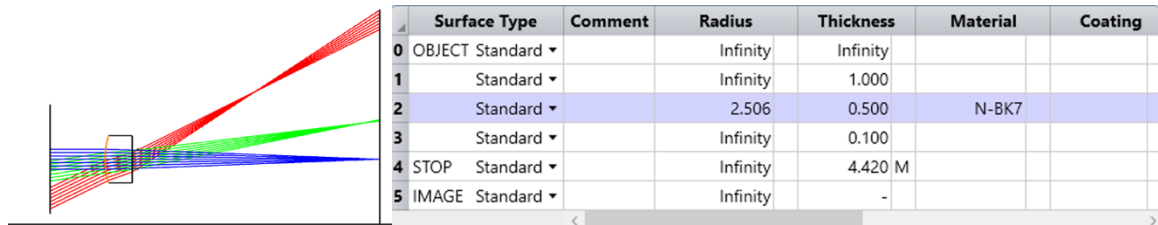


Figure 11. Flame Camera Initial Simulation

Initial Lens system with Plano Convex lens.

As we can see, there is extreme field curvature present and astigmatism in the system. To correct this, we shall make an optimization with the effective focal length and make the radius of surface 1 and surface 2 variable. We will optimize with respect to the target focal length of 4.85mm. In doing this we ultimately correct the field curvature of the lens and achieve our desired focal length. Figure 12 displays the output lens system.

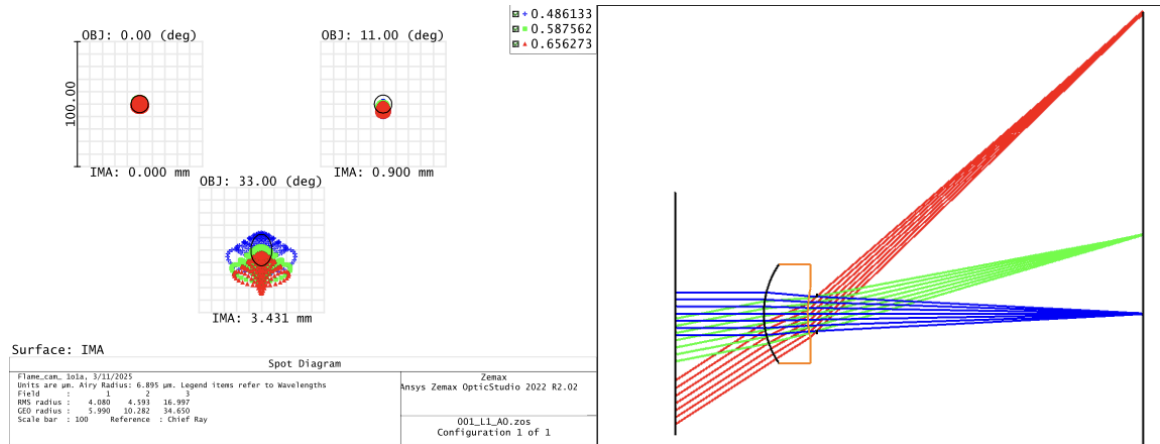


Figure 12. Optimized Imaging System – Radius Optimization

Optimized Radius to achieve effective focal length of 4.85mm

Currently, there persists a persistent issue of lateral color, as evident in the ray spot diagram. In the previous optimization, the issue of field curvature was addressed by adjusting the radius of curvature. Traditionally, achromatization of the lens would be necessary to rectify this issue. This can be achieved by employing a combination of crown and flint glass. The crown glass exhibits lower dispersion compared to the flint glass, which modifies the optical path length for different colors. To address this challenge, an additional surface needs to be introduced.

Furthermore, within the ray spot diagram, another prevalent aberration can be identified as coma. To resolve this issue, the stop position within the lens system will be allowed to vary. The output lens system is depicted in Figure 13.

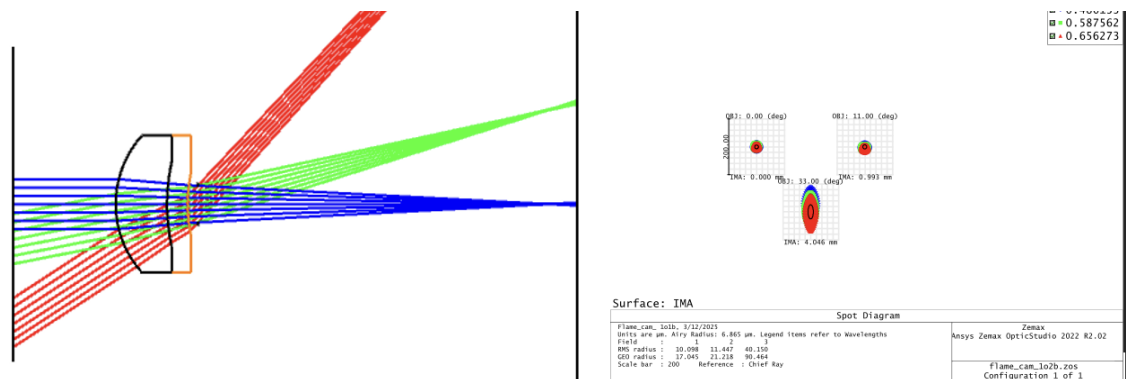


Figure 13. Achromatic Doublet Simulation Results

Optimized lens system. Reduction of coma and lateral color for near on axis fields. Second surface has been added. Second surface is less dispersive.

The center thicknesses of the glasses are not realistic, as there are overlapping regions in the lenses. Consequently, constraints on the air and glass thicknesses have been established.

Additionally, the radius of curvature of the lenses has been set as variable to further enhance the system's performance. Figure 14 presents the resulting lens for this iteration of optimization.

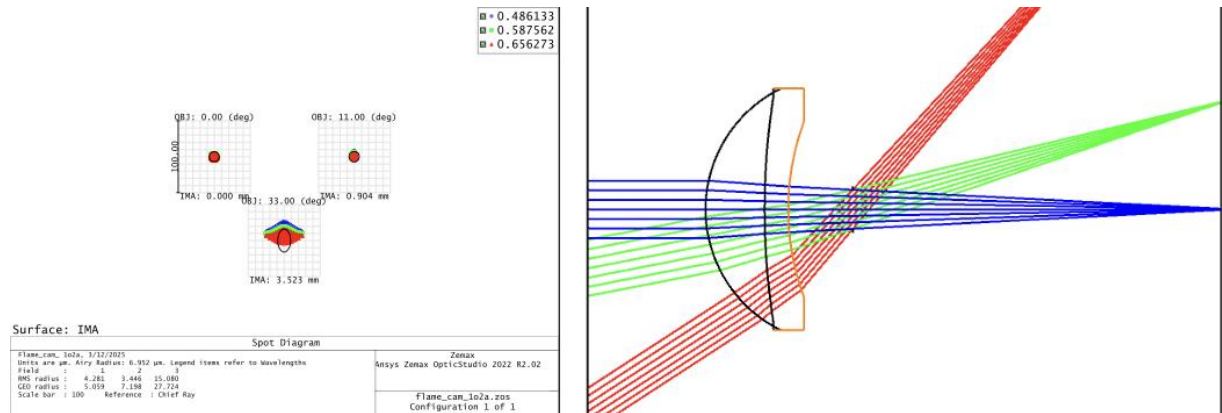


Figure 14. Lateral Color and Coma Correction Results

In this image, the resulting lens system is depicted. The problem of lateral color and coma at the near axis fields has been resolved.

The subsequent step involves rectifying the field curvature. As evident from the ray bundle depicted in Figure 13 there is a significant deviation from the ideal curvature. A plane piece of glass with zero curvature will be inserted a predetermined distance from the first lens. We will also constrain the thickness of the glass and the air in this step to ensure that a realistic lens is achieved. The radius of curvature for the plane glass lens will also be varied at this step. Figure 15 depicts the field flattener lens, which should ultimately improve the field curvature.

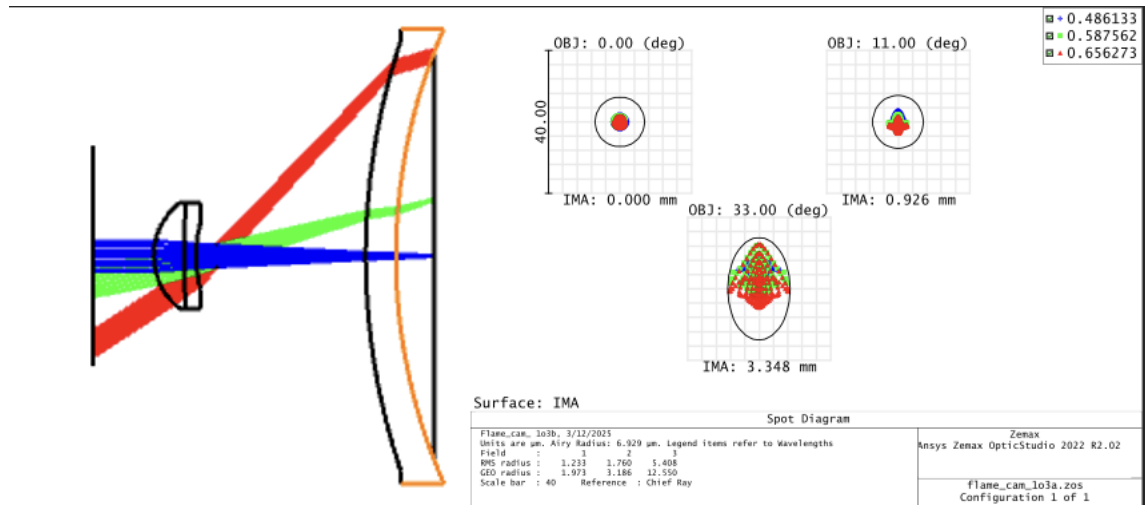


Figure 15. Finalized Simulated Imaging System

This figure depicts the resulting lens system. A third and fourth surface with a specified radius of curvature have been introduced into the lens system to correct the off-axis field curvature. In this step, we are progressing closer to achieving diffraction-limited performance, as indicated in the ray spot diagram.

Finally, the lens has undergone a hammer glass optimization process. This process involves experimenting with various glass combinations to optimize the lens based on the merit function's input arguments. Figure 16 presents the final lens configuration, along with the corresponding ray spot diagram and prescription.

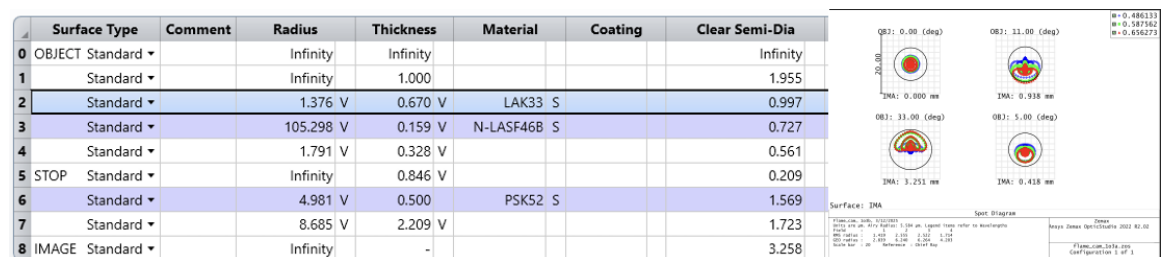


Figure 16. Imaging System Prescription and Spot Diagram

Final lens prescription post optimization with spot diagram

6.3 Theoretical Optical Design to Off the Shelf Lenses

The final lens prescription reveals that the final lens produces an image with vignetting around the edges. Vignetting is caused by some physical blockage of the lens either due to excess material blocking or light being clipped by the edge of the lens. As we can observe from the spot diagrams, the final image at 66 degrees is diffraction limited. One of the most important things to note is that the final prescription contains glass materials that are unique

and are not readily available off the shelf. In the following Zemax iterations, we will compare similar off-the-shelf lenses that have the same focal lengths, and similar indices of refraction for the imaging system. To start the comparison, I will evaluate the effective focal length of each lens independently. As shown in Figure 17 the effective focal length due to the achromatic doublet in the theoretical solution is calculated to be 5.77903 mm. For intentions of purchasing, we shall round this to 6mm. Repeating the same process, surfaces 1-4 are removed and the effective focal length due to the second theoretical lens is shown. In Figure 17. The effective focal length due to this surface is simulated to be 18.3298 mm. We shall take this to be 18 mm for the purposes of scouting out appropriate lenses.

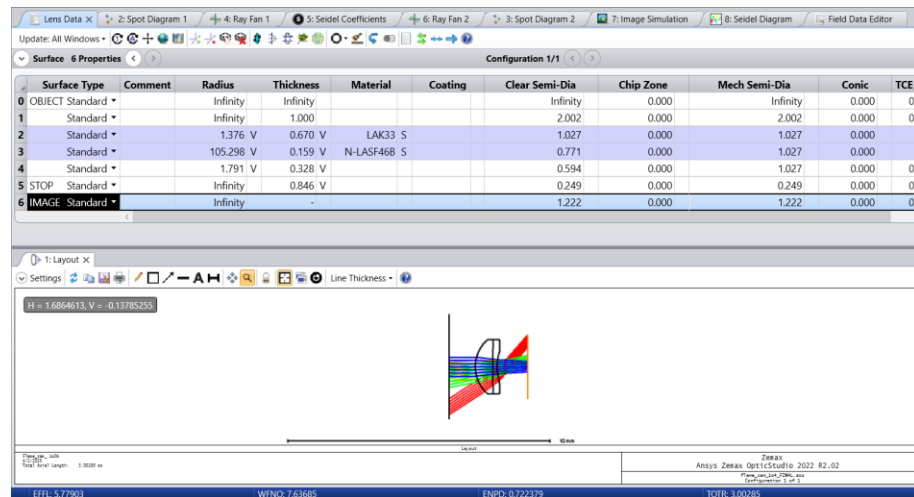


Figure 17. Effective Focal Length Due to 1st Element

Effective focal length is due to achromatic element. Effective focal length simulated to be 5.779903 mm.

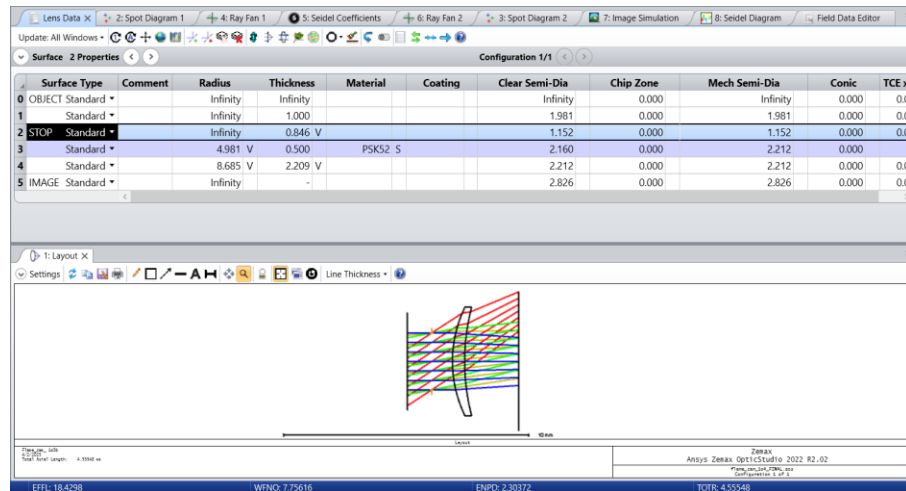


Figure 18. Effective Focal Length Due to 2nd Element

Effective focal length is due to meniscus. Effective focal length simulated to be 18. 4298mm.

By simulating the focal length due to the individual lenses, we have narrowed our searches to find a focal length from off the shelf suppliers that match closely. Once the selection of the lenses for the imaging system has been decided, a simulation shall be done to compare the imaging results. Important imaging criterion that will be compared includes the image quality at 66 degrees, and the ability to handle infinite objects. In other words, how well does the off-the-shelf system perform as an infinite conjugate imaging system. In section 6.4 we will discuss the results of the off-the-left lens system and more importantly how it can be improved. The addition of a pinhole either between the lenses or in front of the lens system can improve the resolution of the image and the depth of field for the system. Depth of field refers to the amount of deviation from the ideal image plane that can be tolerated before incurring a loss in imaging quality. Because the fire or spark can be ignited at a distance of 1- 5 meters is provided, the imaging system needs to tolerate a larger distance from the ideal imaging plane.

6.4 Selection and Simulation of Off the Shelf Lenses

My initial search for commercially available optical components commenced by evaluating lenses with focal lengths comparable to those specified in the theoretical design documents. Although the system was conceived with an achromatic doublet in mind, I have opted to select lens 354105-A from Thorlabs. As per my original design, the first optical element requires a focal length of approximately 5.77 mm. The chosen lens possesses a focal length of 5.5 mm and a diameter of 7.2 mm. The second lens has been selected using the same criteria. LA1472 – B has been substituted for the meniscus lens simulated in the theoretical limit. This offering from Thorlabs has a diameter of 9 mm and an effective focal length of 19 mm.

When simulating off-the-shelf lenses, we have set the field angles and aperture type to match the theoretical solution. It is crucial to note that an achromatic doublet was employed

in the theoretical solution, while in the off-the-shelf simulation, an aspheric lens is employed to correct for chromatic aberration. Upon searching the catalogs of retailers such as Edmund Optics and Thorlabs, we discovered a limited variety of achromatic doublet lenses that possessed a similar effective focal length to the theoretical solution. To enhance the performance of the system, a physical aperture has been used. In simulation, the aperture was shifted in the optical system to correct for coma. Per the simulated image, an $f\#$ of 8 was utilized. Per the simulation results, as the $f\#$ increases, the resolution of the image decreases. A pinhole sized between 400 microns and 1 millimeter has been inserted into the system. The imaging performance of the pinhole and placement will vary upon testing and simulation results. The figure below shows the lens configuration to be used in the finalized design. The image also shows the dimensions of the lenses along with the spacing between them for mounting purposes. Figure 20 showcases the output image simulation where the stop aperture is 400 microns to satisfy the $f/10$ system.

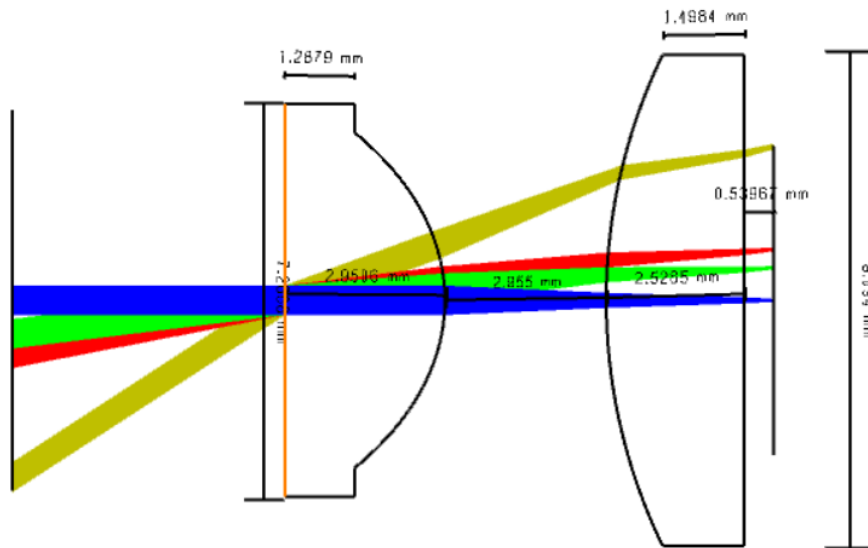


Figure 19. Custom Imaging System constructed with COTS lenses



Consider changing the field type to object height for improved accuracy. See Help Files for more details.

Image Simulation: Geometric Aberrations

4/19/2025
Object height is 46.6690 degrees.
Field position: 0.00 (deg)
Center: chief ray
Image size is 5.2550 W x 3.9413 H (Millimeters)

Zemax
Ansys Zemax OpticStudio 2022 R2.02

Design2_400um_pinhole.zos
Configuration 1 of 1

Figure 20. COTS Lens System Output Image Quality

Chapter 7 – System Hardware & Software Design

7.1 System Hardware Design

7.1.1 Stepper Motor Controls

The schematic of the DRV8825 motor driver, in Figure 21, shows a carefully designed configuration that ensures precise and efficient control of a stepper motor. At its core, the driver is powered by two main inputs: the VMM line, which supplies motor power, and the 3.3V line, which powers the driver's internal logic. The DIR and STEP pins are key inputs from the microcontroller or FPGA, dictating the rotation direction and step pulses, respectively — both crucial for controlling motor positioning and speed. Additionally, the ENBL pin allows the controller to enable or disable the driver, giving direct control over motor activation.

The SLEEP and RESET pins are to ensure the driver is active and properly initialized on power-up. The AVREF and BVREF pins receive reference voltages, setting the current limits for each motor coil, ensuring the motor receives appropriate power without overheating. Sense resistors R2 and R3 are placed on the ISENA and ISENB pins to monitor current through each coil, providing feedback and protection. Capacitors like C1, C2, and C3 near the power input and C5, C6 for internal charge pump stability help filter noise and maintain smooth operation. Together, these components allow the DRV8825 to provide precise, safe, and reliable motor control which is critical in applications where smooth, predictable scanning and motor response are essential.

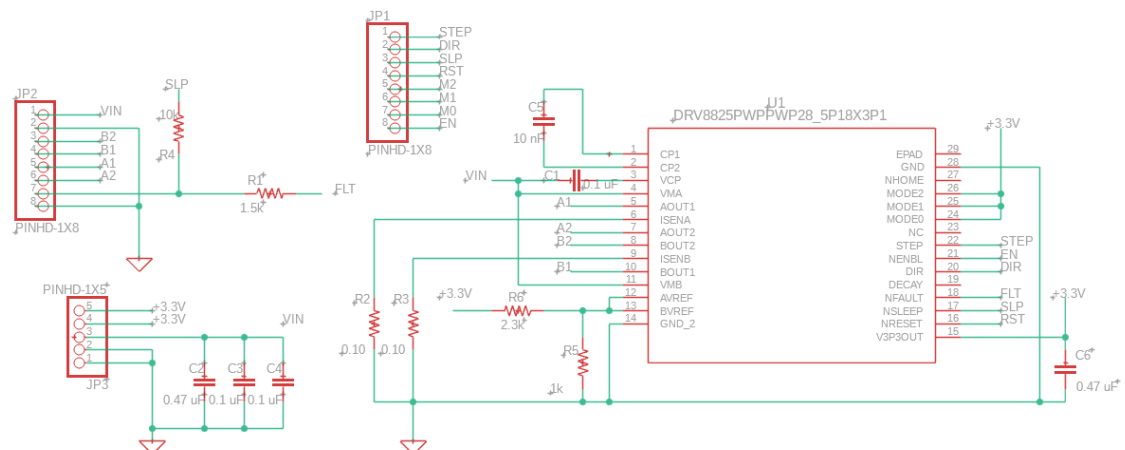


Figure 21. DRV8825 Motor Driver Schematic

7.1.2 Visual/Audio Indicator Interface

The visual and auditory indicator interface with the MCU is designed to provide immediate, real-time feedback once the fire detection system registers a fire incident. In this instance, the LED is interfaced with a GPIO pin of the MCU with the use of a current-limiting resistor to allow the MCU to modulate its brightness and flashing patterns with the help of

PWM signals for visual alerts. The active buzzer is also wired to another GPIO pin so that the MCU can generate audio signals, tones, or pulses to alert users audibly. Once fire is detected the system provides instant visual and auditory feedback, thus making alerts noticeable. Accurate power control ensures both indicators operate safely without overloading MCU pins, making this a tidy and effective signaling scheme.

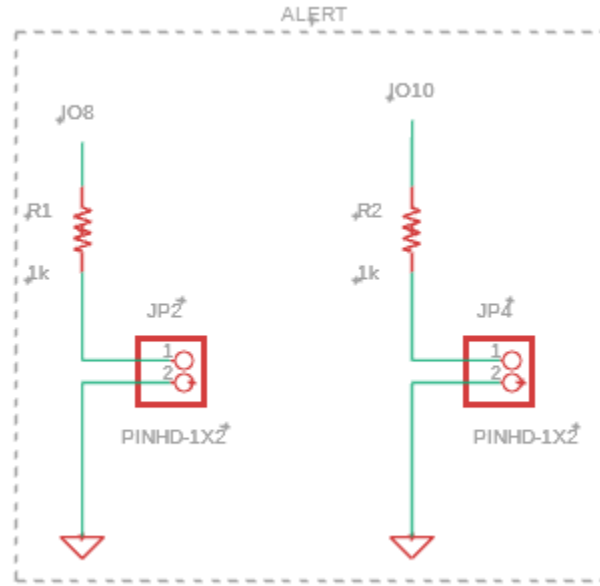


Figure 22. Visual/Audio Alert Interface

7.1.3 MCU Connection

The ESP32 is tasked with responding to detection events by activating external peripherals like a buzzer and LED. The SPI interface cable wiring between the Basys 3 Artix 7 FPGA development board and the ESP32 is set up to enable direct, high-speed communication. The GPIO pins of the ESP32 are connected to corresponding pins on the FPGA, each representing the standard SPI signals: MOSI (Master Out Slave In), MISO (Master In Slave Out), SCLK (Serial Clock), and CS (Chip Select). These paths are wired with clean, dedicated lines so that the FPGA receives clean and direct signals from the ESP32.

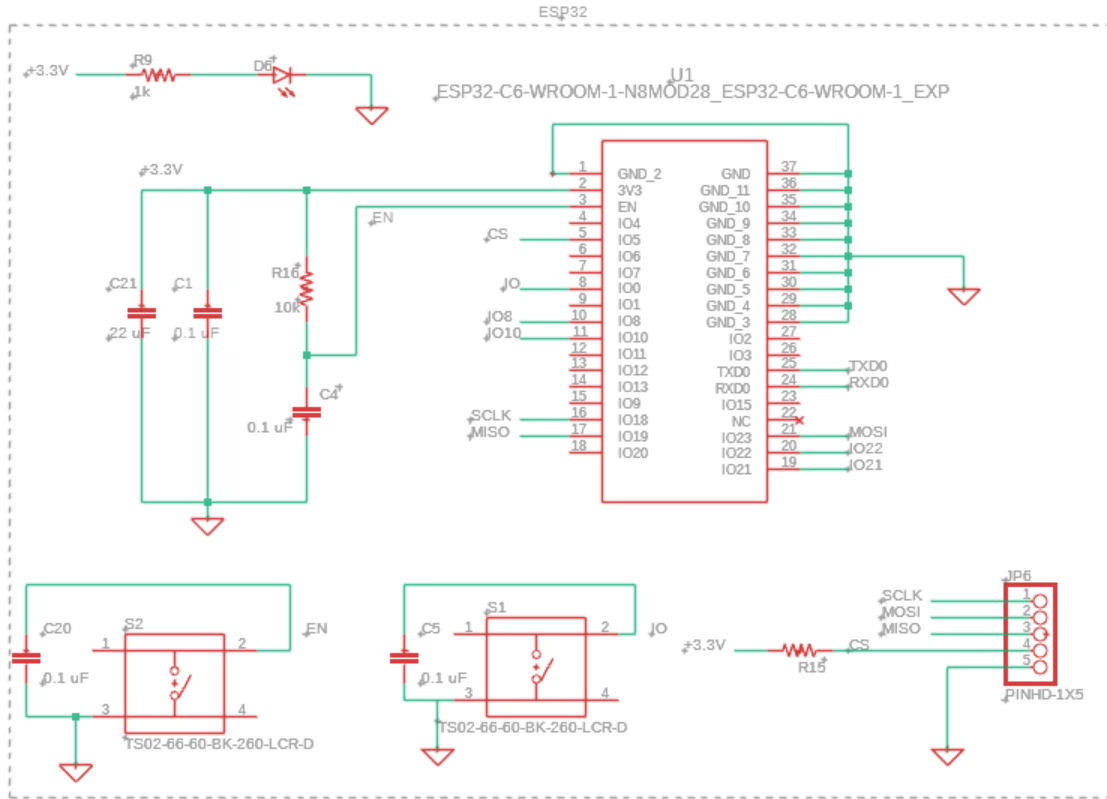


Figure 23. ESP32 MCU Connection

The USB-UART bridge acts as an intermediary that translates USB signals from our PC into UART signals that the ESP32 can understand. This converter allows us to upload code from environments like the Arduino IDE and facilitates real-time debugging through the serial monitor. It manages the TX (transmit) and RX (receive) lines to communicate data and often supports auto-reset functionality through the DTR and RTS lines, simplifying the upload process without manual button presses.

detection, and designed interface ensures that every stage maintains signal fidelity and reliability.

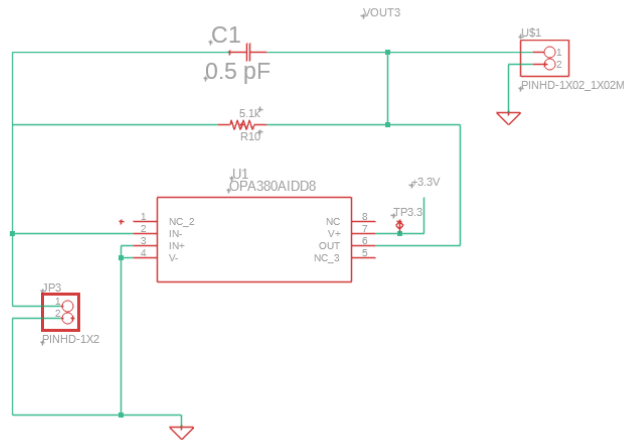


Figure 25. Transimpedance Amplifier Schematic

The output of the transimpedance amplifier is connected to one of the analog-to-digital converter (ADC) input pins on the ESP32 microcontroller. This connection allows the ESP32 to continuously monitor and digitize the voltage signal, which represents the fluctuating photocurrent generated by the photodiode in response to varying light intensities. These fluctuations are then processed in real time by the ESP32 to detect patterns indicative of a potential fire source.

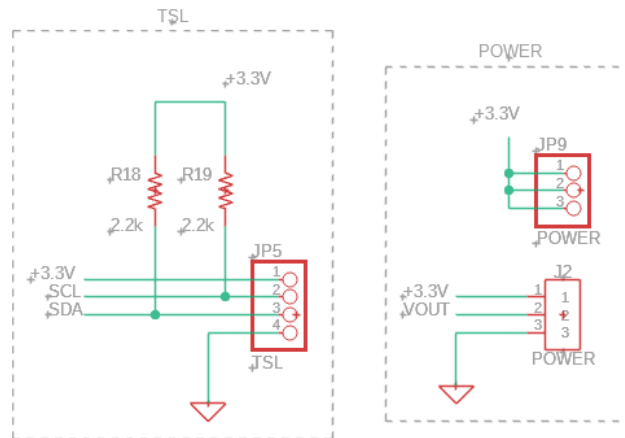


Figure 26. TSL 2591 Schematic

7.1.4 Power Supply Delivery

The power delivery system is thoughtfully designed to efficiently distribute power to all major components. The system begins with a power jack that receives DC power from an

external adapter. This input voltage is then fed into 3 separate LM2679 voltage regulators, each playing a critical role. The first regulator, in Figure 28, is dedicated to powering the system's internal components, such as the FPGA. This ensures that these sensitive devices receive a reliable power supply essential for reliable operation and signal integrity.

The second regulator is specifically allocated for powering the Raspberry Pi 5 via a USB-C connector. By isolating the Raspberry Pi's power supply, it prevents the dynamic load fluctuations and high current demands of the Pi from affecting the rest of the system.

The last regulator is the LM2679 adjustable tuning to 3.3 volts, which is responsible for any of our components that require 3.3V to operate such as the ESP32 and ADC. All regulators are supported by the appropriate input and output capacitors, inductors, and filter components based on the datasheet recommendations. Overall, this dual-regulator power delivery structure ensures reliable, isolated, and regulated power for all devices in the project.

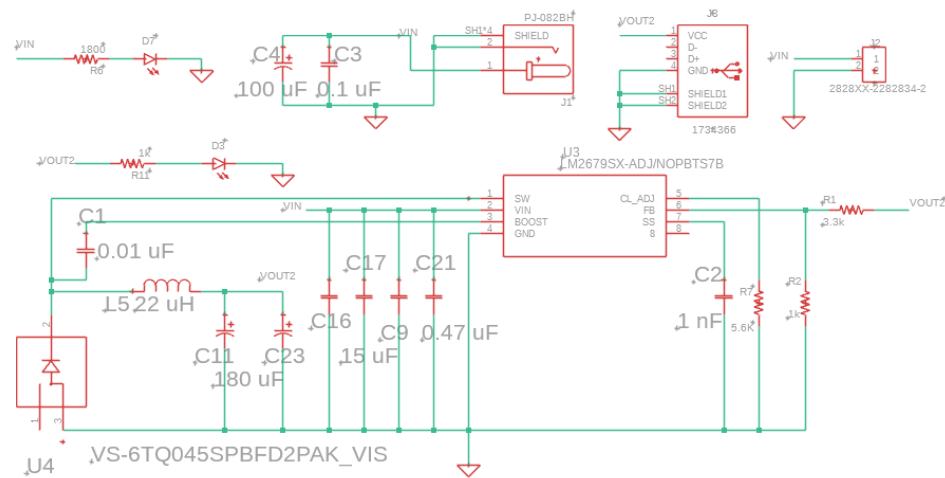
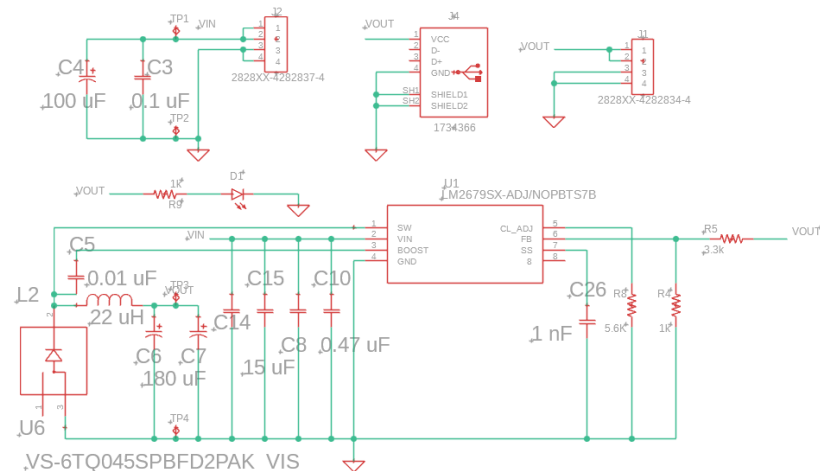


Figure 27. Adjustable 5V Raspberry Pi 5 Voltage Regulator Schematic



[illegible]

7.2 System Software Design

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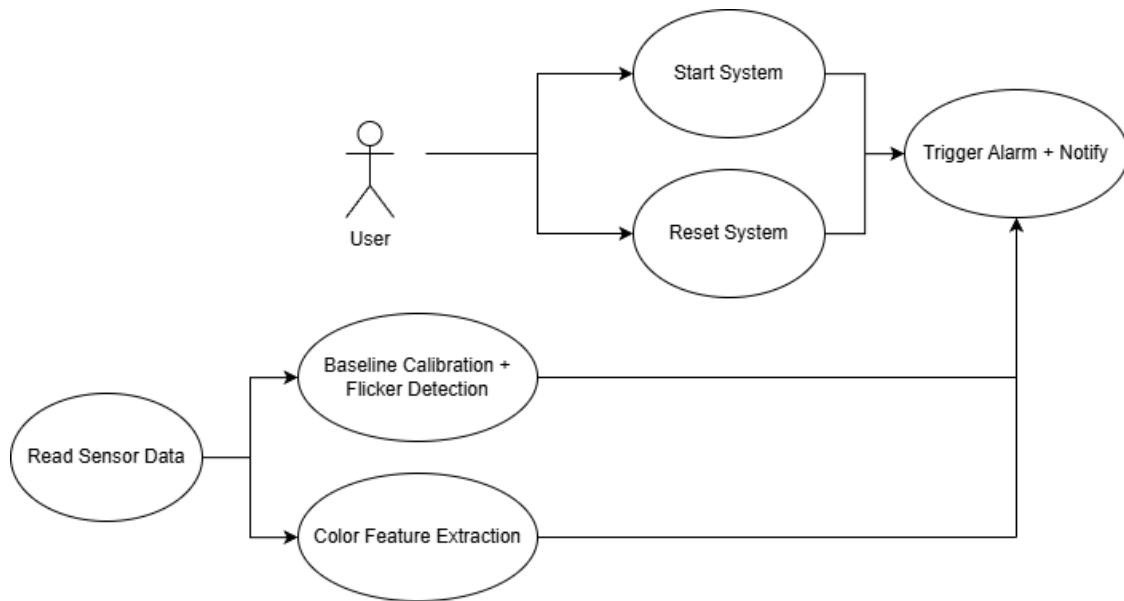


Figure 303132. System Software Use Case Diagram

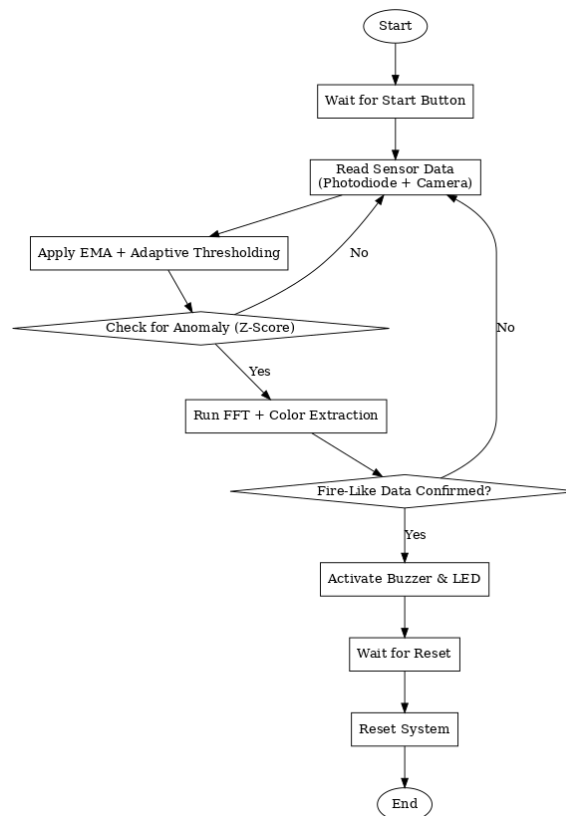


Figure 3133. System Software Activity Diagram

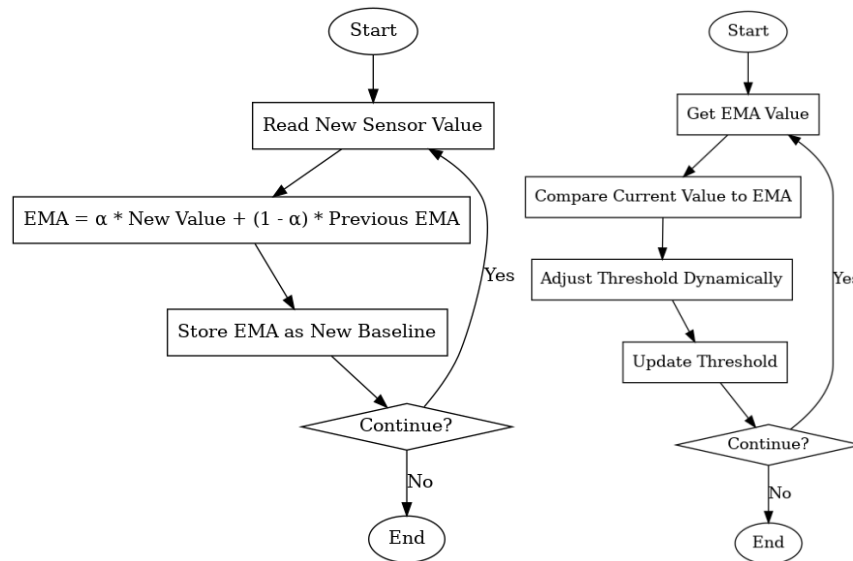
7.2.1 Fire Detection Algorithm and Environmental Baseline Calibration

This subsection details the three foundational components that form the software-driven baseline calibration and environmental change detection for FLAMES

The Exponential Moving Average (EMA) filter is used for photodiode data smoothing. It assigns more weight to recent readings, enabling real-time responsiveness to illumination shifts with minimal computational overhead. The following flowchart illustrates the EMA processing logic applied continuously to incoming photodiode values.

Adaptive thresholding calibrates the environmental baseline dynamically. By adjusting the threshold based on EMA-filtered values, it ensures sensitivity to sudden illumination changes while adapting to natural lighting drift.

Z-score analysis identifies rapid deviations from the baseline. Values that fall outside of ± 3 standard deviations from the mean are flagged for further inspection, distinguishing real anomalies from environmental noise.



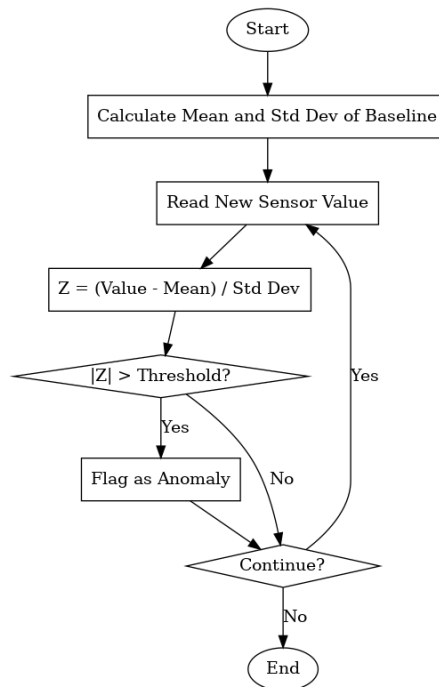


*Figure 3234. System Software EMA, Adaptive Thresholding, & Z-Score Anomaly
Diagrams*

Stepper motor behavior is directly informed by real-time intensity values. The system continuously rotates the motor until a threshold-exceeding region is found, at which point the region is analyzed for potential fire signatures.

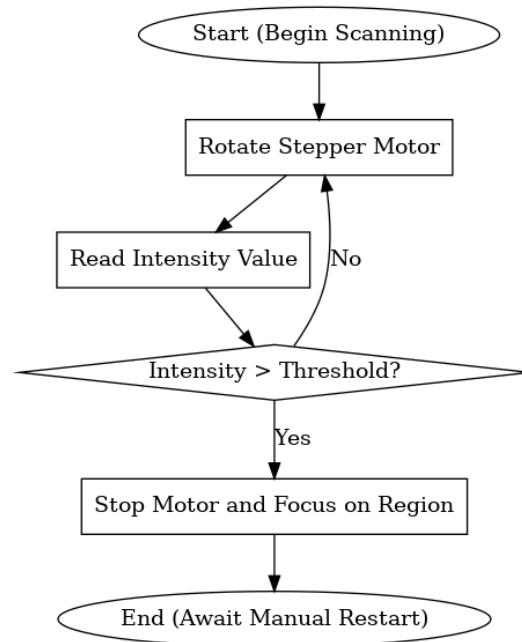


Figure 35. System Software Motor Positioning Diagram

7.2.2 Intensity Threshold and Color Feature Extraction Algorithms

Once a region exceeds the baseline intensity threshold, flicker analysis using the Fast Fourier Transform (FFT) is performed. Fire is characterized by 1–10 Hz frequency fluctuations. If such frequencies are detected, the region is flagged as potentially fire-like.

Color feature extraction uses the Raspberry Pi 5 camera and OpenCV to analyze regions with flagged flicker data. The image is converted to the YCbCr color space, and thresholds are applied to isolate pixels indicative of fire.

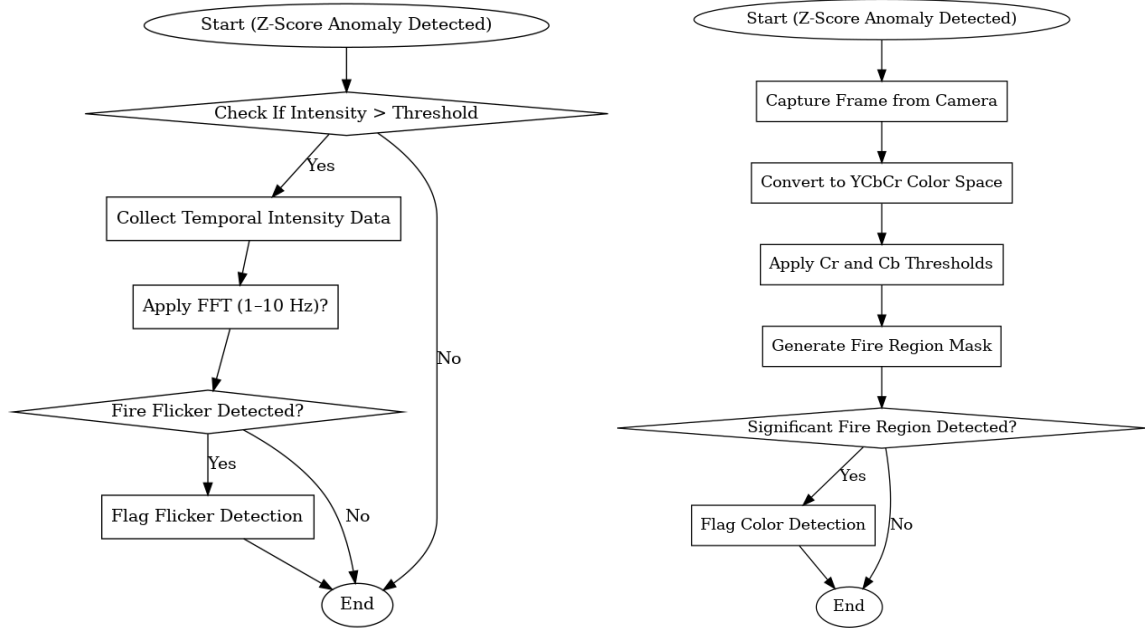


Figure 36. System Software Intensity Threshold & Color Feature Extraction Diagrams

7.2.3 System Response and Notification Handling

When fire-like conditions are confirmed, the MCU activates system responses, including LED and buzzer alarms. The system then enters a holding state, awaiting user input to reset. This ensures false positives do not result in repeated triggering.

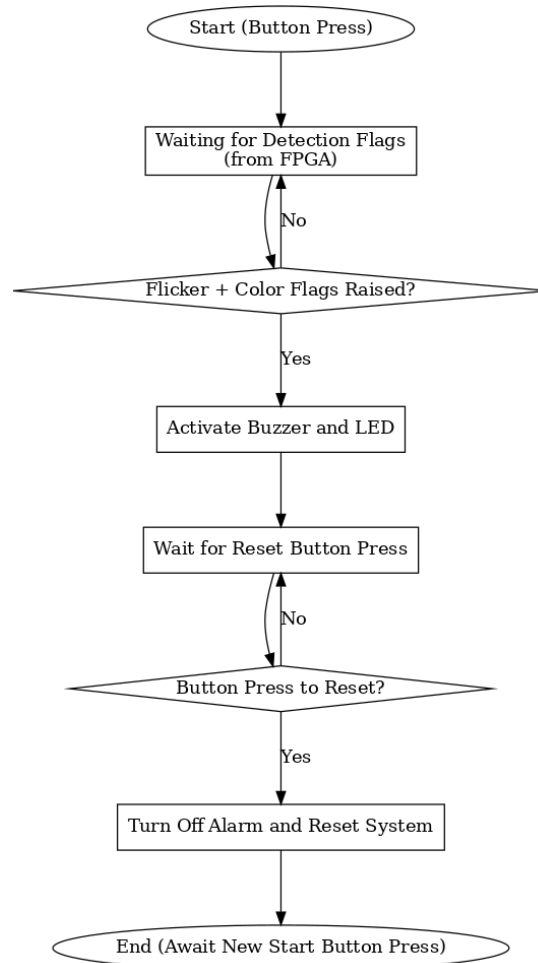


Figure 37. System Software System Response & Notification Handling Diagram

Chapter 8 – System Fabrication/Prototype Construction

8.1 PCB

The PCB fabrication process involved meticulous planning and design to ensure both functional integrity and ease of assembly. A critical step in the layout was the application of polygon pours on both the top and bottom layers, which serve as low-impedance ground planes to reduce electromagnetic interference and improve current handling capacity. The PCB design is completed with the utilization of Fusion360. During the design, careful attention was given to component placement and trace routing to minimize noise and signal degradation, especially in sensitive analog and digital paths. All components and header pin connections were clearly labeled with reference names and signal identifiers, streamlining the soldering process and reducing the likelihood of assembly errors. The use of named headers for external interfacing, such as connections to the FPGA, sensors, and

power systems, enhances modularity and debugging. A well-designed PCB not only ensures robust electrical performance and mechanical reliability but also facilitates efficient testing, scalability, and future upgrades. This structured approach to PCB fabrication underscores the importance of clarity, consistency, and foresight in building complex embedded systems.

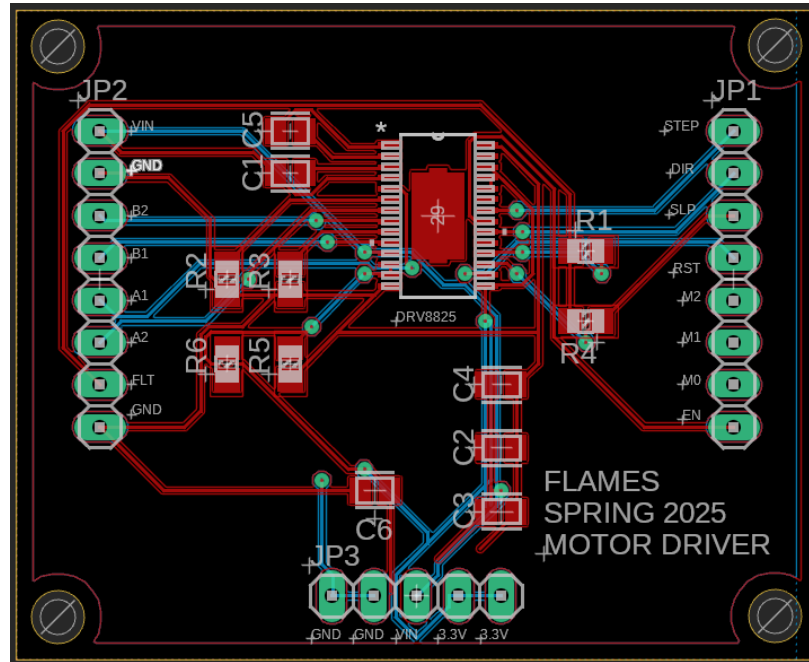


Figure 36. DRV8825 Motor Driver Board

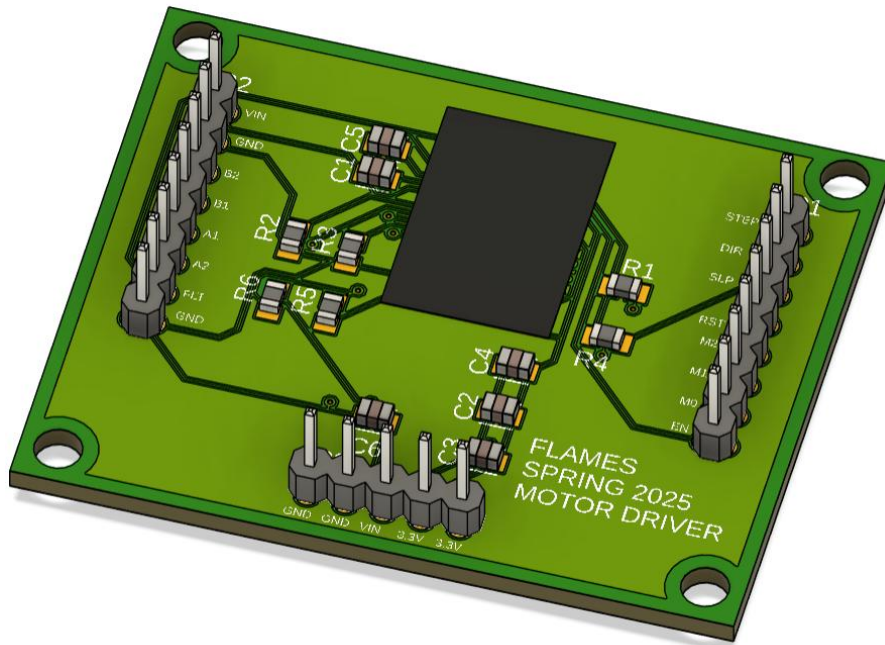


Figure 37. DRV8825 Motor Driver Board 3D View

Due to persistent thermal issues with the DRV8825 motor driver IC—primarily caused by its thermal resistance and limited heat dissipation—we were compelled to revise the PCB layout to address these challenges. To improve thermal performance and reduce the risk of overheating, we introduced thermal vias beneath the IC's exposed pad. These vias help transfer heat away from the IC to the internal and bottom copper layers, enhancing overall thermal conductivity and stabilizing the driver's operation under load.

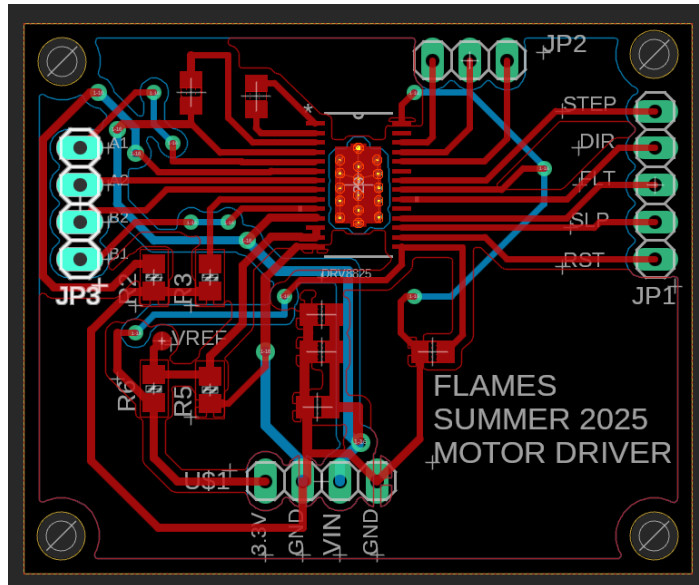


Figure 38. DRV8825 Motor Driver Board 3D View

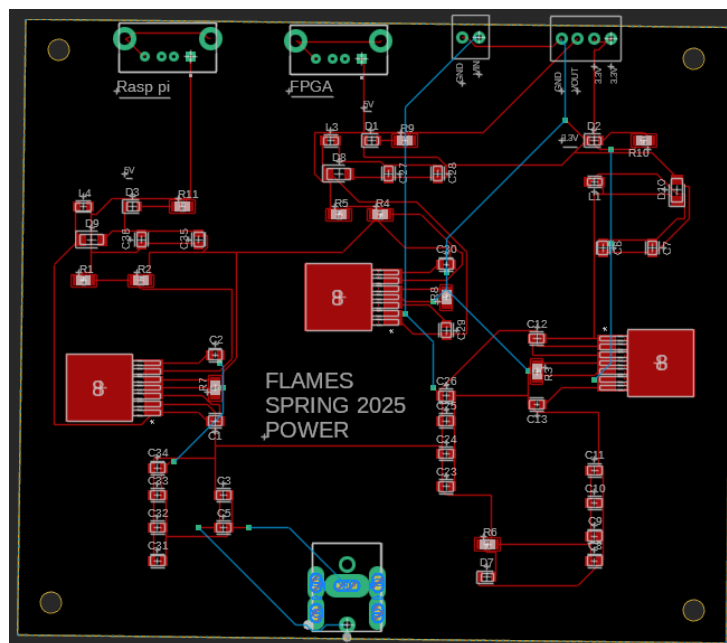


Figure 39. Power Supply Board

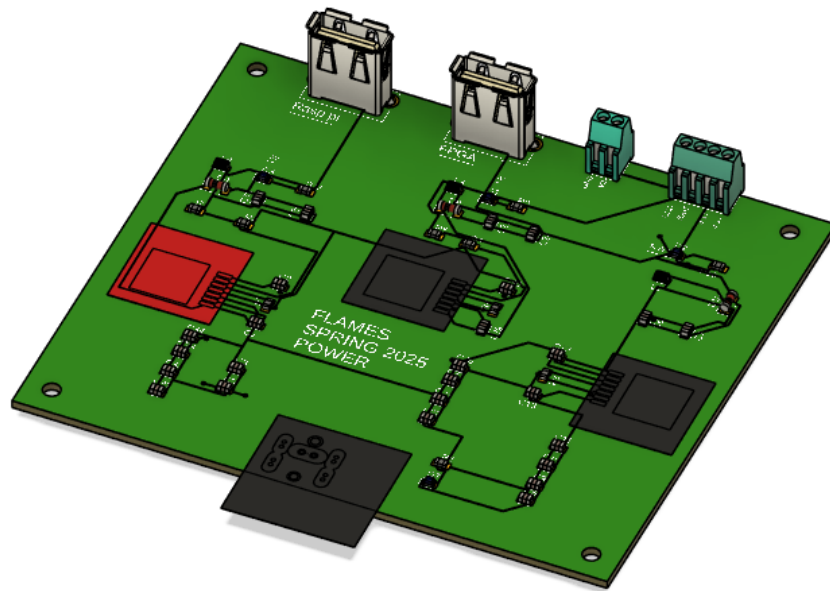


Figure 40. Power Supply 3D View

To simplify troubleshooting and ensure easier fault isolation in the event of power issues, we decided to separate the three voltage regulators into individual regulator boards. This modular approach allows us to test and replace each voltage rail independently, improving reliability and maintainability of the overall power supply system.

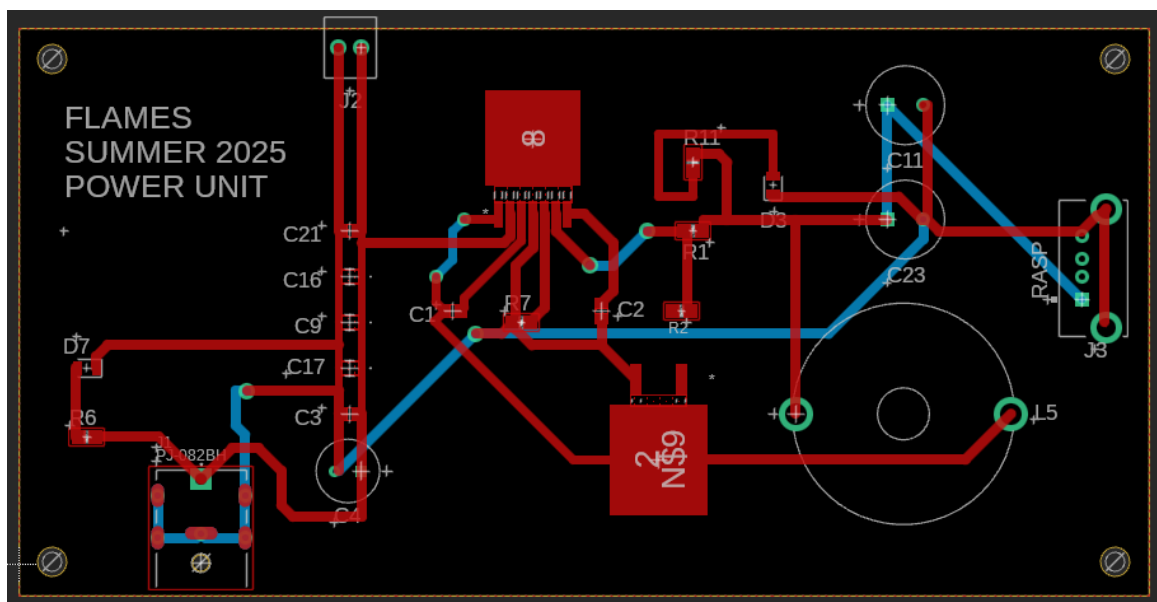


Figure 41. Raspberry Pi 5V Regulator Board

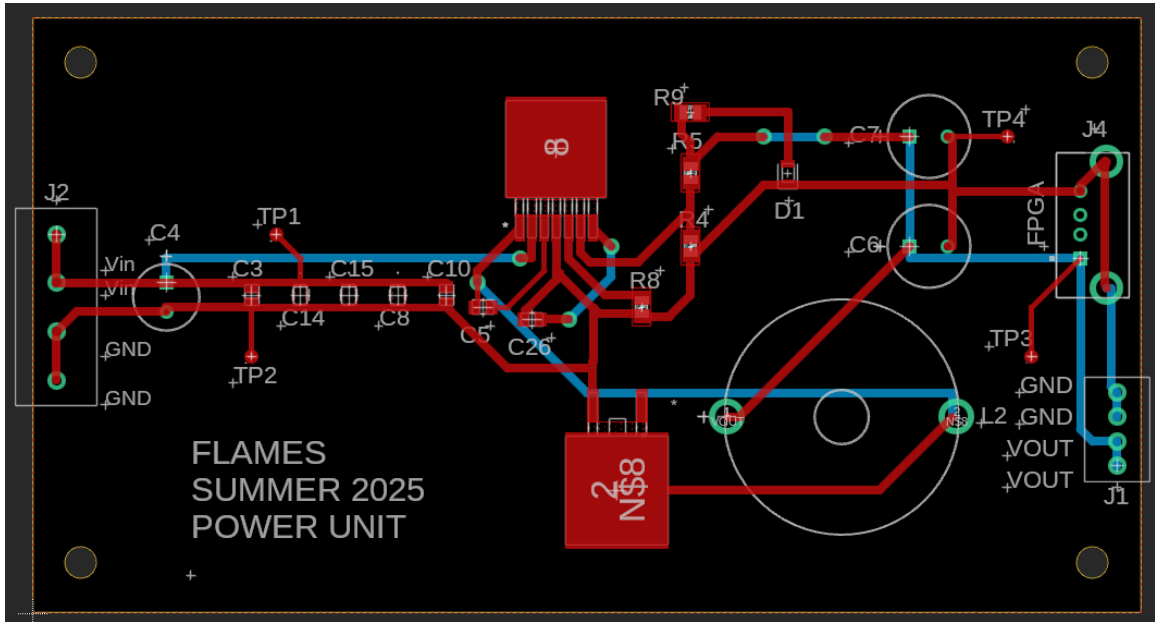


Figure 42. FPGA 5V Regulator Board

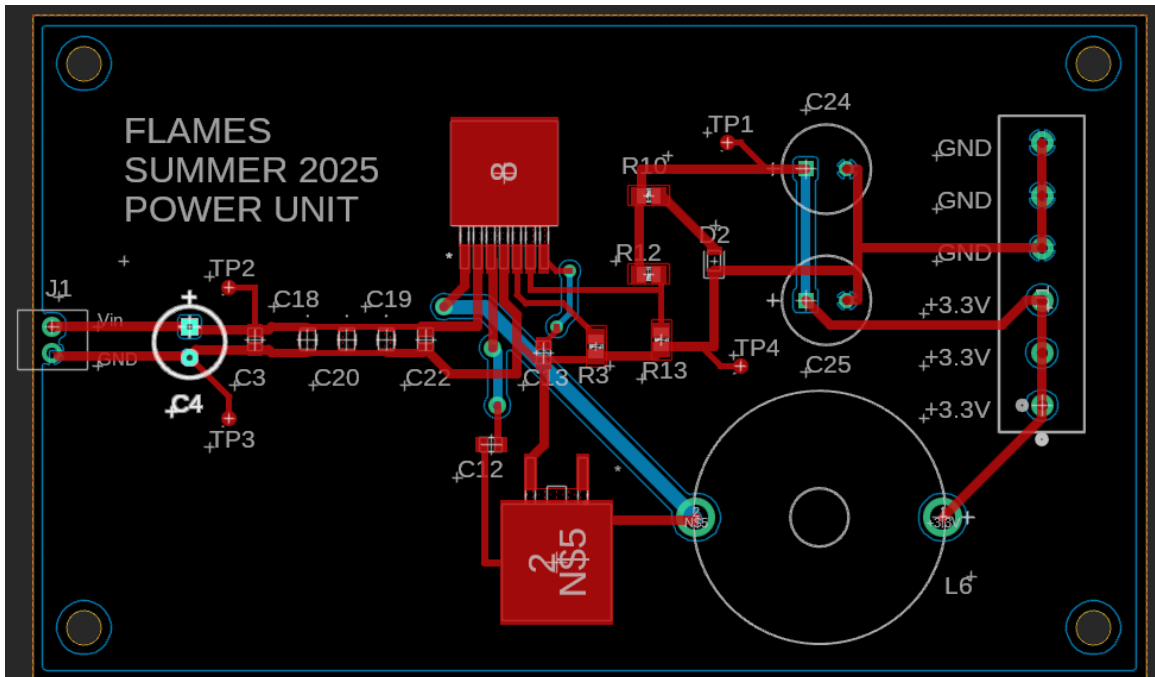


Figure 43. 3.3V Regulator Board

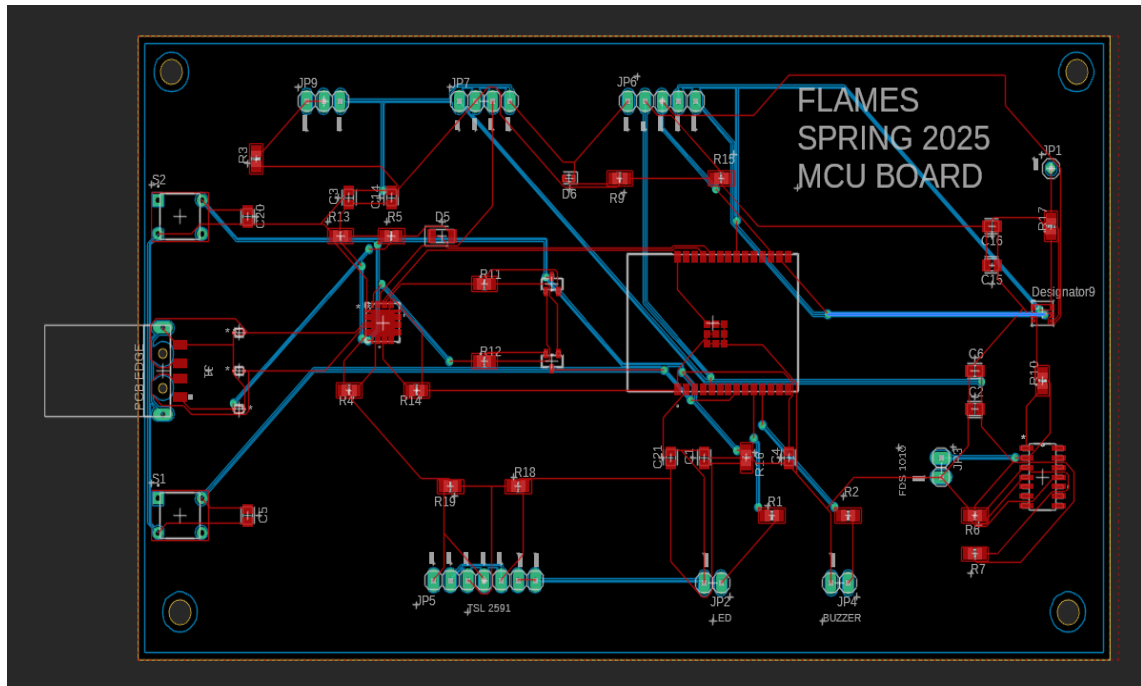


Figure 443839. MCU Board

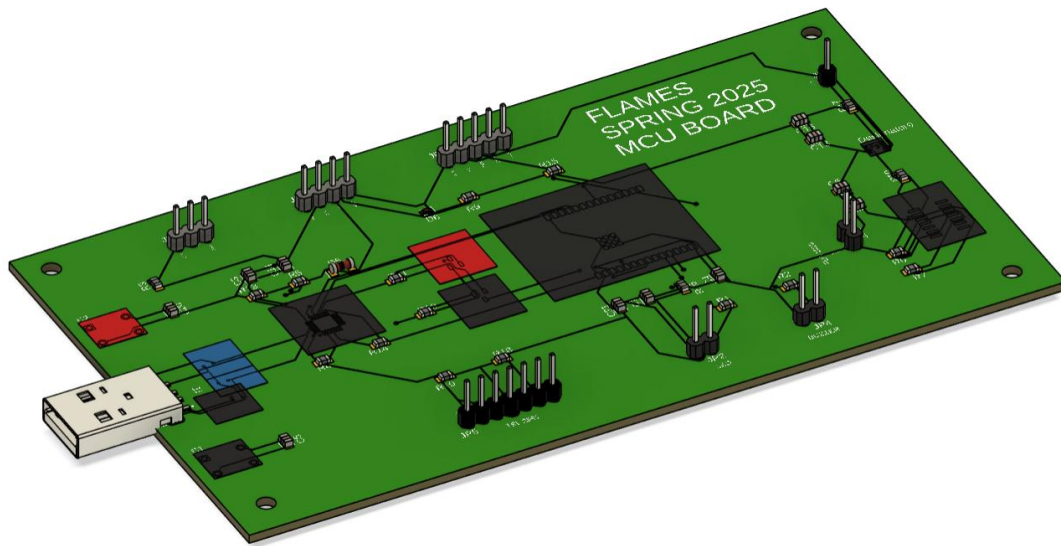


Figure 454041. MCU Board 3D View

8.2 FLAMES 3D Model

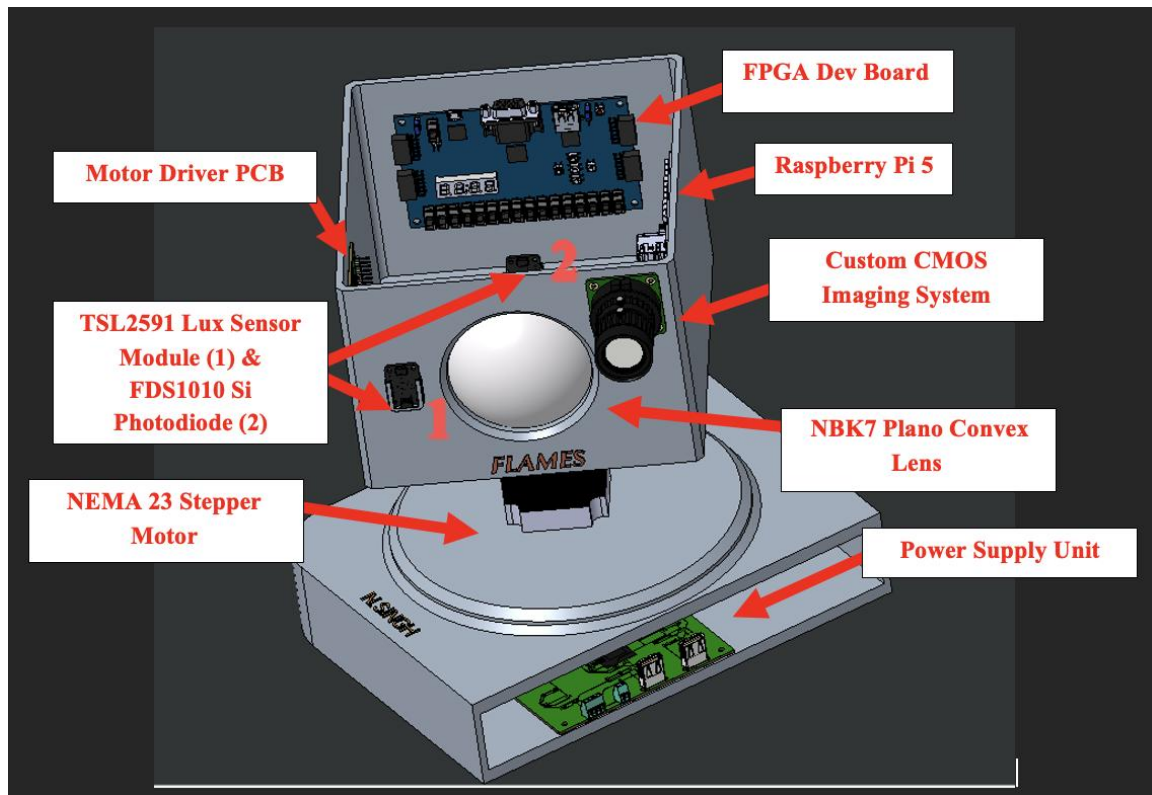


Figure 464243. FLAMES 3D Model

The enclosed system depicted above is the conceptual framework for the FLAMES project, as outlined in Chapter 2. The system will rotate 180 degrees, utilizing a Lux sensor to measure ambient light intensity in Lux units (LUX). This data will be processed by the FPGA, which compares the previous inputs with the current system inputs. If a predetermined ambient intensity threshold is exceeded, indicating the presence of a flame or spark, a stop command be transmitted to the motor. A 3' lens will focus light from the scene up to 1 meter away onto the Silicon Photodiode. The voltage change on the photodiode will be monitored by the FPGA, enabling the determination of whether a fire or spark is present. To enhance the reliability of the detection, a customized imaging system will verify the photodiode's output. The photodiode is of particular interest due to its faster voltage response compared to a camera equipped with software for post-processing. This allows for the detection of fires or sparks more swiftly. To minimize false positives, the camera will serve as a verification tool.

Chapter 9 – System Testing and Evaluation

9.1 Optoelectronics Feasibility

The FLAMES senior design project will utilize two optoelectronic detectors, being the lux sensor, and the 10 mm x 10 mm silicon photodiode. For the system to properly focus the incoming light from the scene, we had to consider how much photons will be impinging

on the detector. To successfully predict the output photocurrent, I have performed a series of radiometric calculations. The equation below was used to determine the amount of optical power incident on the detector. The power (P) of the source shall be simulated using MATLAB.

$$P_{detector} = \frac{P_{Source}}{4\pi r^2} \quad 15$$

It is noteworthy that there is no definitive indicator of the optical power contained within a fire. For simulation purposes, the fire has been constrained to have a power range of 0 to 25 watts. The majority of the radiation emitted by a fire is thermal infrared radiation. Approximately 0.1% to 1% of the total power in a fire is converted into visible light. The figure below illustrates the energy transfer from a small source area to a photodiode.

To accurately model this energy transfer, the simulation assumes isotropic emission from the fire source, meaning the radiant energy is distributed uniformly in all directions. As a result, only a fraction of the total emitted power reaches the photodiode, depending on the solid angle subtended by the detector relative to the fire source and the optical collection efficiency of the lens system. The optical system, which includes one or more lenses, is used to focus a portion of the emitted visible light onto a 10 mm × 10 mm photodiode placed at a fixed distance from the source. Losses due to absorption, reflection, and imperfect lens transmission are also considered in the model to better approximate real-world performance. This approach provides a more realistic estimate of the incident power that the photodiode receives, allowing for more accurate characterization and system response in varying fire conditions.

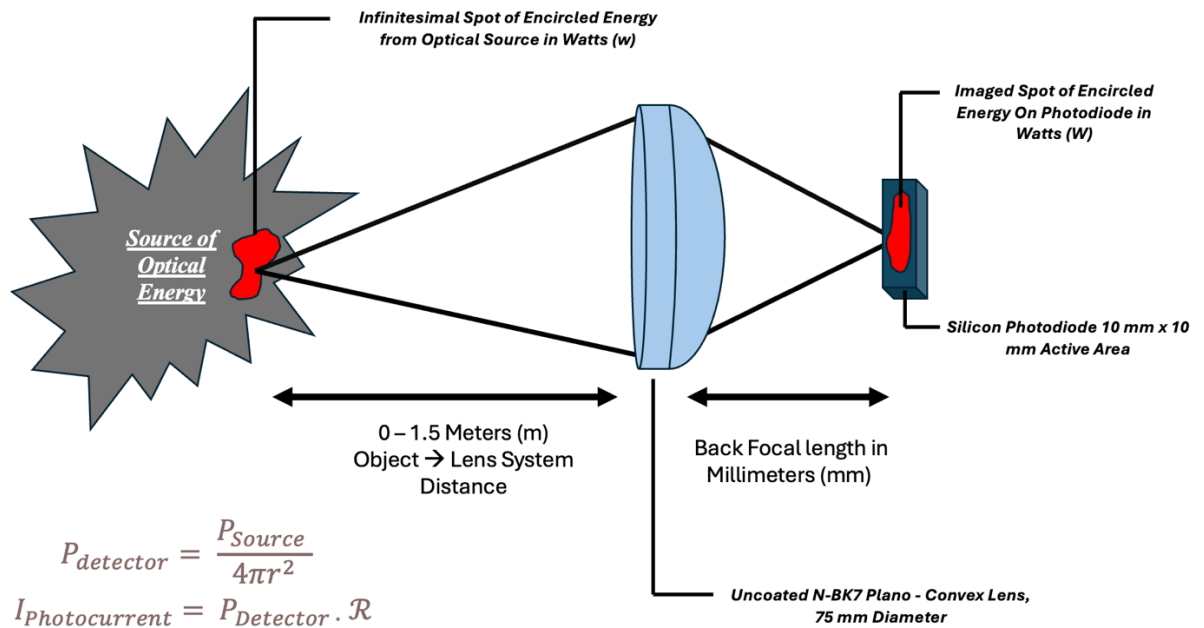


Figure 4744. Transfer of Optical Energy from Source to Photodiode

Although the project utilizes two different sized photodetectors, the same method will be employed for capturing optical energy from the source. The lens will help focus the light to a smaller spot size. If no lens is utilized, the density of photons incident on the detector is reduced, as a larger area of the detector is sparsely filled with photons. As the detector deviates away from the source, the intensity of the light drops off as the square inverse of the distance between the source and detector. We have simulated the effects of distance on the output photocurrent and presented the behavior of the output photocurrent as a function of distance. Once the power on the photodetector is calculated and the estimated source power is chosen, the output photocurrent on the photodiode can be calculated using the following equation. The wavelength of light we are evaluating is between the range of 600 – 800 nm. The responsivity of the selected FDS1010 photodiode at a center wavelength of 700 nm is approximately 0.45 amps per watt.

$$I_{\text{Photocurrent}} = P_{\text{Detector}} \cdot \mathcal{R} \quad 16$$

The following interactive MATLAB script characterizes the behavior of the photocurrent. For demonstration purposes, we have used a fire that has roughly 10 watts of optical power at 1 meter away.

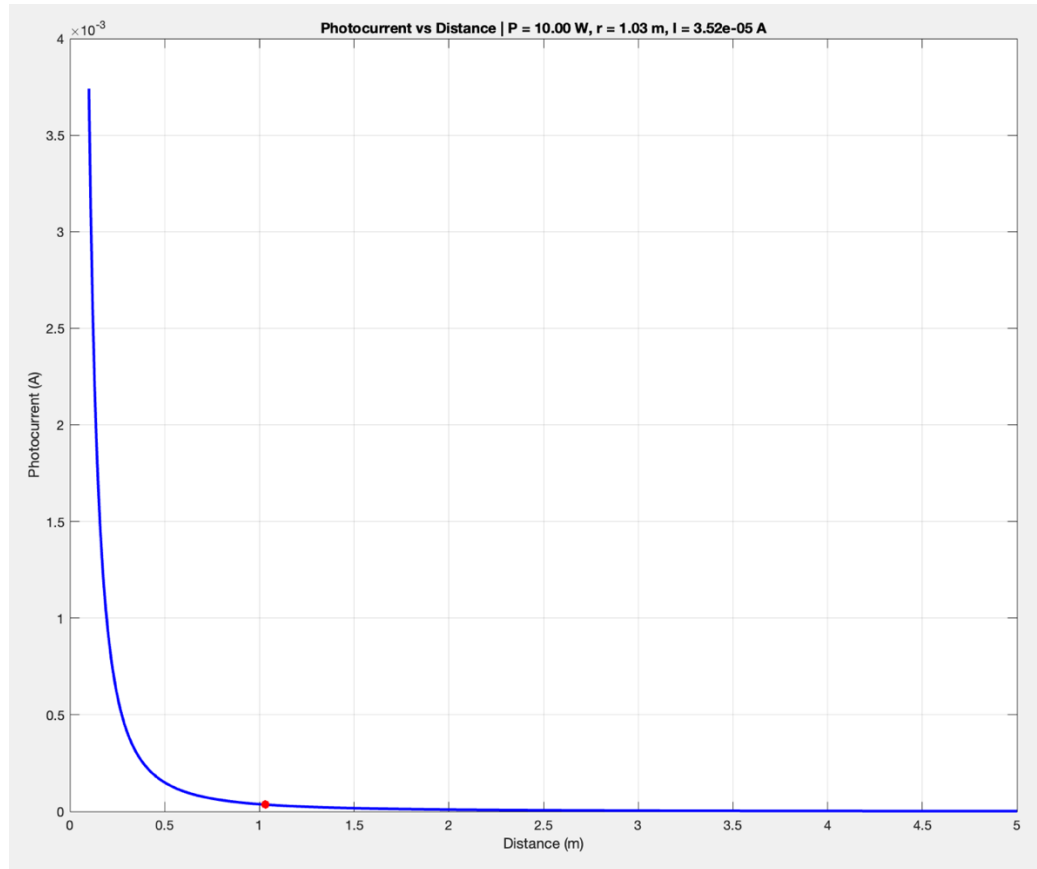


Figure 4845. Output Photocurrent as a function of Distance and Source Power

The graph above displays an output photocurrent of 35.2 micro-amps at 1 meter away and a source power of 10 watts.

Knowing the generated photocurrent from the diode can greatly assist in creating the transimpedance amplifier circuit. To calculate the output voltage gain, we must establish a baseline to ensure that there is sufficient photocurrent. If the photocurrent being produced is on the order of nanoamperes or picoamperes, the surrounding gain transimpedance circuit will not be as effective. For reference, photocurrent on the order of microamps should be sufficient to produce millivolts on the output TIA circuit. As for the analog to digital converter, the maximum voltage should not exceed 5 volts, otherwise noise will be introduced into the circuit diminishing the performance of the system.

To verify that the photocurrent drops off as a function of distance as $\frac{1}{r^2}$, we have collected data that displays power as a function of distance. The experiment incorporates a specially designed lens holder mount and a power meter. The power meter's operational wavelength has been calibrated to 750 nanometers, which corresponds to the center wavelength of the visible spectrum emitted by a flame. As depicted in the accompanying figure, the power meter is positioned in such a manner that the focal spot generated by the lens aligns with its sensor. A meter stick has been used to ensure that the emission source distance can be varied in a repeatable manner. It is also crucial to mention that the source of the emission

is roughly $250\ \mu\text{W}$. In theory we expect that the optical power emitted by the source decreases as a function of distance as $\frac{1}{r^2}$. As we move radially, we expect to see an exponential decrease in power. For this experiment we have opted to vary the source backwards in 2-inch increments.



Figure 4946. Experimental Setup for Characterization of power as a function of distance

The following figures demonstrate that the light indeed adheres to the predicted radiometric behavior depicted in Figure 4845. The experiment was conducted with and without a lens. The lens selected for this experiment is a 75mm N-BK7 visible coated plano convex lens with a focal length of approximately 100 mm. During testing, we observed that employing the lens enhances the sensitivity of the focused spot to the source's angular displacement. In essence, if the object is not aligned with the optical axis of the sensor, the focused spot is imaged elsewhere, thereby missing the photodiode. A similar lens will be required to focus light onto the TSL2591 sensor. Specifically, a wide field of view lens coupled with a 5 mm aperture has been implemented to limit the TSL2591 sensors FOV to 18 degrees. This has greatly increased the motors precision halting abilities to situate the front facia of the system directly in front of the fire. Analysis of the data reveals that the introduction of

a lens enables focusing at greater distances closer to the 1-meter mark. Without the lens, it is evident that at the 1-meter distance, there is minimal power output. Additionally, it is crucial to acknowledge that we are utilizing a common household lighter with a smaller footprint compared to the fire we intend to demonstrate. This modification partially addresses the angular object dependency issue previously discussed.

The angular dependency issue has also been mitigated by positioning the lens closer to the sensor, thereby increasing the spot size at the expense of reduced photons per unit area on the photodiode. The results of the testing conducted with and without the lens are presented below.

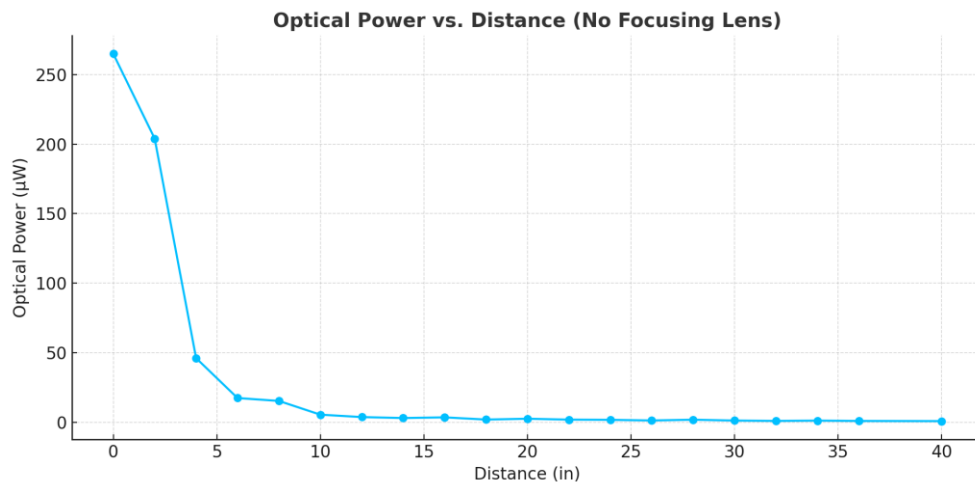


Figure 5047. Optical Power as A Function of Distance No Lens

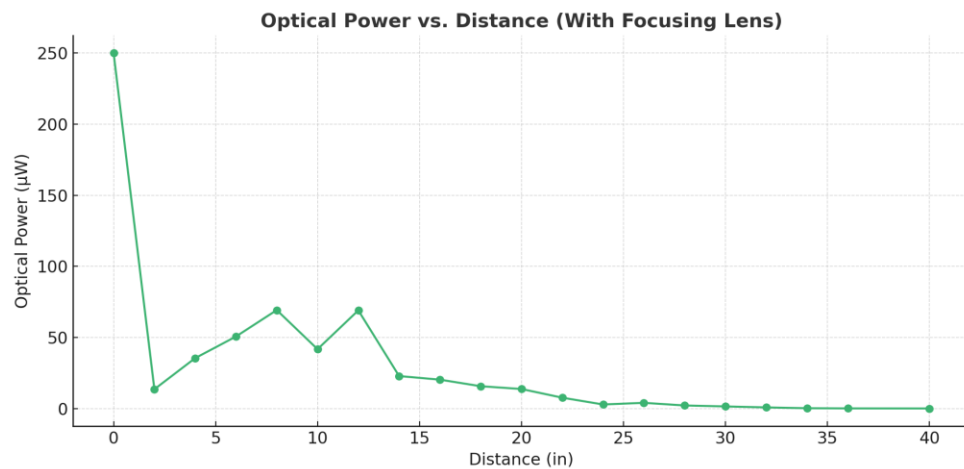


Figure 5148. Optical Power as A Function of Distance with a Lens

Further testing was conducted to verify that the photocurrent measured from a photodiode decreases in accordance with the inverse square law of distance. For this test, we used a Thorlabs FDS100 photodiode, which has an active area of 3.6 mm². A BIC lighter was selected as the light source, and its output power was measured to be approximately 0.934 mW using a calibrated power meter set for a wavelength of 750 nm. Following the procedure described in earlier chapters, the distance between the light source and the photodiode was varied, and the resulting photocurrent was recorded. The experiment was then repeated with double the optical power by using a second lighter flame. The results confirm that the photocurrent is proportional to the incident optical power

The experimental data supports the theoretical prediction that increasing optical power results in a linear increase in photocurrent. The plots in the following figures clearly demonstrate both the inverse-square dependence on distance and the proportional relationship between photocurrent, optical power, and distance.

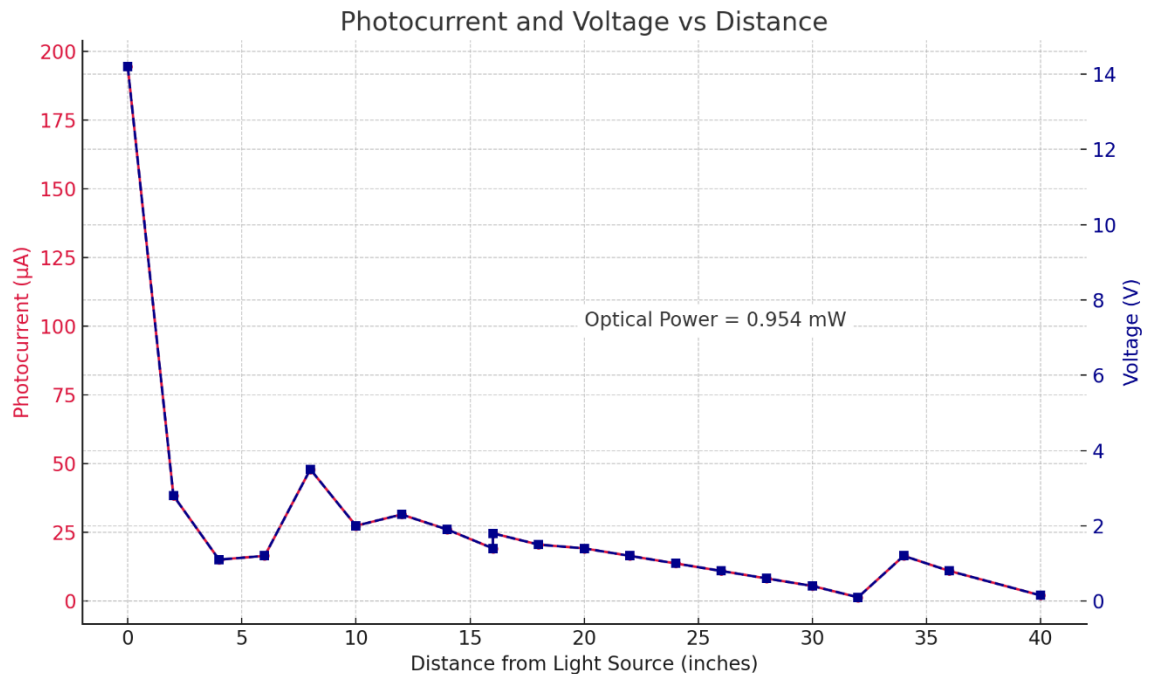


Figure 5249. Photocurrent and Voltage Vs. Distance 0.954 mW

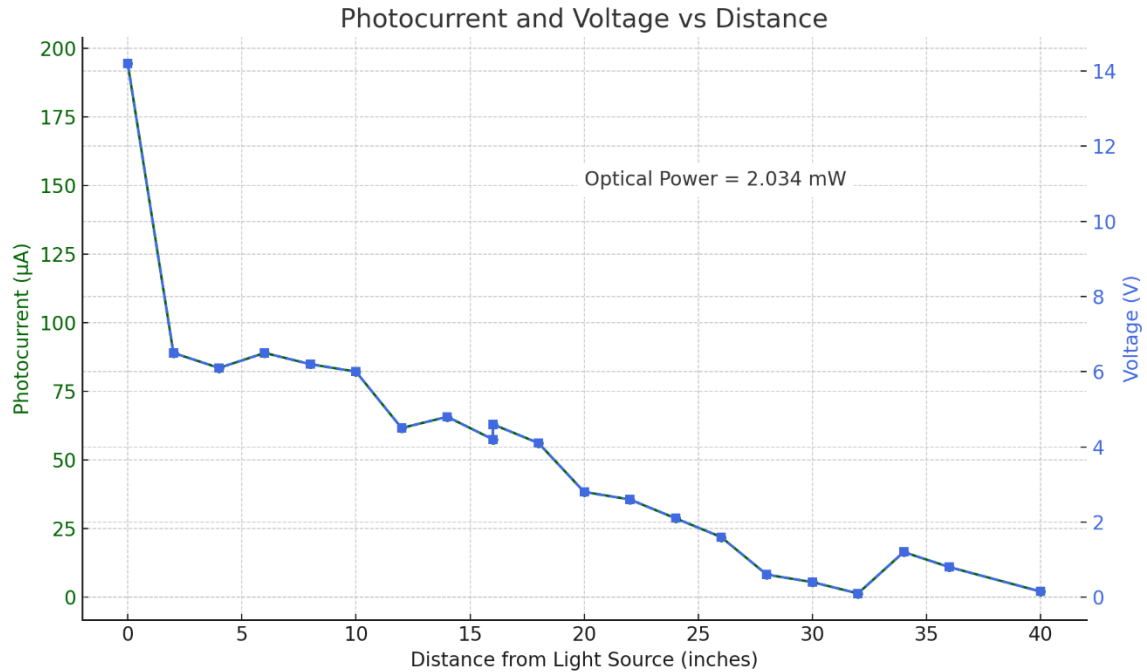


Figure 5350. Photocurrent and Voltage Vs. Distance 2.034 mW

9.2 Motor Testing

To ensure the DRV8825 stepper motor driver limits current to the motor's rated value, one should properly set the VREF (reference voltage) pin. The VREF voltage controls the maximum amount of current the DRV8825 delivers to each stepper motor coil. The current limit helps prevent overheating and ensures the motor operates within its specifications. The VREF voltage's dependence on the maximum motor current is determined by the sense resistor value used in the driver stage. For the DRV8825, the maximum current can be calculated by the following formula:

$$\text{Current Limit} = VREF \cdot 2 \quad 17$$

Since our selected Nema 23HS22-1006S is rated for 1 A per phase, the VREF should be set to 0.5V (since $0.5V \cdot 2\Omega = 1\text{ A}$). This voltage can be measured directly at the VREF pin of the DRV8825 motor driver with respect to ground of the power supply using a multimeter. Adjustments to the VREF are made by adjusting the built-in potentiometer on the board of the motor driver and adjusting it to the proper VREF. Properly setting VREF is essential for reliable motor operation, minimizing heat, and protecting both the driver and motor from overcurrent damage.

Micro-stepping is an important technique in stepper motor control that significantly enhances the performance and precision of motion systems. Unlike full-step or half-step modes where the motor moves in larger, discrete increments, micro-stepping divides each full step into smaller steps by carefully modulating the current through the motor windings. This results in smoother and quieter operation, which is particularly valuable in applications where vibration or mechanical resonance could affect system accuracy or

stability. Since the DRV8825 supports up to 1/32 micro-stepping, this provides the highest resolution and smoothest motion, the micro-step configuration with the mode pins of the DRV8825 are shown below:

MODE0	MODE1	MODE2	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	1/4 step
High	High	Low	1/8 step
Low	Low	High	1/16 step
High	Low	High	1/32 step
Low	High	High	1/32 step
High	High	High	1/32 step

Figure 5451. Micro-step Configuration

By setting up the proper configuration of pins M1, M2, and M3, we can configure 32 micro-steps 3 different ways with low being 0V and high being set 3.3V. To verify that the NEMA 23 stepper motor is correctly configured for 1/32 micro-stepping, a systematic testing approach was implemented. The selected NEMA 23 motor has a full-step angle of 1.8°, and with 1/32 micro-stepping enabled through the motor driver, this translates to a micro-step resolution of 0.05625° per step. Therefore, a full 360° rotation requires exactly 6400 micro-steps ($360^\circ \div 0.05625^\circ$). To confirm this, the motor was programmed using the ESP32 to take exactly 6400 steps. If configured correctly, the motor should complete one full rotation and stop precisely at its original starting position. Observing this confirms that the micro-stepping mode is correctly set and that the driver is accurately interpreting the step pulses from the ESP32. This method provides a straightforward and effective way to validate the micro-stepping configuration without requiring advanced measurement tools.

9.3 TSL2591 and ESP32 Integration and Testing

To begin testing our fire detection system, we integrated the TSL2591 sensor with the ESP32 to enable motor control based on light intensity analysis. For consistency, both tests used the same lighter as the light source. One test was performed with a 6-inch lens to focus the light onto the sensor, while the other was conducted without the lens. The results of both tests are shown below.

The following parameters remained constant across both tests:

- EMA Alpha: 0.6
- Threshold Offset: 10
- Z Threshold: 1.0

The fire detection system relies on several parameters to ensure accurate identification of sudden light intensity changes, such as those caused by a flame. One key parameter is the EMA Alpha, set to 0.6, which determines the weight of recent lux readings in the exponential moving average. A value of 0.6 means that 60% of the weight is placed on the latest sensor input while 40% comes from the previous average. This helps smooth out noise while still allowing the system to respond quickly to significant changes. Another critical parameter is the Threshold Offset, set to 10, which is added to the baseline lux level (determined by the EMA) to establish an adaptive threshold. The system flags potential fire events when the current lux exceeds this threshold, allowing it to dynamically adjust to ambient lighting conditions. Lastly, the Z Threshold, set at 1.0, serves as a statistical filter by ensuring that the current lux reading deviates by more than one standard deviation from recent readings before triggering detection. This helps prevent false positives caused by minor fluctuations. Together, these parameters ensure that the motor is only stopped in response to both a high raw lux value and a statistically significant spike, offering robustness against environmental noise and common light sources.

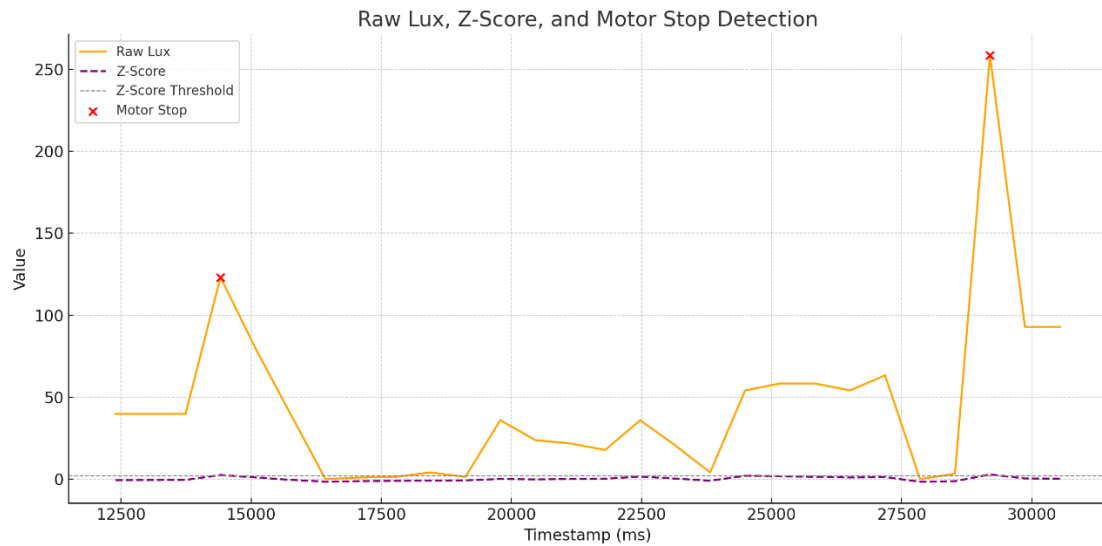


Figure 55. TSL2591 Results with Only Lighter

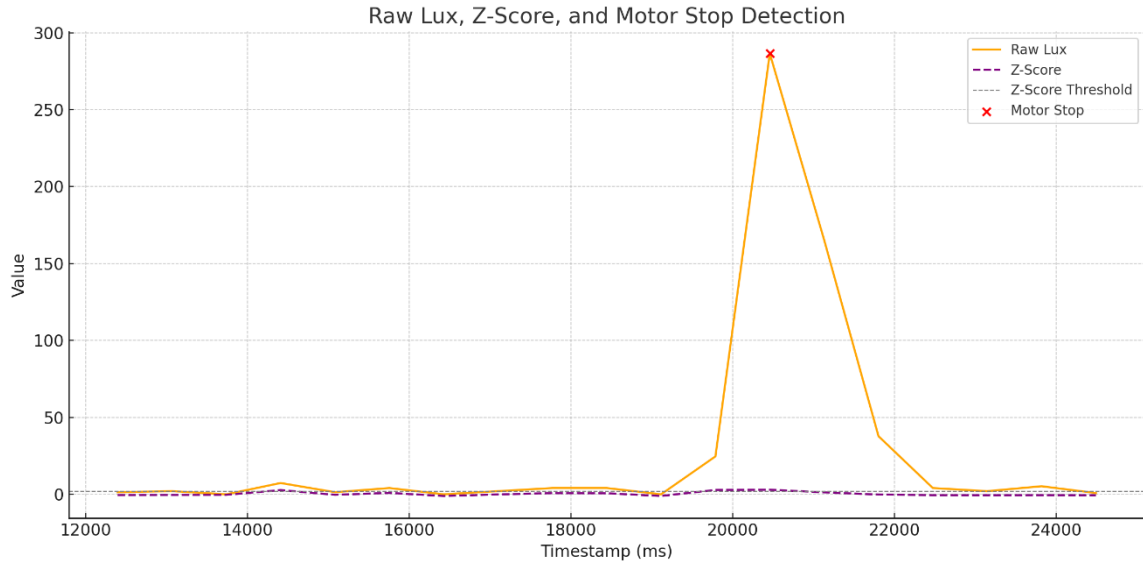


Figure 56. TSL2591 Results with Lighter and Lens

As shown in Figure and Figure, the setup without the lens reached a maximum of just over 250 raw lux, while the lens-assisted setup reached nearly 300 raw lux. In both cases, the motor stops when the raw lux and Z-score exceed their respective thresholds, as indicated by the red X markers on the plots.

The code used to generate these graphs can be seen in Appendix D in Figure [1].

Chapter 10 – Administrative Content

10.1 Budget

Our project budget is capped at \$1000, as agreed upon by all team members to ensure financial feasibility for everyone involved. This budget encompasses a range of optoelectrical and computer systems, including high-cost components such as the photodiode and FPGA prototyping board, as well as lower-cost items like external FPGA memory and the microcontroller. The allocation also accounts for potential replacements or project modifications, allowing flexibility to address unforeseen expenses. A detailed breakdown of costs and the budget distribution for each “engineer” is provided in the Bill of Materials table below.

10.2 Bill of Materials

Table 49. Bill of Materials

Component	Part Name	Quantity	Unit Price	Total Price
Optics Engineer				
Convex plano lens 152 mm	Plano Convex lens	1	\$100	\$100

127 mm EFL				
Dual Si/InGaAs Detector	TSL2591	1	\$6.50	\$6.50
Photodiode	FDS1010 Si Photodiode (Uncalibrated)	1	\$61.18	\$61.18
Plano Convex field flattener Lens	LA1472-B Plano Convex Lens, f = 20 mm, Dia = 9mm	1	\$34.45	\$34.45
Pinhole	400 μ m Pinhole	1	\$70.88	\$70.88
Aspheric Uncoated Lens 7 mm Dia EFL: 6 mm	354105-A Unmounted Aspheric lens	1	\$139.92	\$139.92
Imaging Sensor	Raspberry Pi Global Shutter Cam	1	\$50.00	\$50.00
Electrical Engineer				
Stepper Motor	NEMA 23 Stepper Motor 23HS22-1006S	2	\$10.59	\$21.18
Voltage regulator	LM2679	12	\$3.93	\$47.16
ADC	ADS 8319	3	\$14.51	\$43.53
LED	Kingbright L-934SRD	10	\$0.35	\$3.5
Buzzer	Mallory Sonalert PS-12	3	\$2.90	\$8.70
Button	TS02-66-70-BK-160-LCR-D	6	\$0.13	\$0.78
Power Jack	PJ-082BH	3	\$1.78	\$5.34
Adapter	LeTaoXing Power Supply Adapter	1	\$14.90	\$14.90
Computer Engineer				
FPGA Prototyping Board	BASYS3 Artix-7 FPGA Trainer Board	1	\$165.00	\$165.00
FPGA Chip	Xilinx Artix-7 XC7A35T-1CPG236C	1	\$51.86	\$51.86
Microcontroller	ESP-WROOM-32	1	\$9.99	\$9.99
External Memory	MT25QL256ABA8ESF-0SIT TR	1	\$5.18	\$5.18
Raspberry Pi Board	Raspberry Pi 5 Board	1	\$80.00	\$80.00
Raspberry Pi Fan	Raspberry Pi 5 Active Cooler – Aluminum Heatsink – SC1148	1	\$9.90	\$9.90
Raspberry Pi Debugging Power Supply	GeekPi 27W Power Supply for Raspberry Pi 5 8GB RAM	1	\$12.99	\$12.99
Raspberry Pi Micro HDMI	4K@60Hz Cuteluding Micro HDMI to HDMI adapter	1	\$5.99	\$5.99

to HDMI Adapter				
Total Cost				
Optical Engineer		\$462.93		
Electrical Engineer		\$145.09		
Computer Engineer		\$340.91		
Grand Total		\$948.93		

As seen by the table above, we are below the goal limit of \$1000 allowing for prototyping and replacement parts as needed during the testing phase of the project. We understand that senior design is a learning experience, and parts may be faulty. Keeping the system under \$1000 allows us to truly stick to an affordable format for the product/project. We also understand that the project has been optimized to incur as little cost as possible. In a larger scale format, we expect the cost to rise as more robust equipment shall be used.

10.3 Senior Design Milestones

For a large-scale project like this, involving numerous documents that need to be written, revised, and finalized, a milestones table is essential. It helps keep each team member on track and provides the group with a clear understanding of when each section should be completed, ensuring alignment with the overall project timeline. Our project's milestone table can be found below with each task, start expectancy, and data of expected completion.

Table 50. Senior Design Milestones

Milestone Number	Milestone Description	Start Date	Anticipated End Date	Dependencies & Requirements
1	Finalize Project Idea	1/6/25	1/17/25	Optics Advisory Approval (Dr. Kar)
2	Finalize general Design Choices (Crucial Hardware)	1/6/25	1/21/25	Research Optics, EE, CpE Hardware Compatibility
3	D&C Finalization	1/14/25	1/21/25	Obtain Dr. Chan and Dr. Kar's meeting Availability. Generate Optics Schematic
4	D&C Meeting	1/28/25 3:00-3:30	1/28/25	Complete Divide and Conquer Documentation/ Review Committee Form
5	Committee Formation / Meeting	1/20/25	1/24/25	Email Professors for Committee Availability
6	30 -Page Draft	2/1/25	2/17/25	Communicate Deadline and Split Micro-Objectives

7	30 – Page Draft Revision	2/17/25	2/21/25	Reference Document Guidelines
8	60 – Page Draft	2/24/25	3/17/25	Communicate Deadline and split micro-objectives
9	60 – Page Draft Revision Submittal	3/19/25	3/24/25	Reference Document Guidelines
10	Final Report	4/1/25	4/22/25	Team Parameter Review Required
11	Mini Demo Video	4/7/25	4/22/25	Reference Hardware Milestones for Part Integration
12	Critical Design Review	5/19/25	6/3/25	Create PPT slides to record and post on YouTube
13	Midterm Demo	6/21/25	6/27/25	Record and perform all required specifications
14	Conference Paper	6/30/25	7/7/25	Reference and create a summary of all related inquiries
15	Final Demo Video	7/19/25	7/21/25	House final structure to record specifications with all PCBs
16	Final Demo Presentation	7/19/25	7/21/25	Shorten and re-record slides
17	Live Demo & Review	7/23/25	7/23/25	Meet with EHS and confirm that Demo with fume hood is a go
18	Final Paper	7/26/25	7/29/25	Make final edits and all system modifications to final iteration of the paper

Table 51. Senior Design Hardware Milestones

Hardware Milestone	Start Date	Expected Acquisition Date	Dependencies & Requirements
Optical Light Collection Acquisition	12/17/25	1/6/25	Ordered – Pending Testing
Optical Sensor Acquisition	1/19/25	1/23/25	Source Sensor with active area equivalent

			to optical hardware spot size
Electro-optical Hardware Acquisition	1/23/25	1/29/25	EO components necessary for testing
EO-FPGA Hardware Acquisition	1/23/25	2/10/25	FPGA components necessary for testing
Electro-optical Hardware Integration (Prototype)	2/10/25	3/19/25	Prototype Supporting Components for EO prototype Assembly
EO-FPGA Hardware Integration Prototype	2/10/25	3/19/25	Prototype Supporting Components for EO-FPGA Assembly
PCB Prototype Design	3/21/25	4/16/25	Reflect on Challenges from EO & EO-FPGA Testing
PCB Testing	5/26/25	6/30/25	Test all hardware with existing bench PSU within the lab
Final Prototype	7/1/25	7/17/25	System is housed and function properly with PCB integration

Chapter 11 – Conclusion

Through the FLAMES project, three undergraduate students from distinct ECE/CREOL degree tracks applied and expanded their skills by tackling the complexities of customized optical system design, photodiode integration, FPGA and MCU programming, PCB customization, and related interdisciplinary challenges. The primary goal of FLAMES is to effectively detect fire events without relying on conventional smoke detectors, using only the analysis of optical signals captured by the system. The team's solution emphasizes precision, rapid detection, and robustness against common false positives like welding sparks or variable ambient lighting in confined environments.

This report thoroughly documents the work conducted by the students, highlighting their intentional engagement with new and unfamiliar technologies to enhance both project outcomes and their own professional expertise. The meticulous planning, careful analysis, and innovative engineering solutions developed by these University of Central Florida students affirm that FLAMES is progressing effectively toward successful deployment. Moving forward, the knowledge and insights acquired during this project are expected to significantly contribute to advancements in fire detection technology, enabling higher accuracy in sensitive environments such as cleanrooms and research laboratories.

Chapter 12 – Full System Testing

To validate the system, the team has conducted testing with the entirety of the system. This includes all power supply, voltage regulator, transimpedance amplifier, MCU, and motor driver custom PCB's. Also present in the system is the FPGA and Raspberry Pi development boards. The Figure below showcases the entire system as tested.



Figure 57. Full Enclosed System

The entire unit has undergone testing at a distance of 1 meter with three distinct sources: a citronella torch (11-13 mW), a magnesium sparkler, and a phone flashlight. As previously outlined, the system halts in the same field of view as the optical emission for any light source up to 1 meter away. In the event of a fire, the system responds within 15 seconds, alerting the user with an audible buzzer and LED. For sources such as sparklers or constant light sources like flashlights, the unit resumes rotation.

We have conducted ten trials and presented the data in the subsequent table. It is important to note that the system employs three distinct methods of cross detection:

1. TSL2591 lux sensor paired with a wide-field-of-view lens and 5mm aperture.
2. Raspberry Pi custom imaging system.
3. Lens paired with the FDS1010 silicon photodiode.

By utilizing all three methods, we enhance the detection accuracy to ensure that the system responds to the presence of fire with at least 90% accuracy.

Table 52. Flame Detection Results

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

As evident from Table 52, the three detection methods operate concurrently to attain 100% detection accuracy in the presence of flames. The camera system employs color extraction to discern variations within the YCbCr color spectrum, the photodiode identifies temporal flicker patterns generated by sparks and flames, and the lux sensor triggers the motor to cease movement within the same field of view as the optical source. Similar testing has been performed for a magnesium sparkler at 1 meter away. The data is shown below in table 53.

Table 53. Sparkler Testing Results

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

From the table, it is evident that the system generates an erroneous response from the photodiode. To accurately classify the optical source as a fire or spark, all three layers of

detection must provide consistent results. While the system incorrectly identified the spark as a fire, no false alarm was initiated. Through this testing, we can unequivocally assert that the system satisfies all the demonstrable specifications. The system is capable of detecting flames within 15 seconds, detecting the optical emission at a distance of 1 meter away, and achieving at least 90% detection accuracy.

Appendices

Appendix A – Reference

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Appendix B – Copyright Permission

DRV8825 Micro-step Configuration (Figure 46)

BS

Ben Schmidel <ben@pololu.com>

To: ● Ronex Faustin

Thu 4/17/2025 9:02 PM

Retention: UCF Delete after 10 Years (10 years) Expires: Sun 4/15/2035 9:02 PM

Hello, Ronex.

Thank you for your interest in our stepper motor drivers and for checking with us on this. Yes, you can use our table in your report. Please let me know if you have any further questions or concerns.

Sincerely,
 Ben Schmidel
 (702) 262-6648
<https://nam02.safelinks.protection.outlook.com/?url=http%3A%2F%2Fwww.pololu.com%2F&data=05%7C02%7C6344019%40ucf.edu%7Cf17fcd4d967340cd0d3408dd7e149c38%7Cbb932f15ef3842ba91fc3c59d5dd1f1%7C0%7C0%7C638805349206028434%7CUnknown%7CTWFpbGZsb3d8eyJFbXB0eU1hcGkiOnRydWUsIlYiOiIwIiwjAuMDAwMCIslIiAiOiJXaW4zMtIsIlkFOlJoiTWfPbClslldUljjoyfQ%3D%3D%7C0%7C%7C%7C&sddata=rvlRAMhXxASjQByMI8UYaLL33qHmuFrxaW9ms9WibcoA%3D&reserved=0>

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 Las Vegas, NV 89119

Appendix C – Data Sheet

[FDS1010 Silicon Photodiode](#)

[Raspberry Pi Global Shutter Camera](#)

[TSL2591 Light Sensor Datasheet](#)

[Raspberry Pi 5 Datasheet](#)

[Nema 23 Datasheet](#)

[ADS8319 16-Bit, 500-kSPS, Serial Interface, Micropower, Miniature, SAR Analog-to-Digital Converter datasheet \(Rev. C\)](#)

[TS02-66-43-BK-100-LCR-D Datasheet - Tactile Switches | Same Sky](#)

[L-934ID KINGBRIGHT, LED, Low Power, Red, Through Hole, T-1 \(3mm\), 20 mA, 2 V, 625 nm | Newark Electronics](#)

[PB-12N32MP-12Q Mallory Sonalert | Mouser](#)

[PJ-082BH Same Sky | Mouser](#)

[DRV8825 Stepper Motor Controller IC datasheet \(Rev. F\)](#)

[BASYS 3 Board Reference Manual](#)

[ESP32-Wroom-32 Datasheet](#)

Appendix D – Software Code

[1] TSL2591 C++ Code (ESP32):

```
#include <Wire.h>

#include <Adafruit_Sensor.h>

#include "Adafruit_TSL2591.h"

#include <math.h>

// Pin definitions
#define SLED 4 // Sensor LED
#define MOTOR_LED 2 // ESP32 built-in LED (GPIO 2)

// Sensor setup
Adafruit_TSL2591 tsl = Adafruit_TSL2591(2591);

// EMA constants
const float EMA_ALPHA = 0.6;
float emaLux = 0;
```

```

// Adaptive thresholding
float adaptiveThreshold = 0;
const float THRESHOLD_OFFSET = 3000;

// Z-score detection
const int windowSize = 10;
float luxWindow[windowSize];
int luxIndex = 0;
int samplesCollected = 0; // Count of valid samples in the window
float zThreshold = 1.5;

// Warm-up timer
bool baselineReady = false;
unsigned long baselineStartTime;
const unsigned long warmupDuration = 5000; // 5 seconds

void setup() {
  Serial.begin(9600);
  pinMode(SLED, OUTPUT);
  pinMode(MOTOR_LED, OUTPUT);
  digitalWrite(MOTOR_LED, LOW);

  tsl.setGain(TSL2591_GAIN_MED);
  tsl.setTiming(TSL2591_INTEGRATIONTIME_100MS);

  baselineStartTime = millis();
  Serial.println("TSL threshold detection initializing...");
}

void loop() {
  // Wait for EMA and first luxWindow buffer to fill
  if (!baselineReady) {
    if (millis() - baselineStartTime >= warmupDuration) {
      baselineReady = true;
      Serial.println("✅ Baseline initialized, collecting initial lux data...");
    } else {
      Serial.println("⌚ Warming up...");
      delay(500);
      return;
    }
  }

  float currentLux = readLux();

```

```

if (isnan(currentLux) || isinf(currentLux)) {
    currentLux = 0;
}

// Apply EMA
emaLux = EMA_ALPHA * currentLux + (1 - EMA_ALPHA) * emaLux;

// Adaptive thresholding
adaptiveThreshold = emaLux + THRESHOLD_OFFSET;

// Update sliding window for Z-score
luxWindow[luxIndex] = currentLux;
luxIndex = (luxIndex + 1) % windowSize;

// Fill the window before using z-score detection
if (samplesCollected < windowSize) {
    samplesCollected++;
    Serial.println("📊 Filling lux window...");
    delay(500);
    return;
}

float mean = calculateMean(luxWindow);
float stdDev = calculateStdDev(luxWindow, mean);

// Handle bad stdDev or no variance case
float zScore = 0;
if (stdDev > 0 && !isnan(stdDev) && !isinf(stdDev)) {
    zScore = (currentLux - mean) / stdDev;
} else {
    zScore = 0;
}

Serial.print("Lux:");
Serial.print(currentLux);
Serial.print(",EMA:");
Serial.print(emaLux);
Serial.print(",Threshold:");
Serial.print(adaptiveThreshold);
Serial.print(",Z:");
Serial.println(zScore);

// Detection logic
if (currentLux > adaptiveThreshold && abs(zScore) > zThreshold) {
    Serial.println("⚠️ Motor Stop");
}

```

```

        digitalWrite(MOTOR_LED, HIGH);
    } else {
        digitalWrite(MOTOR_LED, LOW);
    }

    delay(500);
}

float readLux() {
    digitalWrite(SLED, HIGH);
    delay(50);
    uint32_t lum = tsl.getFullLuminosity();
    uint16_t ir = lum >> 16;
    uint16_t full = lum & 0xFFFF;
    digitalWrite(SLED, LOW);
    float visible = full - ir;
    return (float) visible;
}

float calculateMean(float data[]) {
    float sum = 0;
    for (int i = 0; i < windowSize; i++) {
        sum += data[i];
    }
    return sum / windowSize;
}

float calculateStdDev(float data[], float mean) {
    float sumSq = 0;
    for (int i = 0; i < windowSize; i++) {
        sumSq += pow(data[i] - mean, 2);
    }
    return sqrt(sumSq / windowSize);
}

```

[2] TSL2591 with NEMA23 C++ Code (ESP32):

```

#include <Adafruit_Sensor.h>
#include <Wire.h>
#include <math.h>
#include "Adafruit_TSL2591.h"

// --- Pins ---
#define STEP_PIN 18
#define DIR_PIN 19

```

```

#define EN_PIN 5
#define BUTTON_PIN 15
#define BUZZER_PIN 4
#define MOTOR_LED 2

// --- Stepper Motor ---
const int stepDelayMicros = 900;
volatile bool motorRunning = false;
volatile bool motorPermanentlyStopped = false;
bool systemStarted = false;
bool buttonPreviouslyPressed = false;

bool ledBlinking = false;
unsigned long lastBlinkTime = 0;
const unsigned long blinkInterval = 250; // 250ms = fast blink

// --- Sensor ---
Adafruit_TSL2591 tsl = Adafruit_TSL2591(2591);
const float EMA_ALPHA = 0.8;
float emaLux = 0;
float adaptiveThreshold = 0;
const float THRESHOLD_OFFSET = 500;

const int windowSize = 10;
float luxWindow[windowSize];
int luxIndex = 0;
int samplesCollected = 0;
float zThreshold = 1.2;

bool baselineReady = false;
unsigned long baselineStartTime;
const unsigned long warmupDuration = 5000;
unsigned long lastSensorCheck = 0;
const unsigned long sensorInterval = 500;

// --- Task Handle ---
TaskHandle_t stepperTaskHandle;

void setup() {
    Serial.begin(9600);

    // pinMode(SLED, OUTPUT);
    pinMode(MOTOR_LED, OUTPUT);
    digitalWrite(MOTOR_LED, LOW);

```

```

pinMode(STEP_PIN, OUTPUT);
pinMode(DIR_PIN, OUTPUT);
pinMode(EN_PIN, OUTPUT);
pinMode(BUTTON_PIN, INPUT_PULLUP);

pinMode(BUZZER_PIN, OUTPUT);
digitalWrite(BUZZER_PIN, LOW); // start silent
noTone(BUZZER_PIN);

digitalWrite(DIR_PIN, HIGH); // Initial motor direction
digitalWrite(EN_PIN, LOW);

tsl.setGain(TSL2591_GAIN_MED);
tsl.setTiming(TSL2591_INTEGRATIONTIME_100MS);

Serial.println("🌀 System idle. Press button to start.");

// Start stepper motor task on Core 0
xTaskCreatePinnedToCore(stepperTask, "Stepper Task", 10000, NULL, 1,
                        &stepperTaskHandle, 0);
}

void handleButton() {
    static unsigned Long lastDebounceTime = 0;
    const unsigned Long debounceDelay = 200;
    bool pressed = digitalRead(BUTTON_PIN) == LOW;

    if (pressed && !buttonPreviouslyPressed &&
        millis() - lastDebounceTime > debounceDelay) {
        lastDebounceTime = millis();
        // toggle
        systemStarted = !systemStarted;

        if (systemStarted) {
            // → START
            Serial.println("🌀 System Started.");
            motorRunning = true;
            motorPermanentlyStopped = false;
            ledBlinking = false;
            noTone(BUZZER_PIN);

            // reset warm-up & stats
            baselineReady = false;
            samplesCollected = 0;
            luxIndex = 0;
        }
    }
}

```

```

    emalux = 0;
    baselineStartTime = millis();

    // re-enable motor driver if you want
    digitalWrite(EN_PIN, LOW);
    digitalWrite(MOTOR_LED, LOW);
} else {
    // → RESET/STOP
    Serial.println("☒ System Reset.");
    motorRunning = false;
    motorPermanentlyStopped = false;
    ledBlinking = false;
    digitalWrite(MOTOR_LED, LOW);
    noTone(BUZZER_PIN);
    digitalWrite(EN_PIN, HIGH); // disable driver
}
}

buttonPreviouslyPressed = pressed;
}

void loop() {
    handleButton();

    if (!systemStarted) {
        // idle until started
        taskYIELD();
        return;
    }

    // blink logic
    if (ledBlinking && millis() - lastBlinkTime >= blinkInterval) {
        lastBlinkTime = millis();
        digitalWrite(MOTOR_LED, !digitalRead(MOTOR_LED));
    }

    // warm-up phase
    if (!baselineReady) {
        if (millis() - baselineStartTime >= warmupDuration) {
            baselineReady = true;
            Serial.println("☑ Baseline ready. Motor running.");
        }
        taskYIELD();
        return;
    }
}

```

```

// sample every sensorInterval
if (millis() - lastSensorCheck >= sensorInterval) {
    lastSensorCheck = millis();

    float currentLux = readLux();
    if (isnan(currentLux) || isinf(currentLux)) currentLux = 0;

    // EMA + threshold
    emaLux = EMA_ALPHA * currentLux + (1 - EMA_ALPHA) * emaLux;
    adaptiveThreshold = emaLux + THRESHOLD_OFFSET;

    // sliding window
    luxWindow[luxIndex] = currentLux;
    luxIndex = (luxIndex + 1) % windowSize;
    if (samplesCollected < windowSize) {
        samplesCollected++;
        Serial.println("📊 Collecting lux window...");
        return;
    }

    float mean = calculateMean(luxWindow);
    float stdDev = calculateStdDev(luxWindow, mean);
    float zScore = (stdDev > 0) ? (currentLux - mean) / stdDev : 0;

    Serial.printf("Lux:%.1f EMA:%.1f Thr:%.1f Z:%.2f\n", currentLux,
emaLux,
                adaptiveThreshold, zScore);

    // detection
    if (currentLux > adaptiveThreshold && fabs(zScore) > zThreshold) {
        Serial.println("🔥 Fire detected! Motor stopped.");
        motorRunning = false;
        ledBlinking = true;
        tone(BUZZER_PIN, 3000);
        digitalWrite(EN_PIN, HIGH); // optional driver disable
    }
}

taskYIELD();
}

void stepperTask(void* parameter) {
    while (true) {
        if (motorRunning && !motorPermanentlyStopped) {

```

```

        digitalWrite(STEP_PIN, HIGH);
        delayMicroseconds(stepDelayMicros);
        digitalWrite(STEP_PIN, LOW);
        delayMicroseconds(stepDelayMicros);
    } else {
        delay(10); // Lower CPU use
    }

    vTaskDelay(1 / portTICK_PERIOD_MS); // Feed watchdog
}
}

float readLux() {
    // digitalWrite(SLED, HIGH);
    delay(50);
    uint32_t lum = tsl.getFullLuminosity();
    uint16_t ir = lum >> 16;
    uint16_t full = lum & 0xFFFF;
    // digitalWrite(SLED, LOW);
    float visible = full - ir;
    return (float)visible;
}

float calculateMean(float data[]) {
    float sum = 0;
    for (int i = 0; i < windowSize; i++) sum += data[i];
    return sum / windowSize;
}

float calculateStdDev(float data[], float mean) {
    float sumSq = 0;
    for (int i = 0; i < windowSize; i++) {
        sumSq += pow(data[i] - mean, 2);
    }
    return sqrt(sumSq / windowSize);
}

```

Appendix E – ChatGPT Prompts and Outcomes

[1a] **Case Study 1 Prompt:** “Explain how a Galilean demagnification system functions and offer suggestions on focal lengths, type of lens, and lens material.”

[1b] **Case Study 1 ChatGPT Outcome:** “To design a Galilean demagnification system, begin by selecting a positive objective lens with a relatively long focal length and a negative eyepiece with a shorter focal length, ensuring their ratio matches your desired

demagnification factor; for instance, a 100 mm objective and a -50 mm eyepiece will yield $0.5\times$ demagnification, while a -25 mm eyepiece would achieve $0.25\times$ demagnification with the same objective. For lens types, use plano-convex or bi-convex lenses for the positive lens to enhance light collection, and plano-concave or bi-concave lenses for the negative lens for effective beam reduction. The choice of lens material depends on the application's wavelength: BK7 glass is suitable for visible light (400–700 nm) due to its cost-effectiveness and low dispersion, Calcium Fluoride (CaF_2) or Zinc Selenide (ZnSe) are appropriate for infrared (700–2500 nm), and fused silica or quartz are preferable for UV applications due to their high UV transparency.”

[1c] **Case Study 1 Deepseek / Perplexity AI Outcome:** “A Galilean demagnification system functions by utilizing a combination of two lenses: a positive (converging) objective lens followed by a negative (diverging) eyepiece lens. These lenses are separated by a distance equal to the algebraic sum of their focal lengths, which creates a much shorter optical arrangement than a comparable Keplerian system due to the negative focal length of the eyepiece. The demagnification occurs when the focal length of the objective lens is smaller in absolute value than that of the eyepiece, as the magnification is calculated by the formula $M = -f_1/f_2$, where f_1 is the focal length of the objective and f_2 is the focal length of the eyepiece (a negative value). For example, combining an objective lens with a focal length of +25mm and an eyepiece with a focal length of -50mm would produce a $0.5\times$ demagnification. For optimal performance, plano-convex or biconvex lenses are recommended for the objective, while plano-concave or biconcave lenses work best for the eyepiece. Regarding lens materials, high-quality optical glass is preferred for precision applications, with BK7 glass being a standard choice for visible wavelengths, while crown glass offers good optical properties with minimal dispersion. A key advantage of Galilean systems is the absence of an internal focus point, making them ideal for high-power laser applications where concentrated energy could cause thermal distortion. Additionally, these systems produce erect images without requiring additional optical components”.

[2a] **Case Study 2 Prompt:** “What is the most powerful MCU in the market, right now?”

[2b] **Case Study 2 ChatGPT Outcome:** “As of March 2025, the microcontroller (MCU) market offers a range of high-performance options tailored to various applications. Among the most powerful MCUs currently available is the STMicroelectronics STM32H5 series, which is built on the Arm Cortex-M33 core and operates at frequencies up to 250 MHz. With up to 2 MB of flash memory and 640 KB of RAM, it provides a strong balance of performance, security, and cost-effectiveness, making it suitable for demanding embedded systems. Another standout is the Espressif Systems ESP32-P4 series, which features a dual-core processor with clock speeds up to 400 MHz and supports both Wi-Fi and Bluetooth, making it ideal for advanced IoT applications. Renesas’s RA8 series, powered by the Arm Cortex-M85 core, delivers exceptional processing power and robust security features, addressing the needs of industrial and IoT use cases. The NXP i.MX RT1170 series also stands out with a dual-core architecture that includes Arm Cortex-M7 and Cortex-M4 cores, with the M7 core reaching up to 1 GHz, making it well-suited for real-time processing and computationally intensive tasks. Lastly, the Raspberry Pi Pico 2 W, featuring the RP2350 microcontroller with dual-core processing and built-in Wi-Fi and Bluetooth, offers a cost-effective solution for educational and wireless IoT projects. When

choosing an MCU, it's important to consider processing speed, memory capacity, power consumption, and available peripherals to ensure it meets your project's specific needs”.

[2c] Case Study 2 Google AI Outcome: *“As of March 16, 2025, the most powerful consumer-oriented microprocessor for gaming and general use is likely the AMD Ryzen 9 9950X or the AMD Ryzen 7 9800X3D, depending on the workload. For gaming specifically, the Ryzen 7 9800X3D stands out as the fastest option, particularly in 1080p scenarios. The Ryzen 9 9950X, on the other hand, is a 16-core, 32-thread processor designed to handle both intensive creative workloads and high-performance gaming, offering a strong combination of power and efficiency. Meanwhile, the Ryzen 7 9800X3D is optimized for gaming, consistently outperforming Intel’s top-tier chips in gaming benchmarks. On the Intel side, the Core i9-14900K remains a competitive high-end processor, delivering excellent all-around performance even if it doesn’t match AMD’s latest chips in gaming. The Intel Core i7-14700K also offers a solid balance of performance and value, making it a strong choice for general-purpose computing.”*

[3a] Case Study 3 Prompt: *“What are some buzzer technologies?”*

[3b] Case Study 3 ChatGPT Outcome: *“Piezoelectric Buzzers*

“Buzzers operate using different mechanisms depending on their type. Piezoelectric buzzers utilize the piezoelectric effect, where a ceramic disc flexes in response to an applied voltage, generating sound. These buzzers are highly efficient, consuming very low power, and are best suited for mid to high frequencies (typically 2–4 kHz). They are available in both active versions, which require only a DC power source, and passive versions, which must be driven by an AC signal or PWM from a microcontroller. Piezo buzzers are known for their lightweight, reliability, and loudness relative to size, though they typically produce higher-pitched tones and offer limited frequency flexibility.

Electromagnetic buzzers function through magnetic force, where a current passing through a coil moves a diaphragm to produce sound. They generally consume more power than piezo buzzers and are designed for lower frequency ranges (around 400–4,000 Hz). These buzzers also come in active and passive variants. Their deeper tone and ease of use make them ideal for alarm systems, but they are bulkier and heavier, drawing more current. Mechanical buzzers, on the other hand, rely on a vibrating mechanism driven by electromagnetic or mechanical contacts. While they are capable of producing very loud sounds and are commonly used in industrial or automotive settings, they are power-hungry, often require AC power, and tend to wear over time due to their moving parts. Finally, magnetic transducers operate similarly to electromagnetic buzzers but are entirely passive, requiring an external AC signal or PWM for operation. Their power usage is moderate and depends on the driving signal. These transducers offer flexibility in tone generation, making them suitable for variable frequencies or melodies, but they require a driver circuit or microcontroller for sound output.”

[3c] Case Study 3 Google AI Outcome: *“Buzzer technologies largely rely on principles of electromagnetism and piezoelectricity, with the most common types being magnetic, piezoelectric, and electromechanical buzzers. Each of these types has distinct characteristics and use cases depending on application needs. Magnetic buzzers, also known as electromagnetic buzzers, operate by vibrating a diaphragm using a magnetic coil*

and typically run at lower voltages but higher currents. They offer a wider range of frequencies and often require an external driver circuit, as seen in passive buzzers. Piezoelectric buzzers, on the other hand, use the piezoelectric effect to generate sound through voltage-induced flexing of a piezoelectric crystal. These are valued for their compact size, low power consumption, and broad frequency response, making them suitable for space- and energy-constrained environments.

Electromechanical buzzers create sound using a magnetic field generated by an electromagnet, producing louder and more robust tones than other types. They are commonly used in environments where strong audio alerts are necessary, such as in alarms or industrial sirens. In addition to these types, buzzers are often classified as either active or passive. Active buzzers come with an internal driving circuit and can produce sound when powered directly, while passive buzzers require a signal input—such as a PWM waveform—from a microcontroller or external driver. Understanding these differences allows for better selection of buzzer types based on power requirements, space limitations, sound characteristics, and control needs.”

[4a] Case Study 4 Prompt: *“I want to design a lens system to image something 3-5 meters away. I will design a custom lens system. What existing lens design style offers a cost-effective solution?”*

[4b] Case Study 4 ChatGPT Outcome: *“Since you’re designing a custom lens system to image objects 3 to 5 meters away, there are several cost-effective lens design styles that could suit your application. One of the best trade-offs between cost and performance is the achromatic doublet system. Achromatic doublets are designed to correct chromatic aberration while remaining relatively affordable. A typical configuration pairs a plano-convex (or bi-convex) lens with a negative meniscus lens to reduce spherical aberration and sharpen focus. These are readily available off-the-shelf from suppliers like Thorlabs or Edmund Optics and can be further optimized with a field flattener if needed.*

If budget is a primary concern, a simple plano-convex lens system is the cheapest option. Using a single plano-convex or bi-convex lens can offer an effective solution for long-distance imaging. Selecting a lens with a short focal length will help maintain a wide field of view while still focusing the image onto your detector. These lenses are widely available and inexpensive, making them a practical choice for basic imaging setups.

For a more compact design, consider a Galilean telescope configuration. This system uses two lenses—a negative diverging lens followed by a convex lens—to achieve magnification without significantly increasing optical complexity. It’s a compact and efficient design that can be assembled using off-the-shelf lenses and requires minimal optical alignment.

Finally, if you’re aiming for higher image quality while keeping costs reasonable, the Cooke Triplet is a strong candidate. This design incorporates three elements—a positive lens, a negative lens, and another positive lens—to effectively correct both spherical and chromatic aberrations. While it involves more components than the previous options, it delivers excellent imaging performance without the need for aspheric surfaces.”

[4c] **Case Study 4 Deepseek Outcome:** *“A cost-effective lens system for imaging objects at 3-5 meters would ideally utilize Commercial Off-The-Shelf (COTS) lenses arranged in an appropriate configuration. COTS lenses offer significant economic advantages, typically costing only tens of dollars per uncoated lens while providing immediate to 8-week availability. For this working distance, a landscape lens design presents a particularly economical solution, being one of the earliest and simplest camera lens designs used historically in Camera Obscura devices. This design employs a meniscus lens (either front or rear configuration) that effectively corrects astigmatism and coma, though it has limitations regarding spherical aberration that can be mitigated by using a smaller aperture. For mounting, consider a lens tube system where elements of the same diameter are secured using retaining rings or custom spacers, with lens tolerances primarily controlling centering and spacer tolerances managing tilt and axial separation. When selecting focal length, calculate based on your desired field of view and sensor size using standard equations that relate working distance to these parameters. Fixed focal length options ranging from 3.5mm to 75mm are readily available in various mounts (C-mount, CS-mount, etc.), offering solutions for different sensor sizes and resolution requirements. The optimal design would balance simplicity (fewer elements) with performance, keeping in mind that while landscape lens designs are simple and cost-effective, they cannot fully correct for distortion due to their asymmetry about the stop.”*

[5a] **Case Study 5 Prompt:** *“What are some algorithm alternatives of quick sorting for determining the most accurate thresholds in a threshold-based system?”*

[5b] **Case Study 5 ChatGPT Outcome:** *“In a threshold-based system, selecting the most accurate thresholds is better approached as an optimization or data-driven segmentation problem rather than a simple sorting task. While quick sort is efficient for ordering data, it does not optimize threshold selection. Instead, several alternative algorithms and methods can be more effective, depending on the nature of the problem.*

Dynamic programming, for instance, is useful when the goal is to segment data optimally; a classic example is Otsu’s method, which minimizes intra-class variance in image thresholding. If the threshold is continuous, binary search variants can help by iteratively evaluating candidate values against a loss or accuracy function. K-means clustering is another approach that identifies natural breaks in data by grouping points into clusters and using the centroids as thresholds.

Decision tree algorithms like CART determine thresholds by maximizing information gain and are commonly used in classification problems. For more complex or nonlinear scenarios, heuristic methods like genetic algorithms or particle swarm optimization explore a wide range of threshold candidates using evolutionary or population-based strategies. Bayesian optimization is also valuable when threshold evaluations are computationally expensive, using probabilistic modeling to select promising candidates.

Statistical techniques can provide practical solutions as well. For instance, ROC curve analysis helps identify the best threshold by maximizing metrics like Youden’s J statistic, while percentile-based methods are often used in anomaly detection. In cases where the problem structure allows, convex optimization methods such as gradient descent or quadratic programming offer a mathematically rigorous way to find optimal thresholds.

Lastly, histogram-based techniques—like gap detection or Jenks Natural Breaks—are effective when the data exhibits clear distribution patterns. Overall, the best approach depends on whether the problem is about sorting, finding cutoffs, or navigating complex, high-dimensional threshold spaces. Let me know if you'd like help implementing or simulating any of these methods for your use case.”

[5c] **Case Study 5 Google AI Outcome:** “When selecting an alternative to quicksort for determining accurate thresholds in a threshold-based system—particularly when accuracy, stability, and system constraints are critical—it’s important to consider the broader context of your data and processing needs. While quicksort is efficient on average, it suffers from potential instability and a worst-case time complexity of $O(n^2)$, which may not be suitable for systems that demand predictable and reliable performance.

Merge sort is a strong candidate when stability is essential. It guarantees $O(n \log n)$ performance across all cases and preserves the order of equal elements, which is crucial if your threshold logic depends on relative ordering. Although it requires additional memory for merging, its consistency makes it valuable in real-time or critical applications where execution time must be predictable.

Heap sort also provides $O(n \log n)$ time complexity but is performed in-place, making it a better option when memory is limited. However, it is not a stable sort, which could be a drawback if equal-value elements need to maintain their original order.

Tim sort, a hybrid of merge sort and insertion sort, is particularly effective for real-world data that is partially sorted. It maintains stability and performs well with runs of pre-sorted elements, making it ideal for many practical thresholding scenarios. This algorithm is the default sort in languages like Python due to its balance of efficiency and stability.

Counting sort and **radix sort** offer extremely fast performance ($O(n + k)$), but they are suitable only when dealing with integer data within a known, limited range. These methods are stable when implemented properly and excel in applications like sensor thresholding, where the input range is predefined.

Insertion sort is less efficient overall, with a worst-case time of $O(n^2)$, but it shines in cases involving small datasets or when data is nearly sorted or added incrementally. Its in-place and stable nature makes it efficient for systems where minor updates to the dataset are common.

Ultimately, the best sorting algorithm for threshold selection depends on the specific characteristics of your data. If stability matters, opt for merge sort, Tim sort, or counting sort. If memory is a concern, consider heap sort or insertion sort. For structured, integer-based data within a known range, counting or radix sort may be optimal. The key is aligning the algorithm with the demands of your threshold logic, dataset distribution, memory availability, and system requirements.”

[6a] **Case Study 6 Prompt:** “What is I2C?”

[6b] **Case Study 6 ChatGPT Outcome:** “I²C, short for Inter-Integrated Circuit and pronounced either “I-squared-C” or “I-two-C,” is a widely used two-wire serial communication protocol that allows multiple devices such as sensors, displays, ADCs, and

EEPROMs to interface with a central controller like a microcontroller or FPGA. The protocol operates over two shared lines: SDA (Serial Data Line) for transmitting data and SCL (Serial Clock Line) for synchronization. In this setup, one master device initiates and controls the communication, while multiple slave devices respond, each identified by a unique address. Data transmission occurs through small address-data packets, enabling efficient device coordination with minimal wiring.

Key features of I²C include its minimal requirement of just two wires, support for multiple slave devices (typically up to 128), and data speeds ranging from 100 kHz in standard mode up to 1 MHz in fast-mode plus. It's best suited for short-distance communication within PCBs or closely placed modules. I²C is commonly used for tasks like reading sensor data, communicating with displays, interfacing with memory chips, and connecting small integrated circuits in embedded systems. Advantages include simplified wiring and ease of device expansion, though it does come with limitations such as slower speeds compared to SPI and a more complex communication protocol. For example, in a basic application where an FPGA acts as the master and interfaces with a temperature sensor and ADC, the FPGA would initiate communication, address the ADC, request voltage data, receive the data, and terminate the exchange—all efficiently handled over the two I²C lines."

[6c] Case Study 6 Google AI Outcome: *"I²C, or Inter-Integrated Circuit, is a two-wire serial communication protocol designed for short-distance communication between microcontrollers and various peripheral integrated circuits (ICs). It operates using just two lines: the SDA (Serial Data Line) for data transmission and the SCL (Serial Clock Line) for synchronization. As a synchronous and single-ended bus, I²C can support multiple masters and multiple slaves, making it a versatile and efficient protocol for intra-board communication. Its primary role is to enable communication between low-speed peripherals and processors or microcontrollers, particularly when simplicity and space are important design considerations.*

One of the key strengths of I²C lies in its simplicity and robustness. With only two communication lines required, it is both power-efficient and cost-effective, making it suitable for compact systems. Additionally, its scalability allows for flexible architectures, supporting multiple devices on the same bus. I²C is widely used in applications such as reading data from sensors (e.g., temperature, pressure, accelerometers), controlling displays like OLEDs, accessing EEPROM memory chips, and enabling communication between different microcontrollers on a single board. These advantages have made I²C a standard choice in embedded systems and consumer electronics for managing peripheral communications efficiently."