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Design and Development of a Smart Fire Alarm System for Early Fire Detection and Loss Reduction

By

Alaa Majed[1], Zahraa Abdulmohsen[2] ,Tabarak Ali[3] , Duha Abdulameer[4], Tuqa Sami[5] Benin Nafea[6]

[1,2,3,4,5,6]Department of Medical Physics and Radiotherapy, Technical Engineering College, Sawa University, Almuthana, Iraq

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Abstract

In this paper, a stand-alone, low-cost fire alarm system, a feature-less, basic instrument for early flame detection in small indoor environments, based only on an infrared flame sensor, is designed, implemented, and experimentally evaluated. The design is based on Arduino Uno microcontroller, that is responsible for instantaneously tracking the output of flame sensor for immediate local fire alarm through a buzzer, LED for high-intensity warning and status-indicator LED. An LCD display is provided to show real-time system messages, including standby conditions, flame detection alerts, etc.

It employs the Arduino Uno's small footprint microcontroller to conduct a low-power mode of high-throughput infrared flame detection, to create a short, effective fire alarm system at low energy demand. While many present day fire-alarm systems rely on smoke or gas sensors, network interfacing, or mechanical ventilation elements in order to work, this design is fully off the grid and does not depend on any internet, IoT modules, exhaust fans, or smoke sensors. The system architecture specifically maintains small, rugged, and cost effective architecture to be suitable for low resource settings, educational research facilities as well as small residential rooms. In a miniaturized indoor experimental setup to examine the prototype's response accuracy, detection reliability, and false alarms response under different conditions, a series of controlled trials were performed. The system is shown to detect open flames quickly and be stationary in the presence of non-flame stimuli as steam, dust, and changes in ambient lighting or heat source (without combustion) which leads to an extremely low false-alarm rate. The paper discusses some design issues concerning sensor placement and threshold tuning and discusses the suitability of flame-based offline detection in settings where traditional smoke detectors or IoT-enabled platforms are impractical. Recommendations for future improvements are also provided, such as multi-sensor integration and optional wireless notification for more advanced deployments.

Keywords: *flame sensor; Arduino Uno; stand-alone fire detection; low-cost embedded system; offline alarm device; early flame recognition.*

1. Introduction:

Fire is one of the major hazards that affects residential buildings, educational laboratories and small industrial premises, where confined spaces and few escape routes can quickly convert a first fire into a deadly event. In these contexts, rapid detection and local alerting become critical to minimize loss of life, equipment protection and site damages. Recent reviews on fire detection technologies have highlighted that existing systems have a need for continual measurement of factors including temperature, smoke, gas emissions, and flame signatures with unique advantages & limitations related to detection of flame over time (sensitivity, selectivity, and response time) (Khan et al., 2022). However, even with such advances, traditional smoke- and heat-based alarm systems display a range of well-publicised flaws when it comes to real-world activities.

Optical smoke detectors suffer from nuisance alarms, from harmless aerosols, dust, steam, cooking activity, which leads to "alarm fatigue" and distrust of alarm signals (BRE Group,

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2018). Moreover, smoke needs to build up at the detector site before any response can be triggered, which introduces inherent delay in early stage fires, especially in high-ventilated/open spaces where smoke has a slow dispersion and remains non-uniform (Khan et al., 2022). Smoke handling is affected by environmental factors (airflow, ceiling height, compartment, etc.) with resultant changes in smoke transport, and may reduce the performance and sensitivity of conventional detectors. Concurrently, there has been an extensive utilization of IoT driven fire alarm tools that combine wireless communication, cloud solutions, and smartphone warning. They provide remote observation and sophisticated analytics capabilities, and require stable network access, larger costs for deployment and more complicated maintenance that in low-resourced settings, small laboratories and education systems with insufficient technology base can not be realized (Rahman et al., 2022; Fernandino et al., 2020). In fact, in many instances the expense and intricacy of networks are more hindrances than things that keep people safe. At the hardware level, microcontroller-based prototypes have appeared as a cheap option that provides a short- and intermediate-range solution, covering the distance between stand-alone detectors and fully connected IoT appliances. Arduino-based fire alarm systems that use smoke, gas, and temperature alarms with buzzers, LEDs, and GSM or Wi-Fi modules have been shown in different studies providing an early alarm system for remote detection (Myint and Zaw Tun, 2020; Rahman et al., 2022; Chua et al., 2024).

Nevertheless, most of those architectures are still based mostly on smoke or gas sensing (MQ-series), or multi-sensor fusion, and mechanical device includes exhaust fans or fire-suppression actuators, in particular pumps or blowers. These types of designs are, however, computationally expensive and unnecessarily dense for small educational or laboratory settings for which only on-site early warning is necessary.More recently, research has also explored multi-sensor and learning-based approaches that fuse data from several detectors (smoke, gas, temperature, humidity) to reduce false alarms and enhance early detection performance. Examples include multi-sensor photoelectric alarm devices for campsites that dynamically adjust detection thresholds based on ambient conditions (Lee et al., 2024) and transfer-learning frameworks that classify incipient fire scenarios using multi-sensor nodes in standardised test rooms (Solórzano et al., 2024). While these solutions achieve impressive detection accuracy and robustness, they typically require more sophisticated hardware, data-processing capabilities, and calibration procedures that are beyond the scope of low-budget, stand-alone devices.

In contrast to smoke- and gas-based detection, optical flame sensors measure the ultraviolet and infrared radiation emitted by open flames and can provide rapid response in scenarios where combustion begins with heat and light but produces little or delayed smoke. Prior work indicates that flame-based detection can outperform smoke sensors in specific settings—such as localised ignition in laboratories, small rooms, or areas with frequent aerosols—by triggering alarms as soon as a visible flame is present rather than waiting for smoke accumulation (Khan et al., 2022; Lee et al., 2024). Nevertheless, many flame-based systems described in the literature are either part of complex multi-sensor architectures or are tightly coupled with suppression mechanisms, which again increases cost and design complexity.

1.1 Research Gap and Motivation

Taken together, the existing body of work reveals an imbalance between high-end, multi-sensor or IoT-based fire-detection systems and the practical needs of small offline environments. There is still a lack of simple, stand-alone, flame-only detection platforms that:

- operate entirely offline, without Wi-Fi, GSM, or cloud connectivity;
- avoid smoke and gas sensors, which are prone to nuisance triggers in aerosol-rich settings;
- exclude mechanical ventilation components such as fans and pumps, reducing cost and maintenance;
- are sufficiently low-cost, transparent, and easy to assemble to be used as educational prototypes in engineering and health-physics laboratories.

In particular, educational and training environments require platforms that students can build, program, and test themselves, while still adhering to basic principles of safety engineering and early warning. For such contexts, a lightweight, flame-sensor-based alarm device that provides immediate local audible and visual alerts—without any remote infrastructure—can serve both as a didactic tool and as a practical safety enhancement.

1.2 Aim and Contributions of This Study

In response to this gap, the present study focuses on the design, development, and experimental evaluation of an Arduino-based fire-alarm system that:

1. Operates as a fully stand-alone unit: the device works entirely offline, without any internet, Wi-Fi, GSM, or IoT modules, and does not incorporate smoke, gas, or temperature sensors, nor any exhaust fans or pumps.
2. Relies exclusively on an infrared flame sensor for early flame detection, using a simple threshold-based control algorithm implemented on an Arduino Uno microcontroller.
3. Provides purely local alerts through a buzzer, a high-intensity warning LED, a status LED, and an LCD display that communicates real-time system messages and alarm states.
4. Targets low-resource, small-scale environments, such as educational laboratories and small residential rooms, where the primary requirement is immediate on-site notification rather than remote monitoring.

The specific contributions of this work can be summarised as follows:

- Design and implementation of a compact, low-cost, stand-alone fire-alarm prototype that uses a single infrared flame sensor integrated with an Arduino

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Uno and basic alerting components, deliberately avoiding network connectivity and mechanical ventilation.

- Experimental evaluation of the prototype's responsiveness, detection range, and susceptibility to false alarms under different non-flame conditions (for example, steam, dust, heat sources without combustion, and ambient light changes) in a confined indoor test setup.
- Practical design guidelines for sensor placement, distance, and threshold tuning to achieve reliable flame detection with minimal false alarms in small indoor spaces.
- Discussion of future extensions, outlining how the current stand-alone platform can be scaled into more advanced systems by adding multi-sensor inputs or optional wireless modules, while preserving its educational value and low-cost character.

This paper is described in other sections and it is organized as follows. The problem statement and research aims, complemented with the general methodological approach are presented in Section 2. Hardware design, system architecture, and implementation procedure are presented in Section 3. Experimental results from controlled tests are presented in Section 4. Section 5 comments on the results based on related research and describes strengths and limitations of the proposed system. Finally, Section 6 summarises the paper and suggests avenues for future work.

Methodology

2.1. Problem Statement

However, traditional fire detection systems, especially those based on smoke and heat sensors, still have a number of major shortcomings which hinder their potential to deliver timely and accurate early warning. Optical smoke detectors are often triggered by non-fire triggers, e.g., dust, steam, or cooking aerosols, which can have a great impact on high nuisance alarms occurrences and "alarm fatigue," which occurs when indoor occupants start to ignore or doubt alarm signals (BRE Group, 2018; Fernandino et al., 2020).

Moreover, smoke-based detectors require that smoke accumulate and transport towards the sensor location before triggering, which is inherently slow in detecting the early-stage fire, particularly in a ventilated or geometrically complex indoor environment (Khan et al., 2022). Air quality in microlabs, workshops, and residential spaces is often variable, aerosols are common, and quick evacuation or manual intervention is needed. Moreover, air-flows, ceiling heights, and room dimensions are environmental factors that may delay smoke transport (Khan et al., 2022; Solórzano et al., 2024), resulting in additional delays in detectability and allowing fires to grow before alarms are raised, beyond their incipient phase. Simultaneously, sophisticated IoT-based solutions that include wireless communication, cloud platforms, and smartphone alerts necessitate stable connectivity of networks, increased initial expense, and more sophisticated maintenance processes likely not to be possible in numerous low-resource settings (Rahman et al., 2022; Fernandino et al., 2020).

Such limitations are aggravated within educational and training environments and systems should be reliable, transparent, low cost and easy to build and understand by students. The present study suggests a clear demand for a basic, stand-alone flame-based detection platform that works entirely offline, avoids the nuisance triggers associated with smoke or gas sensors, and can be used as a reliable functional proof-of-concept in the laboratory or small indoor environments.

2.2 Research Objectives

In light of the above problem, this study pursues the following specific objectives:

1. To design and develop a low-cost, stand-alone fire-detection system that operates entirely offline, without internet, Wi-Fi, GSM, or cloud connectivity, and relies exclusively on an infrared flame sensor for early flame recognition.
2. To implement a simple and robust alerting mechanism based solely on local audible and visual indicators—namely a buzzer, a warning LED, a status LED, and an LCD display—to ensure immediate on-site notification without dependence on mechanical ventilation components or external infrastructure.
3. To experimentally evaluate the performance of the proposed system in a confined indoor environment, including its detection responsiveness, effective sensing range, and susceptibility to false alarms under different non-flame conditions such as steam, dust, ambient light changes, and heat sources without combustion.
4. To derive practical design guidelines for sensor placement, threshold tuning, and prototype configuration that can inform future implementations of low-cost, flame-based fire-alarm devices in educational and low-resource settings.

These objectives collectively aim to bridge the gap between complex multi-sensor or IoT-based fire-detection solutions and the practical needs of small offline environments that require simple, reliable, and easily reproducible fire-alarm platforms.

2.3 Overall Methodological Approach

To achieve the above objectives, the study adopts an experimental prototyping methodology comprising four main phases: system specification, hardware and software design, prototype implementation, and performance evaluation.

1. System specification

Based on the literature review and the identified research gap, functional and non-functional requirements for the fire-alarm system were defined. Functionally, the device should continuously monitor for the presence of open flames and

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trigger immediate local alerts upon detection. Non-functional requirements include low cost, stand-alone operation without any form of network connectivity, and sufficient simplicity for deployment in educational laboratories. These requirements were informed by prior work on sensor-based fire detection and low-cost microcontroller platforms (Khan et al., 2022; Rahman et al., 2022; Myint and Zaw Tun, 2020).

2. Hardware and software design

A system architecture was then developed that integrates an Arduino Uno microcontroller with an infrared flame sensor, a buzzer, red and blue LEDs, an LCD display, and a 9 V battery supply. The microcontroller is responsible for continuously sampling the digital output of the flame sensor, comparing it against a predefined detection threshold, and controlling the alerting components. A simple threshold-based algorithm was implemented in the Arduino programming environment to minimise computational complexity and ensure deterministic behaviour. The hardware configuration and control logic were guided by standard practices in embedded system design and by recent microcontroller-based fire-alarm prototypes reported in the literature (Rahman et al., 2022; Myint and Zaw Tun, 2020).

3. Prototype implementation

The designed system was first assembled on a breadboard using jumper wires to interconnect all components, enabling rapid iteration and troubleshooting. Once stable operation was achieved, the wiring layout was documented to support reproducibility and potential PCB-based implementations in future work. The Arduino sketch (firmware) was uploaded via USB and tested iteratively to verify correct sensor readings, LED behaviour, buzzer activation, and LCD messaging across different operating conditions.

4. Experimental performance evaluation

Finally, the prototype was evaluated in a confined indoor test environment representative of small laboratory or residential conditions. A series of controlled experiments was conducted to characterise:

- Detection responsiveness and range, by exposing the sensor to small flame sources (for example, a lighter or candle) at varying distances and recording the time between flame appearance and alarm activation.
- False-alarm behaviour, by subjecting the system to non-flame conditions such as steam, dust, ambient light variations, and heat sources without combustion, and registering any unintended activations.
- Operational stability under battery power, by monitoring system behaviour and LCD messages over repeated tests to identify any voltage-related performance degradation.

The collected experimental observations provide the basis for the quantitative and qualitative analysis reported in the Results and Discussion sections. Through this methodology, the study aims to demonstrate the feasibility and practical advantages of a simple, stand-alone, flame-sensor-based fire-alarm system for low-resource and educational environments, while also identifying its limitations and opportunities for further enhancement.

3. System Design and Implementation

3.1 Hardware Components

The proposed fire-alarm system was implemented using low-cost, readily available electronic components that can be easily assembled in a laboratory or educational setting. The main hardware elements are as follows:

- Arduino Uno microcontroller: central processing unit of the system. It reads the flame sensor output continuously, executes the detection algorithm, and operates the alerting devices.
- Infrared flame sensor: detects infrared radiation from open flames in a defined spectral range and distance. The output of the sensor is digital, whose state switches when the value of the measured signal surpasses a pre-defined limit.
- Red LED (warning indicator): lights a visual alarm signal when a flame is detected. It is powered by the digital output pin of the Arduino through a current-limiting resistor.
- Blue LED (status indicator): signifies standby working operation is normal except for a suspicious flame. In normal situations, this LED turns on and then turns off or alters behavior (e.g., blinking) when an alarm is sounded.
- Buzzer (acoustic alarm): generates an audible alert to monitor flame detection. The buzzer is powered by the Arduino digital output pin and is on together with the red LED.
- LCD display (character display): shows real-time system messages like “System ON,” “Standby,” or “Flame detected,” giving users more feedback. To minimize wiring complexity here, a standard 16×2 character LCD was utilized with an I2C interface.
- 9 V battery: to provide portable DC power to the Arduino board and all peripherals attached with it, enabling stand-alone operation without the need for an external power adapter.
- Breadboard and jumper wires: a versatile platform for wire installation and testing that can be quickly changed, debugged before any practical movement towards a printed circuit board (PCB) implementation of the circuit.The selection of these components was guided by the design requirements of low cost, simplicity, and ease of replication in educational laboratories, while still achieving reliable flame detection and local alarm functionality.

3.2 System Architecture and Operation

The overall system architecture consists of the Arduino Uno, which interacts directly with the flame sensor, LEDs, buzzer, and LCD display. In the final configuration, the flame sensor is connected to one of the Arduino’s digital input pins, while

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the red LED, blue LED, and buzzer are connected to separate digital output pins via appropriate current-limiting resistors or driver circuitry. The LCD is connected via the I2C interface (SDA and SCL pins), reducing the number of microcontroller pins necessary.

In standard operation, when no flame is present within the sensor's field of view, the flame sensor output remains in its default (no-fire) state. The Arduino continuously polls this input and keeps the blue LED illuminated and displays a status message on the LCD, such as "System ON – No Flame." The buzzer remains off and the red LED is not activated. Once an open flame reaches the sensor's detection range and produces sufficient infrared radiation, the sensor output changes state, indicating a potential fire condition.

The Arduino registers this transition and instantly makes the system switch to alarm mode. In this state, the red LED is ON (or made to blink), the buzzer is activated to generate an audible warning, and the LCD displays a clear alarm message such as "Flame Detected – Warning." This structure makes sure the device behaves like a stand-alone local alarm system. All sensing, decision-making, and alerting capabilities are included at the microcontroller and associated parts, with no internet connection, no external servers, and no mechanical ventilation including fans or pumps required.

3.3 Software Design and Control Algorithm

The control logic was implemented using the Arduino integrated development environment (IDE) in the C/C++ programming language. The software structure follows a standard embedded development pattern composed of an initialisation phase and a continuous main loop.

During the initialisation phase (setup function), the Arduino configures the digital pins associated with the flame sensor, LEDs, and buzzer as inputs or outputs, respectively. The LCD interface is also initialised, and an initial status message (for example, "System Initialising" followed by "System ON – No Flame") is displayed to confirm that the device is ready for operation.

In the main loop (loop function), the Arduino performs the following steps repeatedly:

1. Read the digital state of the flame sensor input.
2. Compare the sensor state against the expected no-flame condition.
3. If the sensor indicates no flame:
   - Ensure that the blue LED (status indicator) remains on.
   - Turn off the red LED and the buzzer.
   - Display or maintain a standby message on the LCD (for example, "System ON – No Flame").
4. If the sensor indicates the presence of a flame:
   - Activate the red LED (steady or blinking) as a visual alarm.
   - Activate the buzzer as an audible alarm.
   - Optionally turn off or change the behaviour of the blue LED to emphasise the alarm state.
   - Update the LCD message to indicate flame detection (for example, "Flame Detected – Warning").
5. Introduce a small delay, if necessary, to debounce the sensor signal and avoid excessive LCD updates, while ensuring that the overall response time remains sufficiently fast for early detection.

This simple threshold-based algorithm was chosen to minimise computational overhead and to maintain deterministic, transparent behaviour suitable for educational use. More advanced processing, such as dynamic thresholding or temporal filtering, can be incorporated in future iterations if required, but were not the focus of the present prototype.

3.4 Implementation Procedure

The implementation of the proposed system followed a sequence of practical steps designed to ensure correct operation and reproducibility:

1. **Circuit assembly**
   All electronic components were first mounted on a solderless breadboard. The flame sensor, LEDs, buzzer, and LCD were connected to the Arduino Uno using jumper wires according to the planned wiring schematic. Care was taken to respect polarity, supply-voltage limits, and current ratings for each component, and to include appropriate series resistors for the LEDs.

2. Firmware development and upload
   The control program was written in the Arduino IDE, following the logic described in Section 3.3. The code included pin assignments, LCD initialisation, sensor reading routines, and condition-based control of the LEDs and buzzer. After compilation and verification, the firmware was uploaded to the Arduino Uno via a USB connection.

3. Functional verification
   Initial tests were conducted to confirm basic functionality. With no flame present, the system was checked to ensure that the blue LED was on, the red LED and buzzer were off, and the LCD correctly displayed the standby message. Subsequently, a small open flame (for example, from a lighter or candle) was introduced within the sensor's detection range. The system's response was observed to verify that the alarm behaviour (red LED, buzzer, and LCD warning message) was triggered promptly and consistently.

4. Refinement and documentation
   Based on the initial tests, minor adjustments were made to the code (for example, delays or message formatting) and, where necessary, to the wiring layout to improve stability and clarity. The final wiring configuration and software were documented to facilitate replication of the prototype in other laboratory settings or future design iterations.

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This implementation procedure resulted in a fully operational, stand-alone fire-alarm prototype that could be powered from a 9 V battery and used as the basis for the experimental performance evaluation described in the subsequent Results section.

4. Results

4.1 Experimental Test Conditions

The prototype was evaluated in a confined indoor room representative of a small laboratory or residential space. The primary aim of the experiments was to verify that the system can detect open flames within a realistic operating range, remain stable in the presence of typical non-flame disturbances, and operate reliably when powered by a 9 V battery.

To provide a clear structure, the tests were divided into two main groups:

- **Flame scenarios**, in which a small open flame (for example, from a lighter or candle) was introduced at different distances and positions within the sensor's field of view.
- **Non-flame scenarios**, in which the system was exposed to steam, dust or aerosols, heat sources without visible flames, and changes in ambient lighting.

A concise overview of the experimental conditions and qualitatively observed outcomes is given in Table 1.

Table 1. Summary of experimental scenarios and observed outcomes

Scenario ID	Condition type	Description	Observed system behaviour
F1	Flame	Small open flame at short distance (near range)	Alarm triggered promptly (red LED, buzzer, LCD warning)
F2	Flame	Small open flame at medium distance	Reliable alarm activation within the sensor field of view
F3	Flame	Small open flame at longer practical distance	Alarm activation as long as the flame remained clearly visible
NF1	Non-flame	Steam or water vapour released near the sensor	No alarm; system remained in standby mode
NF2	Non-flame	Dust or aerosol disturbance in front of the sensor	No alarm; system remained in standby mode
NF3	Non-flame	Heat source without visible flame (for example, heater)	No alarm; system remained in standby mode; no response to heat alone
NF4	Non-flame	Ambient light variations (lights on/off, torch, lamp, etc.)	No alarm; system remained in standby mode; no response to illumination changes

4.2 Flame-Detection Performance

In all flame-related situations (F1–F3), it was found that the system is responsive consistently to the presence of a visible open flame in the sensor field of view. The moment the flame was introduced from a short distance (Scenario F1), that switch from standby to alarm became entirely instantaneous and pragmatic: once the flame was seen for the sensor the flame sensor output changed state, the Arduino triggered the red LED, activated the buzzer, and updated the LCD to display a clear warning message.

At medium distance (Scenario F2), the system continued to detect the flame reliably, provided that the flame remained reasonably stable and oriented towards the sensor. The qualitative response remained rapid, with no noticeable delay between the visible appearance of the flame and activation of the alarm.

At longer practical distance (Scenario F3), within the limits of a small room, the system still detected the flame correctly as long as the flame was clearly visible and not severely obstructed. In these cases, alarm activation remained prompt, although the sensitivity naturally decreased when the flame was moved towards the edges of the sensor's effective field of view.

Table 2 summarises the flame-detection behaviour as a function of qualitative distance levels.

Table 2. Qualitative flame-detection performance at different distances

Distance level	Qualitative distance description	Flame condition	Observed detection behaviour
D1	Near range	Flame directly in front of the sensor, short distance	Immediate and consistent alarm activation
D2	Medium	Flame	Rapid and

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	range	within central field of view	reliable alarm activation
D3	Longer practical distance within a small room	Flame near the limit of effective field of view	Alarm activation while the flame remained clearly visible

Overall, these observations indicate that the infrared flame sensor, combined with the simple threshold-based control algorithm, is sufficient to achieve rapid and reliable recognition of open flames in the targeted application context of small indoor environments.

4.3 Behaviour under Non-Flame Conditions

A central objective of the proposed design was to reduce nuisance activations compared with smoke- or aerosol-based detectors. In the non-flame scenarios (NF1–NF4), the system was deliberately exposed to conditions that commonly cause false alarms in conventional smoke detectors.

When steam or water vapour was released in front of the sensor (Scenario NF1), the system remained in standby mode: the blue LED stayed on, the red LED and buzzer remained inactive, and the LCD continued to display the normal “no flame” status message. Disturbances caused by dust or aerosols near the sensor (Scenario NF2) likewise did not trigger any unintended alarms.

In all flame-related situations (F1–F3), it was found that the system is responsive consistently to the presence of a visible open flame in the sensor field of view. The moment the flame was introduced from a short distance (Scenario F1), that switch from standby to alarm became entirely instantaneous and pragmatic: once the flame was seen for the sensor the flame sensor output changed state, the Arduino triggered the red LED, activated the buzzer, and updated the LCD to display a clear warning message.

Table 3 provides a consolidated view of the system behaviour under the non-flame conditions examined.

Table 3. System behaviour under non-flame conditions

Scenario ID	Condition description	Observed system behaviour
NF1	Steam or water vapour near the sensor	No alarm; blue LED on, red LED off, buzzer off, normal LCD status
NF2	Dust or aerosol disturbance in front of the sensor	No alarm; system remained in standby mode
NF3	Heat source without visible flame (for example, heater)	No alarm; system did not respond to heat alone
NF4	Ambient light variations (lights, torch, lamp, etc.)	No alarm; no response to illumination changes; system stayed in standby mode

Collectively, the non-flame tests demonstrate that the prototype is low in the presence of nuisance alarms for the tested settings. This qualitative behaviour suggests that the flame-based technique is suitable for use in scenes where smoke detectors could misinterpret nonhazardous aerosols, vapour, or changes in lighting as the presence of a fire.

4.4 Power Supply and Operational Stability

For the entire experimental campaign, the whole system was powered through a 9 V battery connected to the Arduino Uno and other peripherals (flame sensor, LEDs, buzzer, and LCD). In repeated trials in flame and non-flame conditions, the prototype was stable and failed to restart unexpectedly, which is useful for monitoring the system. When left in standby, the blue LED remained lit and the LCD showed the standard status message, which implies that the microcontroller and peripherals were working fine as expected. When a flame appeared in the sensor’s field of view, the shift to alarm mode was a smooth one: the red LED lit as intended, a buzzer warned us clearly, and the LCD updated immediately to show the alarm message. The standby status without hysteresis or oscillation was restored when the flame had been extinguished. From a practical point of view, these results of the experiment indicate that this design can be used as a portable power unit, which is possible for certain devices in locations with limited or unavailable fixed power. While quantitative analysis of battery duration is beyond the scope of this preliminary prototype, the stability over many tests suggests that the hardware configuration is suitable for small indoor small to medium-duration deployments.

5. Discussion

The experiment shows that the stand-alone fire detection system based on an infrared flame sensor could detect the presence of open flames quickly and effectively in confined indoor spaces. The flame sensor had very good sensitivity to the infrared emission of fire sources thus triggering an alarm instantly without the need for smoke accumulation or temperature elevation. The simplicity of the system's design and its lack of connection to any existing infrastructure has been one of its main strengths. As it does not demand internet connectivity, some mechanical ventilation devices such as fans and smoke sensors, there is a strong need and good fit for low-resource environments, small labs, and school projects. Also, the test evidence showed that without flame stimuli (heat sources that are not generating combustion, other types of ambient lighting, steam, dust), the system does not make a false alarm and therefore became very reliable. The device also exhibited consistent performance when powered with a 9-

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volt battery, without noticeable voltage drops impacting the flame sensor, alarm buzzer, and LED indicators. This is an indicator that portable power is applicable to locations without stable electrical facilities. Moreover, the simplicity of the control algorithm allowed consistent behavior of output and thus reduction of the chance of operational error. Nevertheless, certain limitations must be acknowledged. The capability of the system completely relies upon direct flame visibility within the sensor's detection range. It is possible that fires that start off as smoldering combustion without flames may not be identified until flames grow visible. In addition, the output of the sensor is affected by the distance and angle which may limit its coverage in larger areas unless a number of sensors or mounting configurations are employed. Another limitation on detection is the dependence on local alarms (buzzer and LED indicators), the latter not being as effective without occupants present. In general, results validate that a flame detection method is possible and beneficial in cases where smoke detectors can be impractical and in which a low-cost offline solution is required. Based on the existing state-of-the-art technologies, the system allows for further developments (e.g., installation of more sensors, expanding system coverage, improving detection algorithms, adding wireless communication modules to allow for remote notification as needed when resources permit).

Discussion and Conclusion

The results of this study show that a basic, stand-alone fire alarm system with an infrared flame sensor and an Arduino Uno microcontroller is capable of fast and accurate detection of open flames in a small indoor scene and is less likely to cause nuisance activations in typical non-flame environments. Unlike the standard smoke sensors, which are vulnerable to false alarms arising from aerosols, steam, and dust, as well as the delay in triggering due to the time required for smoke to accumulate at the sensing point (BRE Group, 2018; Khan et al., 2022), the proposed prototype responded promptly whenever a visible flame entered the sensor's field of view and did not respond differently with qualitative exposure to steam, dust, non-flame heat, as well as lighting variation.

The previous work also shows that optical flame detection can provide an advantage in scenarios where combustion starts with heat and light but produces little or delayed smoke (Khan et al., 2022; Lee et al., 2024) and more recent attempts in enhancing the safety of the fire-alert system with selective sensing strategies (Solórzano et al., 2024). Furthermore, these solutions do not require the complexity, cost, or dependence on network infrastructure associated with IoT-based fire-alarm solutions (Rahman et al., 2022; Fernandino et al., 2020) and it also excludes mechanical ventilation, smoke or gas sensors, and remote communication components.

Thus, it is a unique hybrid between the traditional, stand-alone smoke detectors and the larger-scale multi-sensor or networked platforms and presents a lightweight, low-cost alternative solution that is especially suitable for educational laboratories and other low-resource environments where immediate local warning rather than remote monitoring is most important. From the educational point of view, as the hardware and software design of the prototype is transparent, this design as a prototype is useful for teaching engineering and health-physics students who can inspect, modify and extend the system while gaining practical knowledge about embedded programming and safety engineering concepts.

However, there are a few caveats: the system works by identifying only visible flames and does not work on purely smouldering or smoke-dominant fires, effective coverage is limited by the sensor's distance and field-of-view, and the system performance has been tested qualitatively rather than through extensive quantitative testing. Consequently, future work will focus on systematically measuring detection range, response time, false alarm rates, and battery lifetime under controlled conditions, as well as investigating modular extensions that add additional sensors (such as temperature or smoke) or optional wireless communication, to keep the core benefits of simplicity, low cost, and stand-alone operation of our proposed configuration.

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*Corresponding Author: **Alaa Majed** .
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