F.L.A.M.E.S.

Fire Localization and Analysis for Emergency Situations

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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 F.L.A.M.E.S. 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 F.L.A.M.E.S., 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. F.L.A.M.E.S. builds on this legacy by explicitly addressing false alarms through a sophisticated multi-layer optical analysis, further enhancing fire detection accuracy. F.L.A.M.E.S., 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 F.L.A.M.E.S. share similarities in their layered detection approach. Heat detectors confirm fire presence using fixed temperature and rate-of-rise methods, while F.L.A.M.E.S. 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 F.L.A.M.E.S. addresses false alarms and detects fires across varied temperature conditions. Their signal processing differs, with heat detectors analyzing temperature changes and F.L.A.M.E.S. 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 F.L.A.M.E.S. emphasize early fire detection to enable swift responses and reduce damage. While ASDs rely on active air sampling, F.L.A.M.E.S. utilizes optical photodetectors and FPGA-based multi-layer analysis. ASDs mitigate false alarms through filtration and particle analysis, whereas F.L.A.M.E.S. 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 F.L.A.M.E.S. is optimized for confined spaces. Additionally, F.L.A.M.E.S. 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. F.L.A.M.E.S. 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, F.L.A.M.E.S. 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 F.L.A.M.E.S. 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 F.L.A.M.E.S. 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, F.L.A.M.E.S. 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, F.L.A.M.E.S. 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.

2.2.7 Summary – To be completed near the end of SD1

2.3 Goals and Objectives

Below are the goals and objectives we established for F.L.A.M.E.S. 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 and or cleanroom.
- Isolate peak wavelengths commonly found in fires via spectral filtering with a wavelength tuned filter biased at 694 nm.
- Notify the end user of a fire via buzzer and LED.
- Perform algorithmic and signal processing computation tasks using a customizable computer as opposed to an MCU.

Advanced Goals:

- Mount the F.L.A.M.E.S. system such that the entirety of the system rotates 360 degrees and collects 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 characteristics and amplitude signal processing techniques
- Notify the end user through integrated audio and visual feedback using an LED and buzzer.
- 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 error-checking protocols to ensure constant communication between the FPGA and MCU.
- Detect and alert fire hazards using temperature monitoring.

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 will trigger post-spectral analysis to warn others in area of the presence of fire.
- All optical components and supporting electronic hardware will be contained in a singular 3D printed package with no optical alignment required from the user.
- Develop and implement spectral analysis algorithms in the FPGA using the I(λ) data format to differentiate between fire and other intense stochastic optical emissions based on temporal characteristics.
    - Intensity Threshold Analysis: Quickly identify potential fire sources by filtering out low-intensity signals that are unlikely to be fires, while establishing an environmental baseline for further analysis.
    - Temporal Analysis: Verify that the detected light source is consistent and sustained, ruling out transient bright sources. Additionally, with an optical red filter applied, to differentiate characteristic spikes in fire intensity data from other intense light sources, such as welding sparks or nearby non-fire emissions.
- Utilize an MCU to manage communication, data logging, power, and alert triggering.
- Warm temperature laboratory environment: Account for thermal noise through the system by ensuring the system remains in a contained environment with thermal shielding to reflect harboring radiation in the form of heat.
- 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 FPGA to output a pulse-width modulated signal with pulse width adjustments for desired motor position, rotation speed, and direction.
- A broadband 350-1100 nm silicon detector will capture wavelengths from stochastic light sources, such as sparks from various ignition events. Potential fire sources will be characterized by the photocurrent output, analyzed by an FPGA.

When a wavelength-specific filter is introduced, the FPGA will compare the filtered photocurrent to the unfiltered frontmost photodiode response to assess intensity variations over time.

- A transimpedance amplifier will be implemented to convert AC current into a 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.
- Activate low-power idle mode when inactive and apply dynamic power scaling to reduce unnecessary power usage.
- Maintain total system power consumption to remain below 16.71 W during active detection.
- Ensure log retention during power cycles by using non-volatile memory or transferring data to an external system before shutdown.
- The ESP32 and Artix-7 FPGA will communicate via high-speed SPI or UART protocols, enabling efficient data transfer for real-time fire detection and system control.
- The ESP32 and Artix-7 FPGA use a checksum with ACK/NACK handshaking for efficient and realistic error detection and retransmission.

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 will check 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.

2.3.1 Hardware

2.3.1.1 Fire Detection System – Basic Goals:

The F.L.A.M.E.S. optical fire detection system's primary function is to identify potential hazards effectively across diverse darkened small room environments including confined laboratory spaces, ducts, 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. The secondary photodetector is situated behind a bandpass filter rated for 694nm. Naturally, the emission from the source will be focused onto the detector and the components of the emission containing "red" wavelengths will solely contribute to the photocurrent detected by the secondary photodetector. The expected photocurrent signal on the output of the secondary photodiode is expected to have a lower energy spectral density and fluctuate periodically as a function of time.

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. F.L.A.M.E.S. 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 F.L.A.M.E.S. system ideal for confined spaces such as laboratory environments.

2.3.1.2 FPGA & MCU Integration – Basic Goals:

The FPGA and MCU integration in the fire detection system provides distinct and complementary roles in managing hardware communication. The FPGA is responsible for advanced data analysis, as outlined in the software section, while the MCU coordinates interactions with various hardware components. Communication between the FPGA and MCU is facilitated via high-speed SPI or UART protocols, ensuring efficient real-time data transfer for the F.L.A.M.E.S. system. A robust error-checking system, utilizing checksums with ACK/NACK handshaking, ensures accurate data transmission and effective error recovery.

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.

2.3.1.3 Thermistor – Stretch Goal:

Adding temperature feedback to F.L.A.M.E.S. 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 F.L.A.M.E.S. 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.

2.3.2 Software

2.3.2.1 Fire Detection Analysis – Basic Goals:

The FPGA will conduct a two-layer analysis to confirm that any detected heat source is indeed a fire before triggering an alert. The process begins with Threshold Analysis, which establishes a baseline for the environment in which it is deployed. This is followed by Temporal Analysis, which ensures the detected light source is consistent and sustained, effectively ruling out transient sources. Additionally, by utilizing an optical red filter, the system can determine if the source is a fire by identifying characteristic spikes in frequency and wavelength plots derived from a Fast Fourier Transform (FFT) on the intensity data.

The fire detection system is designed to adapt to various laboratory environments to ensure accurate and reliable performance. In a bright laboratory environment, optoelectronic sensors equipped with a single narrowband filter are used to isolate wavelengths commonly associated with fires. FPGA algorithms process the current signal output from these detectors, enabling the system to differentiate between welding, soldering, and potential fires. In a warm laboratory environment, the system accounts for thermal noise by operating within a closed environment, mitigating interference from ambient temperature variations. For flickering lights, dusty, and environment-changing small-scale single room environments, like a laboratory, the system establishes a baseline threshold by measuring environmental conditions when the start button is pressed through the threshold analysis. This baseline is tailored to the pre-fire conditions of the specific environment and automatically resets in new environments, ensuring consistent and precise fire detection capabilities.

2.3.2.2 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.

2.3.2.3 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.

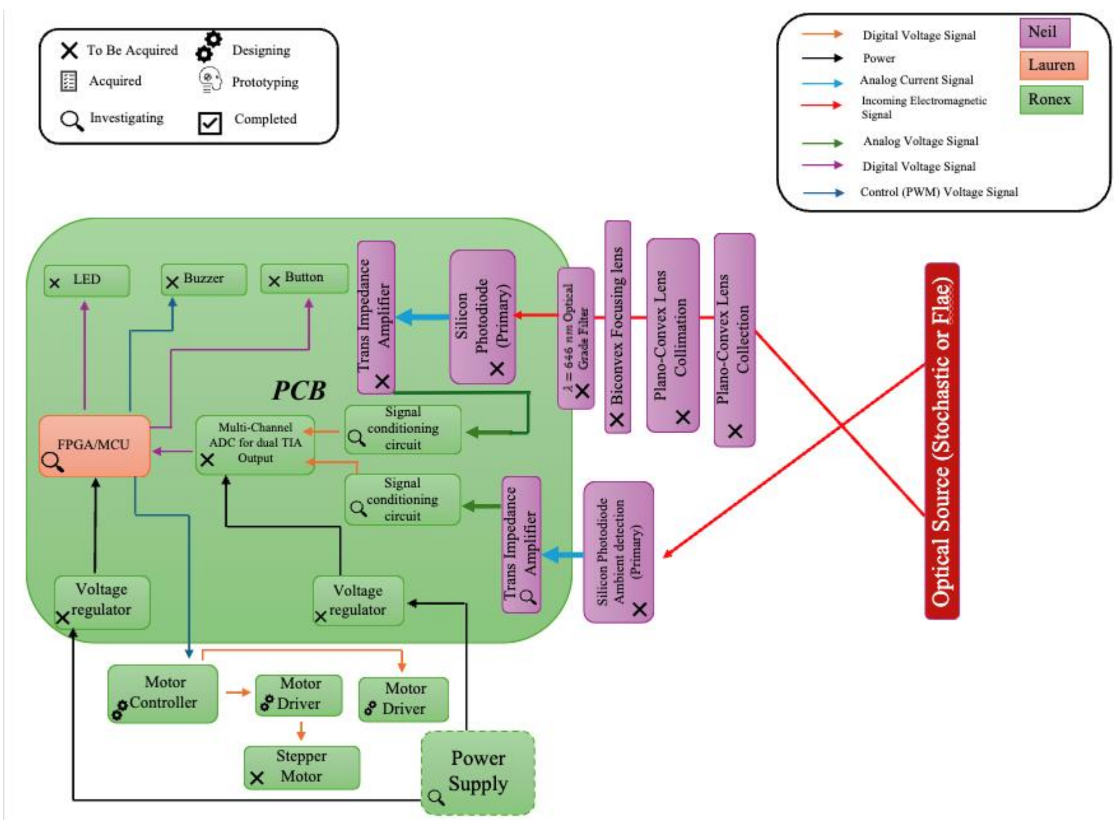
2.4 Required Specifications

Specifications:

Table 2.4.1 Specification of Optical Based Fire Detection System

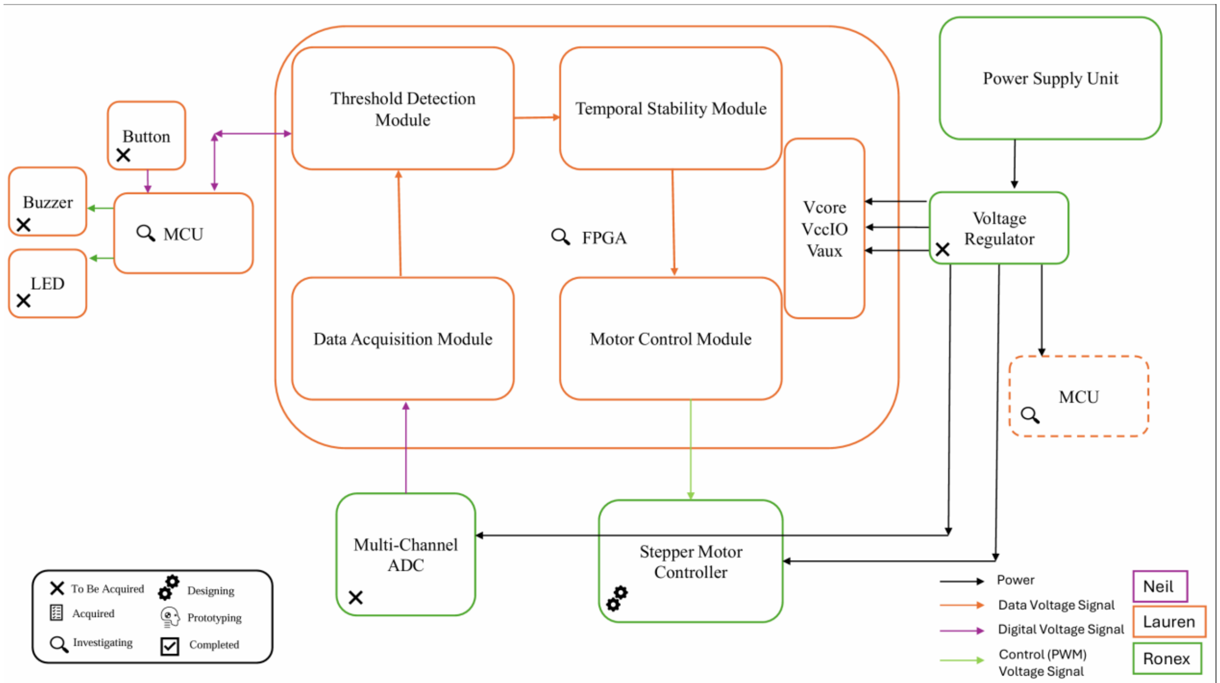
Fire Detection System	
Dynamic System Threshold Intensity Range	(watt/m^2)?
Stop and Hold Precision	Degree Tolerance allowed
Scanning Area Coverage	360 Degrees
Response Time to Finish	5-10 Seconds
Detection Threshold Accuracy	90%
Power Consumption	16.72 W
Onboard Data Storage	512KB – 1MB SRAM
Detection Distance	0-2 meters radially
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^2C
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^2C
Optoelectronic / Lens System	
Full Field of View	__deg Zemax Calculations need to be performed
Min Detectable Intensity	__µA Threshold for detection in Voltage
Photodetectors Focus Spot Size	10 mm Zemax Calc. needed for verification



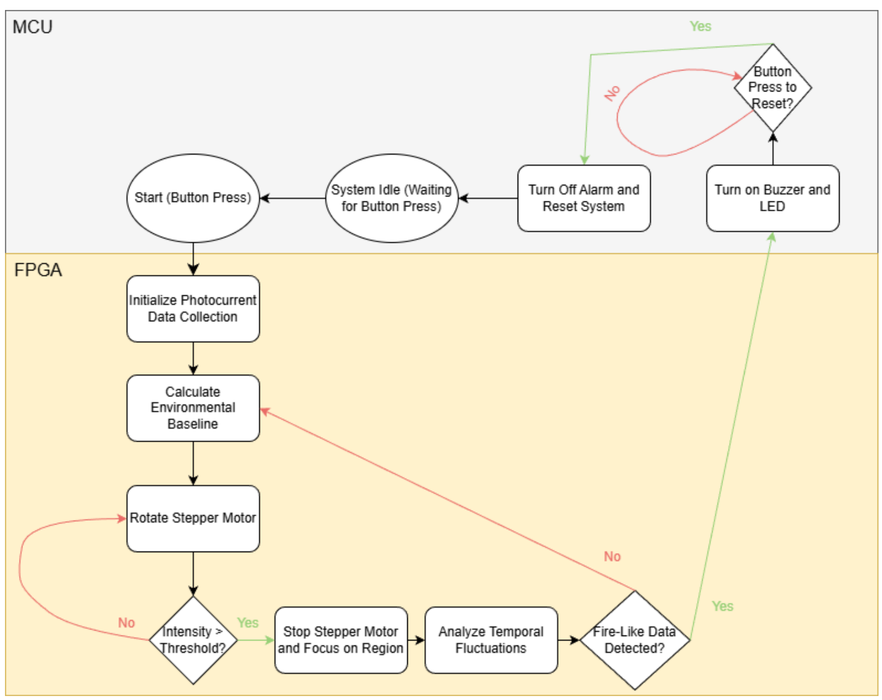
F.L.A.M.E.S. hardware system diagram is shown above. This diagram demonstrates the core hardware components needed for F.L.A.M.E.S. to conduct its detection. Separated by color, are the contributions by discipline. The arrows demonstrate the flow of detection, originating at the red "Source" on the right-hand side.

Figure 2.4.1 System Hardware Diagram by Authors



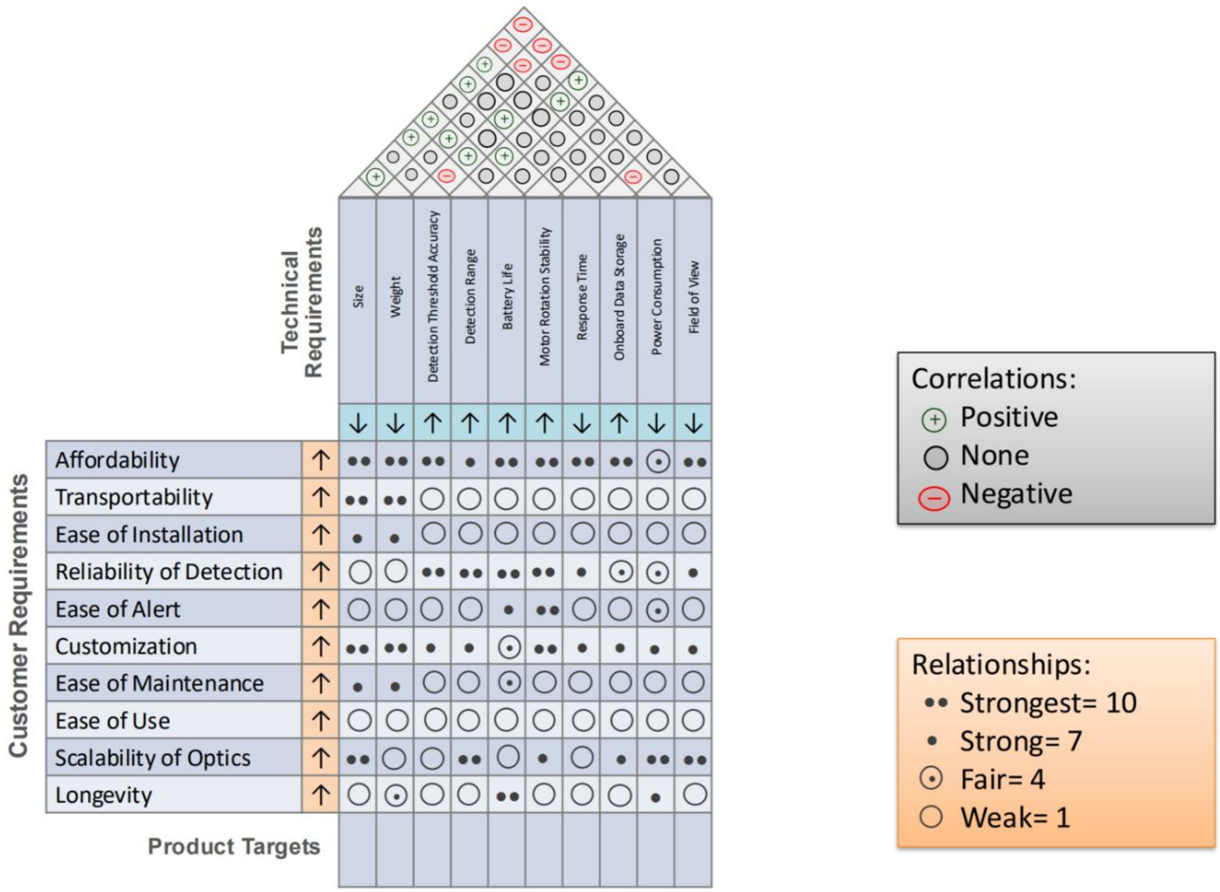
Above is the FPGA Hardware Diagram, illustrating the setup of FPGA modules for analysis and the integration of FPGA components with electrical hardware for power and control specifications.

Figure 2.4.2 FPGA Hardware Diagram by Authors



The Software Flowchart outlines the process F.L.A.M.E.S. 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 2.4.3 Software Flowchart by Authors



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.

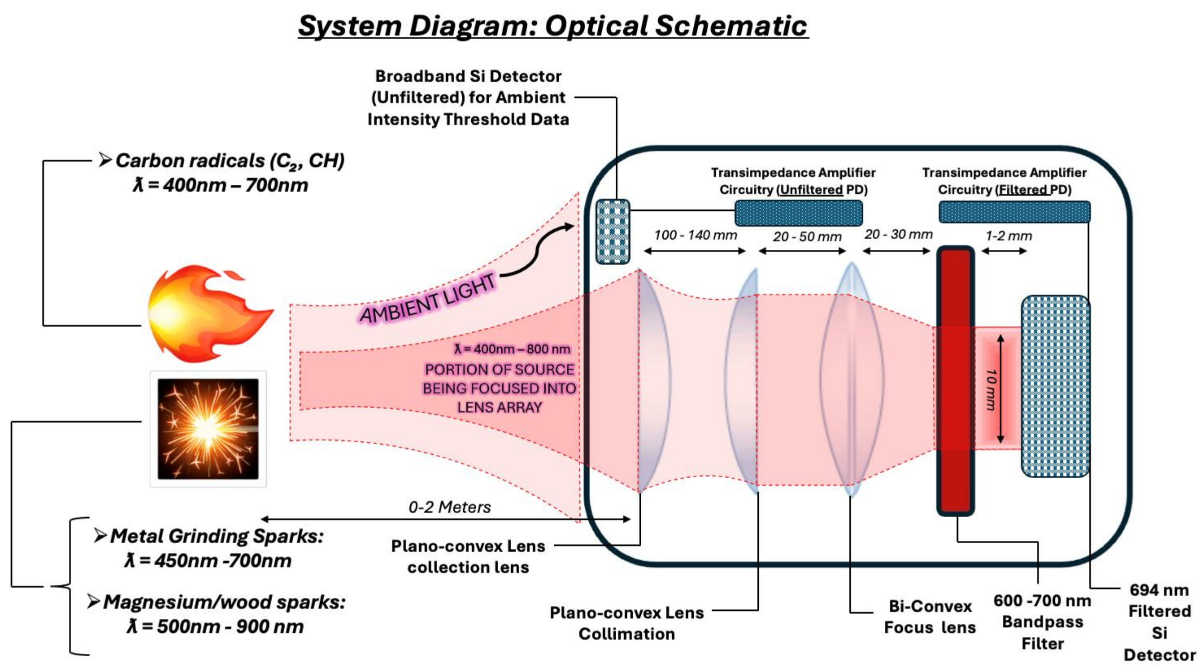
Figure 2.4.4 House of Quality by Authors

2.5 Optical Hardware Description

2.5.1 Infinite Object Focusing Lens Assembly

The optical system employed in F.L.A.M.E.S. 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 F.L.A.M.E.S. must effectively capture light from sources within a 0 to 2-meter range and focus it onto a 10 mm^2 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.

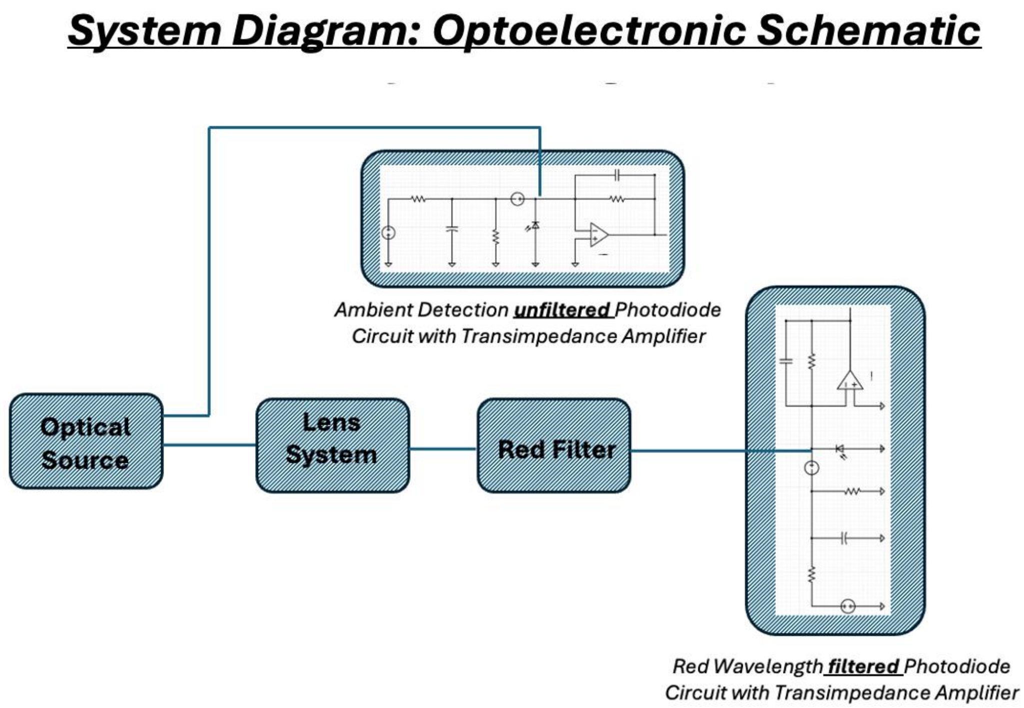
2.5.2 Focusing Lens System Schematic



Lens wavefront shaping and focusing system for filtered detector consisting of 2 plano-convex lenses, and a biconvex focusing lens.

Figure 2.5.1 Optical Schematic

The lens system outlined in Section 2.5.1 is depicted in Figure 2.5.1 As 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, as shown in Figure 2.5.2. The FPGA 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 covert 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 amlifier is comprised of a feedback resistor and parasitic capacitor which are electrically connected to an operational ampifier. By fine tuning the gain of the operatonal amplifier, the photocurrent that was previously in the micro ampere range can now be converted into the volts range at the input of the FPGA. An example shcematic of the photodiode is shown below in figure 2.5.2.

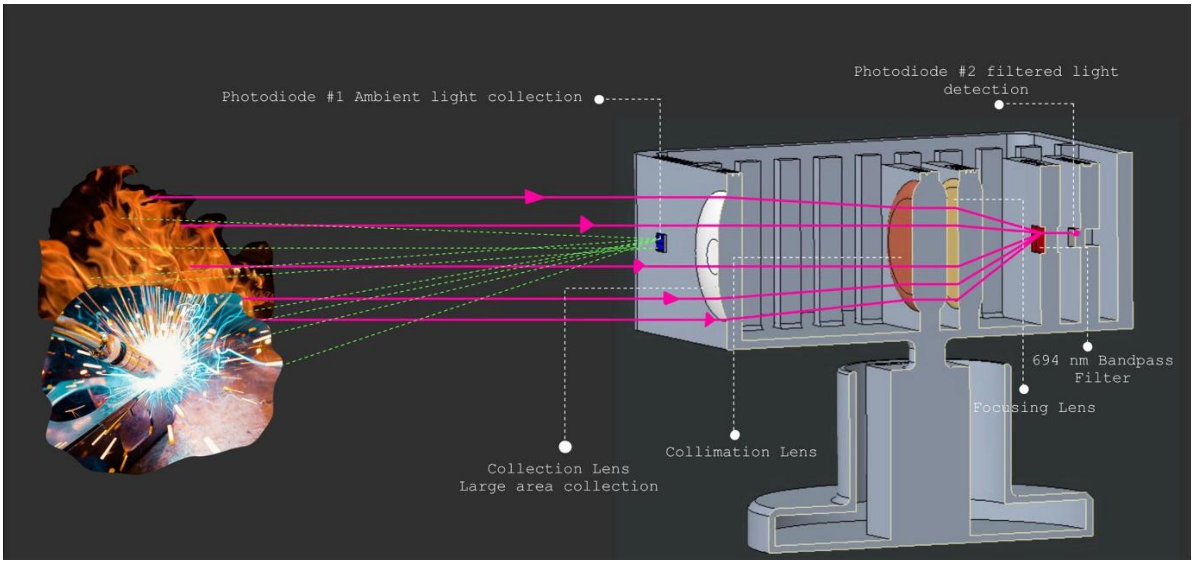


Example circuit of optoelectronic components in F.L.A.M.E.S design. Illustrated here, is the transimpedance amplifier and current limiting circuit necessary to convert the output from amperes to volts.

Figure 2.5.2

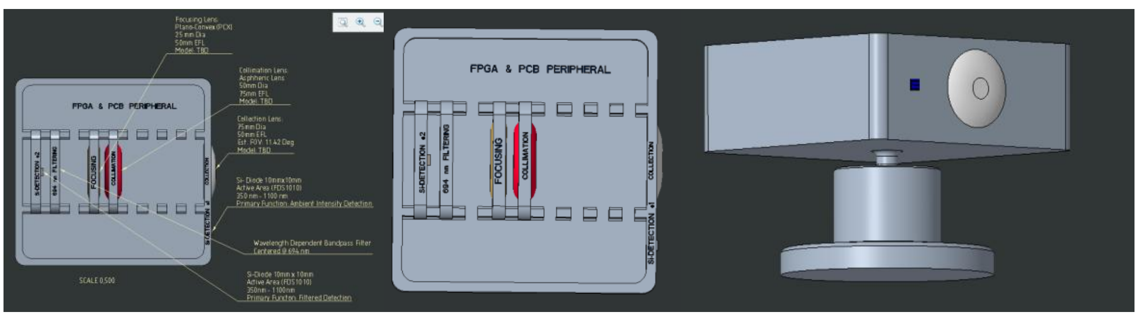
2.5.3 Cross Sectional Ray Trace of Enclosed Unit

A cross-sectional view of the F.L.A.M.E.S. system is presented in Figure 2.5.3, illustrating an idealized ray interaction model with the optical elements. This depiction demonstrates how incident rays interact with the lens surfaces, ultimately focusing onto the filtered detector. The source is represented as either a fire or a stochastic emission, such as a spark. The pink rays in the diagram indicate the focusing path onto the 10 mm detector, highlighting the system's optical precision. The green rays in the illustration show the ambient light captured on the photodiode for further signal processin. As shown in Figure 2.5.3, the lenses are enclosed within a protective housing designed to minimize thermal noise interference from the surrounding environment. The base of the housing is mounted onto a stepper motor, enabling precise alignment of the optomechanical axis with the detected source. This integration ensures stable and accurate light collection, enhancing the system's overall detection capabilities.



Section View of Ray Interaction at Lens Surface. Light from distant source is focused through a series of visible wavelength lenses onto 10mm Silicon Photodetector.

Figure 2.5.3



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.

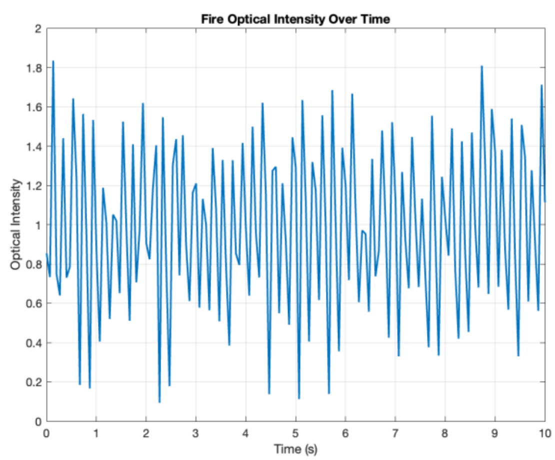
Figure 2.5.4

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. Figures 2.6.1 and 2.6.2 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.



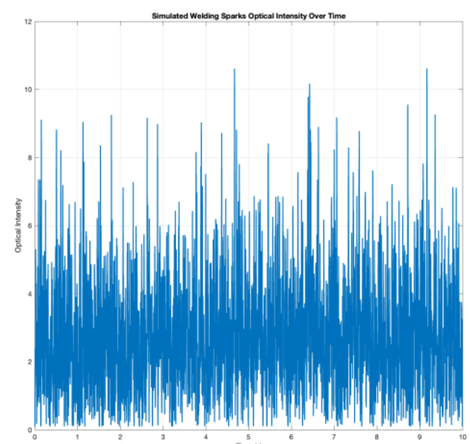
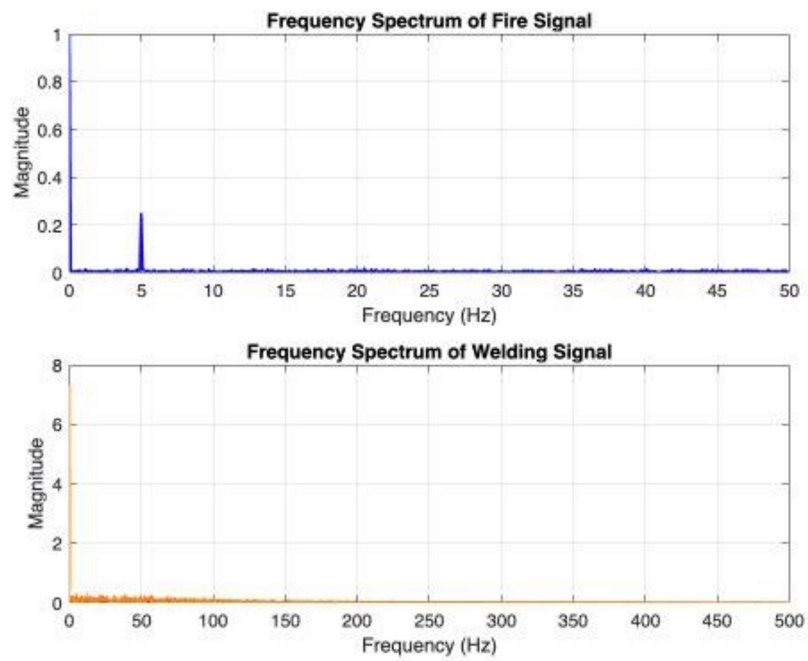


Figure 2.6.1 pictures the expected intensity profile fluctuation of a flame after being focused onto the rear filtered photodetector. A shown the signal seems to be relatively periodic and is indicative of a lower energy spectral density. Figure 2.6.2 shows a higher frequency stochastic source (i.e. welding) indicative of a higher energy spectral density.

Figure 2.6.1 (L), 2.6.2 (R)

Although the patterns vary slightly in time domain, doing the Fourier transform reveals that the frequency patterns are governed the source of optical emission. The equation, $\xi = \frac{hc}{\lambda} =$ hf dictates the peak in the frequency domain. 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.



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.

Figure 2.6.3

A red filter bounded between 600-70 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 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 10.2.1 Bill of Materials

Component	***Part Name***	***Quantity***	***Unit Price***	***Total Price***
Optics Engineer				
Plano-Convex Lens Collection	#32-970	1	$48.50	$48.50
Color Filter	λ= 646 nm Color Filter	1	$96.50	$96.50
Plano-Convex Lens Collimation	#32-972	1	$81.50	$43.75
Silicon Photodiode	FDS1010 Si Photodiode (Uncalibrated)	2	$61.18	$122.36
Bi-Convex Lens	#320-980	1	$48.50	$48.50
Electrical Engineer				
Stepper Motor	NEMA 23 Stepper Motor	1	$25.99	$25.99
Motor Driver	Eason Stepper Motor Driver	1	$10.89	$10.89
Voltage regulator	Texas Instrument TPS54233DR	2	$1.43	$2.86
ADC	Texas Instrument ADS8320	1	$13.19	$13.19
LED	151051RS11000	1	$0.15	$0.15
Buzzer	WST-1210	1	$0.85	$0.85

Button	TS02-66-70-BK-160-LCR-D	1	$0.13	$0.13
Power Jack	Wurth Elektronik 694106402002	1	$0.92	$0.92
Adapter	9V 1A Power Supply	1	$1.00	$1.00
Computer Engineer				
FPGA Prototyping Board	Basys 3 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
Total Cost				
Optical Engineer		$359.61		
Electrical Engineer		$60.93		
Computer Engineer		$232.03		
Grand Total		**$662.32**		

As seen by the table above, we are below the goal limit of $1000 by exactly $337.68 allowing for prototyping and replacement parts.

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 10.3.1 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

Table 10.3.2 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	TBD SD2	TBD SD2	NA
Final Prototype	TBD SD2	TBD SD2	NA

Appendices

Appendix A – Reference

[1] O. US EPA, "Americium in Ionization Smoke Detectors." Accessed: Dec. 12, 2024. [Online]. Available: https://www.epa.gov/radtown/americium-ionization-smoke-detectors

[2] S. S. I. Staff, "What the Numbers Tell Us About False Fire Alarms," Security Sales & Integration. Accessed: Dec. 12, 2024. [Online]. Available: https://www.securitysales.com/contributed/what-the-numbers-tell-us-about-false-fire-alarms/

[3] "Fire Alarm Initiation | NFPA." Accessed: Dec. 12, 2024. [Online]. Available: https://www.nfpa.org/news-blogs-and-articles/blogs/2021/04/14/a-guide-to-fire-alarm-basics-initiation

[4] "At What Temperature Do Heat Alarms Trigger?," Alarm Grid. Accessed: Dec. 12, 2024. [Online]. Available: https://www.alarmgrid.com/faq/at-what-temperature-do-heat-alarms-trigger

[5] "FLAMEX Detectors," Flamex Inc. Accessed: Feb. 05, 2025. [Online]. Available: https://www.sparkdetection.com/components-of-fire-protection-systems/detectors/

[6] "Industrial Flame Monitoring (IFM) | Honeywell." Accessed: Feb. 05, 2025. [Online]. Available: https://process.honeywell.com/us/en/products/thermal-solutions/burner-management-systems/industrial-flame-monitoring-ifm

[7] "40/40I Triple IR (IR3) Flame Detector | Spectrex US." Accessed: Feb. 05, 2025. [Online]. Available: https://www.spectrex.net/en-us/flame-gas-detectors/flame-detectors/40-40-series/40-40i-triple-ir-ir3-flame-detector

[8] S. Kirchner, "Temperature Sensors - Thermistors versus Thermocouples," Ametherm. Accessed: Feb. 05, 2025. [Online]. Available: https://www.ametherm.com/blog/thermistors/temperature-sensors-thermistors-vs-thermocouples/

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