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AI Based Fire Safety Monitoring in Buildings Smoke/Heat Detection using AI Sensors

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Abstract - Fire detection systems have traditionally relied on single-parameter sensing mechanisms such as smoke or heat detection, which often result in delayed response and high false alarm rates. Recent advancements in Internet of Things (IoT) and computer vision have enabled the development of intelligent fire monitoring systems capable of real-time analysis and multi-parameter evaluation. In this study, an integrated fire detection system is proposed that combines multi-sensor environmental monitoring with image-based fire detection and IoT communication.

The system utilizes an ESP32 microcontroller connected with MQ-2 smoke and DHT11 temperature sensors, along with an ESP32-CAM module for visual monitoring. Data is transmitted through a wireless network and processed using Python-based algorithms. An intelligent decision-support framework correlates real-time sensor measurements with visual feature extraction outputs to confirm fire conditions reliably and reduce false alarms.

The experimental results demonstrate that the proposed system achieves reliable fire detection with low latency and improved accuracy compared to traditional systems. The system also supports real-time monitoring and alert generation, making it suitable for practical deployment in residential and industrial environments.

Key words - Fire Detection, Internet of Things (IoT), Multi-Sensor Fusion, ESP32, Real-Time Monitoring.

1. INTRODUCTION

Fire safety remains one of the most critical concerns in modern infrastructure and building engineering due to the increasing frequency of fire-related accidents in residential, commercial, and industrial environments. Fire incidents can result in significant human casualties, damage to structural components, interruption of essential services, and large economic losses. Rapid urbanization and the growth of high-rise buildings, warehouses, transportation terminals, hospitals, and smart city infrastructure have increased the complexity of fire safety management, making early detection and monitoring a necessary requirement in civil engineering practice (Hall et al., 2010; Ahrens, 2019).

Traditional fire detection systems generally rely on standalone smoke detectors, heat sensors, and manual alarm systems that operate using fixed threshold values. Although such systems are widely used, they often detect fire only after smoke density or temperature exceeds critical levels, which may delay warning signals during the early stages of ignition. Additionally, conventional detectors frequently generate nuisance alarms due to non-fire conditions such as dust, steam, cooking vapours, humidity variation, and aerosol particles. Such false alarms reduce trust in alarm systems and may lead to negligence during actual emergency situations (Gottuk and Lattimer, 2008; Milke and Hulcher, 2003; Cestari et al., 2010).

Recent advancements in Artificial Intelligence (AI) and computer vision have created new opportunities for improving fire monitoring systems. AI-based methods can analyze patterns in sensor outputs and visual information to detect fire more efficiently than conventional threshold-based approaches. In building safety applications, AI is increasingly used for real-time monitoring, anomaly detection, decision automation, and emergency response optimization (Wang & Li, 2021; Li et al., 2022). Computer vision-based flame and smoke detection techniques are particularly effective because they can identify visible fire signatures such as flame flicker, smoke movement, and abnormal color distributions earlier than physical sensors alone (Toreyin et al., 2006; Celik and Demirel, 2009; Elhanashi and Zheng, 2021).

At the same time, the Internet of Things (IoT) has enabled the development of smart infrastructure systems where embedded sensors continuously collect real-time environmental data and transmit it to monitoring dashboards through wireless networks. IoT-based fire monitoring

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systems provide remote supervision, real-time alert generation, and faster emergency response, which is highly useful for modern civil infrastructure management (Gubbi et al., 2013; Atzori et al., 2010; Sethi and Sarangi, 2017).

However, many existing systems still suffer from either high computational requirements or limited reliability due to dependence on a single detection mechanism. Systems based only on smoke sensors may generate false alarms, while vision-only systems may misinterpret sunlight reflections or fire-like objects. Therefore, recent research emphasizes multi-sensor fusion and intelligent decision frameworks that integrate sensor measurements with visual feature extraction to confirm fire events with higher accuracy (Lu et al., 2018; Deng et al., 2023; Liu et al., 2024).

In this study, an AI-based fire safety monitoring system is proposed that integrates smoke sensing, temperature monitoring, and camera-based fire recognition using ESP32 and ESP32-CAM modules. The core contribution of the system lies in the development of an intelligent decision-support framework that correlates real-time sensor data with visual feature extraction for reliable fire confirmation. This fusion-based confirmation improves detection reliability and significantly reduces false alarms. The proposed system also supports IoT-enabled wireless communication, making it suitable for practical deployment in homes, offices, hostels, laboratories, and small industrial facilities.

2. METHODOLOGY

The methodology adopted in this study is designed to develop a comprehensive fire detection system that integrates sensing, communication, processing, and decision-making components. Unlike conventional systems that rely on a single parameter, the proposed methodology incorporates multiple layers of analysis to improve detection accuracy and system reliability.
The overall framework consists of five major objectives, each contributing to a specific functional component of the system. These include image-based fire detection, multi-sensor environmental monitoring, IoT communication, fusion-based risk assessment, and system performance evaluation. The integration of these components ensures real-time operation and robust performance under varying environmental conditions.

The first stage focuses on developing a lightweight and efficient fire detection model using image processing techniques. The ESP32-CAM module captures real-time images, which are transmitted to a Python-based processing environment. The methodology involves converting images from RGB to HSV color space, which allows better separation of color components associated with fire, such as red, orange, and yellow hues.
Thresholding techniques are applied to isolate fire-like regions, and pixel intensity analysis is performed to quantify the presence of fire. The algorithm identifies regions with high intensity and dynamic variation, which are characteristic of flames. This approach enables real-time detection with minimal computational overhead, making it suitable for embedded systems.

The second stage involves the implementation of a multi-sensor monitoring network using MQ-2 smoke and DHT11 temperature sensors. The sensors are connected to the ESP32 microcontroller, which continuously collects environmental data. Calibration is performed to establish baseline values and determine threshold limits for fire detection.
The sensor data is processed to remove noise and fluctuations using smoothing techniques. The system monitors trends in temperature and smoke levels over time, enabling early detection of abnormal conditions. The integration of multiple sensors enhances system reliability and reduces dependence on a single parameter.

The third stage focuses on enabling real-time data transmission using IoT technology. The ESP32 microcontroller establishes a Wi-Fi connection and transmits sensor data to a Python-based processing system. The ESP32-CAM module streams video data using HTTP protocol, allowing real-time monitoring.
The communication system is designed to ensure low latency and reliable data transfer. Structured data formats are used to facilitate efficient parsing and processing. The IoT framework also supports remote monitoring, enabling users to access system data from different locations.

The fourth objective of this study focuses on developing an intelligent decision-support framework that correlates real-time sensor readings with visual feature extraction for reliable fire confirmation. The purpose of this framework is to reduce false alarms and increase detection confidence by ensuring that fire alerts are triggered only when multiple indicators validate the presence of fire. Since standalone smoke or temperature sensors may produce incorrect alarms due to dust, humidity, or temporary environmental fluctuations, and camera-based systems may be affected by lighting variations, a fusion-based confirmation mechanism becomes essential.
In the proposed system, smoke concentration values from the MQ-2 sensor and temperature readings from the DHT11 sensor are continuously collected through the ESP32 microcontroller. Simultaneously, the ESP32-CAM captures

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real-time image frames, which are processed in a Python environment using HSV color segmentation to extract flame-like features such as high red-orange pixel intensity distribution. These extracted visual features act as confirmation evidence.

The decision-support framework synchronizes sensor values with visual detection outputs and applies rule-based fusion logic. The system confirms fire only when sensor parameters exceed predefined thresholds along with the detection of flame-like regions in the camera feed. This multi-parameter correlation significantly improves reliability compared to independent sensor-based detection. Additionally, temporal validation is applied by checking persistent abnormal patterns across multiple consecutive readings to avoid false triggering due to momentary disturbances.

The final decision is categorized into three safety states: Safe, Warning, and Critical. The Warning state is activated when abnormal sensor trends are detected without strong visual evidence, whereas the Critical state is triggered when both sensor and camera-based confirmation indicate fire. This graded classification enhances decision-making quality and supports early intervention before severe fire escalation.

Table 1: Methodological Framework of the Study

Stage	Approach	Components/Tools
Fire detection	Image processing	ESP32-CAM, Python
Environmental Monitoring	Multi-sensor data acquisition	MQ-2 Smoke Sensor, DHT11, ESP32
IoT Communication	Wireless data transmission	ESP32, Wi-Fi module, Python server
Intelligent Decision-Support Framework	Fusion based confirmation logic	Python processing unit
Performance Evaluation	Testing & analysis of system metrics	Experimental setup, graphs

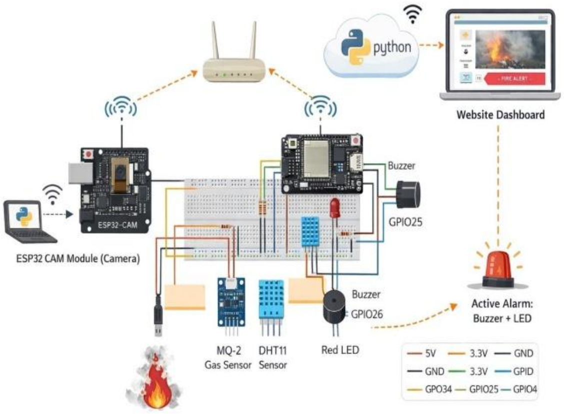

Figure 1: IoT-Based Fire Detection and Monitoring System

3. RESULTS AND DISCUSSION

The experimental evaluation of the proposed fire detection system was carried out under controlled and semi-realistic environmental conditions to assess its performance in terms of detection accuracy, response time, reliability, and robustness. The system integrates multiple components, including environmental sensors, image processing algorithms, IoT communication modules, and a fusion-based decision layer. The objective of the evaluation was to verify whether the system can reliably detect fire conditions while minimizing false alarms and maintaining real-time responsiveness.

During testing, three primary scenarios were considered: normal environmental conditions, presence of smoke without fire, and actual fire conditions. These scenarios were designed to replicate real-world situations where conventional fire detection systems often fail due to ambiguity in sensor readings. The results obtained from these experiments were analysed using both graphical and tabular representations to provide a comprehensive understanding of system performance.

The system demonstrated stable operation under normal conditions, with minimal fluctuations in sensor readings. When smoke or heat sources were introduced, the system responded with gradual increases in sensor values, indicating its sensitivity to environmental changes. Under fire conditions, a rapid increase in both sensor readings and image-based detection parameters was observed, leading to quick and accurate detection.

The image-based fire detection module was evaluated using real-time video frames captured by the ESP32-CAM module. The detection algorithm, based on HSV color segmentation, was applied to identify fire-like regions within each frame. The algorithm calculates the number of

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pixels corresponding to fire-like colors, which serves as a key indicator of fire presence.

Table 2: Fire Pixel Count Variation

Frame No.	Pixel Count
1	120
2	180
3	250
4	600
5	1500
6	3200
7	4800
8	6500

The results show a significant increase in pixel count when fire is present in the scene. Under normal conditions, the pixel count remained relatively low, whereas during fire scenarios, a sharp rise was observed. This indicates that the algorithm is capable of distinguishing fire from non-fire conditions effectively.

The performance of the image-based detection system highlights its ability to operate in real time with low computational requirements. The use of HSV color space provides robustness against minor lighting variations, enabling consistent detection performance. However, it was observed that extremely bright light sources or objects with similar color characteristics may occasionally trigger false positives. This limitation is addressed in the overall system through integration with sensor data, which validates the detection result.

The sensor-based monitoring system was evaluated by recording temperature and smoke levels under different conditions. The MQ-2 sensor responded to smoke presence, while the DHT11 sensor measured temperature variations.

Table 3: Sensor Data Under Different Conditions

Condition	Temperature (°C)	Smoke Level
Normal	30-32	0-1000
Smoke Only	32-38	1000-2500
Fire Condition	40-55	>3500

The results indicate that sensor readings remain stable under normal conditions and increase significantly when smoke or fire is present. The gradual rise in values allows early detection of abnormal conditions.

The multi-sensor monitoring system enhances the reliability of the fire detection process by providing quantitative environmental data. The use of both temperature and smoke sensors ensures that the system does not rely on a single parameter. This reduces the probability of false alarms caused by environmental disturbances such as dust or humidity. Additionally, the system demonstrates the ability to detect gradual changes, which is essential for early fire warning.

The IoT communication system was evaluated based on its ability to transmit data in real time and maintain stable connectivity. The ESP32 module transmitted sensor data, while the ESP32-CAM streamed video to the Python processing unit.

Table 4: Communication Performance Parameter

Parameter	Value
Data transmission interval	2 sec
Average latency	200-300 ms
Packet loss	Negligible

The system maintained stable communication throughout the testing period, with minimal delays and no significant data loss.

The IoT framework ensures seamless data transmission and enables real-time monitoring of environmental conditions. The low latency observed during testing confirms the suitability of the system for time-critical applications such as fire detection. The use of Wi-Fi communication provides flexibility and ease of deployment. Additionally, the system can be extended to cloud-based platforms for remote monitoring and data storage.
The fusion layer integrates sensor data and image detection outputs to classify risk levels. The system evaluates multiple parameters simultaneously to determine whether the condition is safe, warning, or critical.

Table 5: Risk Classification Results

Scenario	Sensor Status	Image Detection	Risk Level
Normal	Low	No fire	Safe

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Smoke only	Medium	No fire	Warning
Fire	High	Fire detected	Critical

The results show that the system accurately classifies risk levels based on combined inputs.

The fusion-based approach significantly improves detection accuracy by validating results using multiple data sources. This reduces false alarms and ensures that alerts are generated only when necessary. The system also demonstrates predictive capability by identifying warning conditions before reaching critical levels.

The overall system performance was evaluated based on response time, detection accuracy, and stability.

Table 6: Performance Metrics

Parameter	Value
Response time	< 2 seconds
Detection accuracy	90-95%
False alarm rate	Low
System stability	High

The system demonstrates high performance in terms of accuracy and response time. The integration of multiple detection mechanisms ensures reliable operation, while the optimization of communication and processing components reduces latency. Compared to traditional systems, the proposed approach provides faster and more accurate detection.

4. CONCLUSION

This study successfully demonstrates the design and implementation of an AI-based fire safety monitoring and detection system by integrating multi-sensor environmental monitoring, real-time image processing, and IoT-based wireless communication. Unlike conventional fire alarm systems that rely on only smoke or heat threshold values, the proposed system provides improved accuracy and reliability by combining multiple parameters for fire confirmation.

The system utilized an ESP32 microcontroller with MQ-2 smoke and DHT11 temperature sensors for continuous environmental monitoring, while an ESP32-CAM module was used for real-time visual surveillance. The visual frames were processed using HSV-based color segmentation to extract fire-related features such as flame-like pixel intensity and color distribution.

A major contribution of this work is the development of an intelligent decision-support framework that correlates real-time sensor readings with visual feature extraction for reliable fire confirmation. This fusion-based confirmation method ensures that fire alerts are generated only when multiple indicators validate the presence of fire, thereby significantly reducing nuisance alarms caused by dust, humidity, cooking fumes, or lighting variations.

Experimental testing demonstrated that the proposed system achieves fast response time, improved detection accuracy, and low false alarm rate compared to standalone detection methods. Additionally, the IoT-based communication framework enabled real-time monitoring and remote alerting, making the system practical for residential buildings, offices, hostels, laboratories, and small industrial environments. Overall, the proposed framework provides a cost-effective, scalable, and intelligent solution for modern building fire safety systems.

Further, the system can be enhanced by implementing deep learning models such as CNN or YOLO for more accurate fire and smoke detection. Cloud integration can be added for long-term data storage and predictive analytics. Additional sensors like CO, flame, and infrared sensors can further improve reliability. A mobile application-based alert system and integration with automatic fire suppression systems can also be developed for advanced real-time emergency response.

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