IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology
Impact Factor 8.311 ⁘ Peer-reviewed & Refereed journal ⁘ Vol. 13, Issue 5, May 2026
DOI: 10.17148/IARJSET.2026.13546

An IoT-Based Smart Smoke Alarm System Using Multi-Sensor Fusion and Intelligent Monitoring for Enhanced Fire Safety

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Abstract: Early detection of fire hazards is essential to minimize loss of life and property in residential and commercial buildings. Traditional smoke alarm systems tend to use a operating system that is based on a single sensor, resulting in a large false alarm rate and lack of situational awareness. In this paper, a smart smoke detector, implemented using Internet of Things (IoT) and multi-sensor fusion, real-time visual and intelligent alert mechanisms to enhance reliability in detecting fire are introduced. The proposed system has a multiple sensors that detect smoke and fire related parameters, thus minimizing false alarms, an integrated web camera, and operated by a servo motor to do a live monitoring of the environment. The predefined floor plan achieves fire localization of the source of fire, which facilitates the evacuation and fire fight work. The functional reliability and practical feasibility of the system is experimentally proven. The proposed solution can be scaled and applicable to implementation in daily residential and commercial locations and is a large improvement over the traditional fire alarm systems.

Keywords: Internet of Things (IoT), Smart Smoke Detector, Fire Safety System, Multi-Sensor Fusion, Intelligible Monitoring, Smart Buildings.

I. INTRODUCTION

Fire accidents are a major hazard to human life, property and infrastructure both in residential, commercial and industrial setups. The costs of building materials and safety checks have improved; however, it is clear that fire-related cases have resulted in high casualties and economic damages all over the world. The prompt reaction and detection of fire is a key aspect of reduction of the fire damage and safe evacuation. Even though conventional smoke alarm systems are commonly used, they have weaknesses such as dependence on single sensor technologies, lack of connectivity and failure to give situational awareness other than audible alerts [1], [9].

The traditional smoke detectors adopt the photoelectric or ionization sensing method to identify smoke particles. Although these are useful in certain fire conditions, false alarms due to cooking smoke, dust or change in humidity levels can be easily triggered by these systems, and this can be followed by alarm fatigue and diminished confidence of the users [1], [9]. In addition, the traditional detectors are also independent devices that cannot be monitored remotely, captured, or linked with the emergency response system, which limits their usefulness in the case of major fires [18].

In recent years, smart sensing and communication technology has become a promising development in terms of upgrading fire detection and monitoring systems in connection with the intensive development of the Internet of Things (IoT). Fire alarm systems based on IoTs allow sending real-time information, sending notifications remotely, and centralized monitoring using a wireless network i.e. Wi-Fi, GSM, ZigBee, and MQTT-based protocols [2], [6], [12], [15]. Such systems go a long way in enhancing the response time as they send instant notifications to occupants and emergency response team personnel even when the users are not within the premises [13].

Recent studies have placed emphasis on enhancing accuracy of detection by use of multi sensor fusion in which data of the smoke, heat and gas sensors are integrated to produce the detection result [9]. The use of multi-signature fire detection algorithms has been observed to minimize false alarms but enhance sensitivity to a smoldering fire and flammable fire [9]. More so, video based smoke and fire detection based on image processing and machine learning processes have received interest in offering early visual verification and situational awareness [3], [17]. Nevertheless, they tend to either be of high computational complexity or expensive hardware, which restricts their implementation.

Smart smoke detection systems can also be expanded to work with smart home systems and building management systems. The integrations permit automated safety measures, including turning off HVAC to stop the spread of smoke, turning on emergency lights, opening exits, and supporting evacuating moves [11], [16]. MQTT and other application-layer protocols are essential in providing efficient resource-constrained IoT devices with low-latency communication [12], [15].

Irrespective of these developments, interoperability of systems, network reliance, privacy, and cost still persist as some of the problems of the mass use of smart fire detection technologies [10], [16]. Thus, a more affordable, scalable and dependable IoT-based smoke detector system that incorporates the detection of multiple sensors, real-time monitoring, and user interfaces is required.

This paper describes the design and implementation of a smart smoke alarm system based on the IoT, which uses multi-sensor fusion to suppress false alarms, a live video monitoring mechanism using a stepper motor-controlled camera, and remote notifications and localization of the fire using a pre-programmed floor plan. The suggested system will be also effective in all the situations both residential and commercial as the program will increase low fire detection, situational awareness, emergency response capacity.

II. RELATED WORK

Fire detection systems, which existed in the early years, have undergone changes in the recent decades moving past the existence of individual smoke detectors to a networked and smart safety systems. Early studies were mainly aimed at increasing the speed of responding by automated alerting system. Asif et al. [1] examined traditional fire detectors and suggested an automated Fire alarm system, which operates on Short Message Service (SMS), thus providing the capability of remote notification when there is an occurrence of fire. Though it was good in enhancing delivery of alerts, the system was based on single sensor input thus was prone to false alarms.

The use of wireless communication technologies is popular to enhance the fire monitoring systems. Fuzi et al. [6] proposed a fire alerting system based on the ZigBee protocols in residential premises so that low power wireless communication can be provided between sensor nodes. On the same note, Islam et al. [14] suggested a ZigBee oriented indoor fire detection system that is localized. ZigBee is energy efficient but on the negative side, it has very low range and can not be extended into large or multi-story buildings. When making comparative studies of wireless protocols, MQTT and Wi-Fi-based systems are noted to be more scalable and lower latency wireless systems to control real-time applications [2], [10], [15].

There has been an interest in the incorporation of gas sensors in fire detection systems that enhance accurate detection. Goldstein [8] has noted the risks of being exposed to carbon monoxide and has reiterated the fact that it is important to detect CO early in confined spaces. Combination of multi-Sensor systems (smoke, temperature, and gas sensors) has been proposed to have a very high reduced false alarms and increased sensitivity to the various fire signature [9]. Gottuk et al. [9] also showed that the multi-signature alarm algorithms are more effective than the conventional single sensor systems in smoldering and flaming fires.

IoT development has additionally changed the fire alarms systems into smart connected systems. The recommendations of Imteaj et al. [13] included IoT-based fire alarming system with the Raspberry PI 3 that provides the facility to monitor the operation real-time and remotely provide alert due to the presence of fire. On the same note, Gaikwad et al. [7] designed a fire monitoring and controlling system, which had remote notification features. Although these systems enhanced connectivity, most of them were not being visually verified and at all alerts interpretation depended on the users.

Videos have also been developed to improve the situational awareness of fire and smoke detection. Chen et al., [3] suggested a smoke detector system, which is a video-processing-based approach to early fire alarming, and Kong et al., [17] suggested a fast flame detector approach based on surveillance video and logistic regression. Video-based systems, though containing useful visual confirmation, tend to be very high-resource in terms of computations and expensive in controlled lighting environments, making them difficult to implement in low-cost or real-time embedded systems.

According to recent studies, the incorporation of smart home and the application-layer protocols in fire detection systems play an important role. The MQTT-based communication has been realized as being a lightweight and efficient protocol to support the constrained IoT devices [12], [15]. Home Assistant platforms provide centralized surveillance, automation, and interaction among intelligent spaces with users [11]. Nonetheless, interoperability, privacy and network dependency issues have not been addressed yet [16].

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Based on the literature, one can note that the various fire detection systems proposed are facing several constraints that include being single sensor based, high false alarms, no real time visualization or small scale, amongst others. This study fills these gaps by suggesting an IoT-based smart smoke alarm system in which the multi-sensor fusion, MQTT-based communication, live video surveillance, and visualization of the real-time dashboard are integrated to increase the accuracy of fire detection and effectiveness of responder efforts.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

A. Overall System Architecture

The proposed smart smoke alarm system follows a layered Internet of Things (IoT) architecture comprising three key modules that include: (i) detector unit, (ii) processing and decision unit and (iii) user notification and surveillance unit. The general architecture aims at offering the reliable detection of fire, minimize false alarms, and automatic response to the emergency in the most timely and appropriate manner.

The detector module contains an ionization smoke detector, temperature and humidity (DHT11) sensor and a carbon monoxide (CO) sensor (MQ-7). These are the sensors that constantly maintain the environmental parameters related to fire hazards. An ESP32 microcontroller accesses and processes sensor data and acts as an edge device in terms of data collection in real-time and wireless communication.

This processing unit is done in Raspberry PI 3 Model B+ with Home Assistant (Hass.io) and Node-RED. This unit undertakes decision making through rules, data aggregation, data visualization and storing data on the cloud. The MQTT publish/subscribe protocol is used to provide communication between the processing unit and the detector unit and is well-fit when it comes to dealing with low-latency and resource-constrained IoT applications [12], [15].

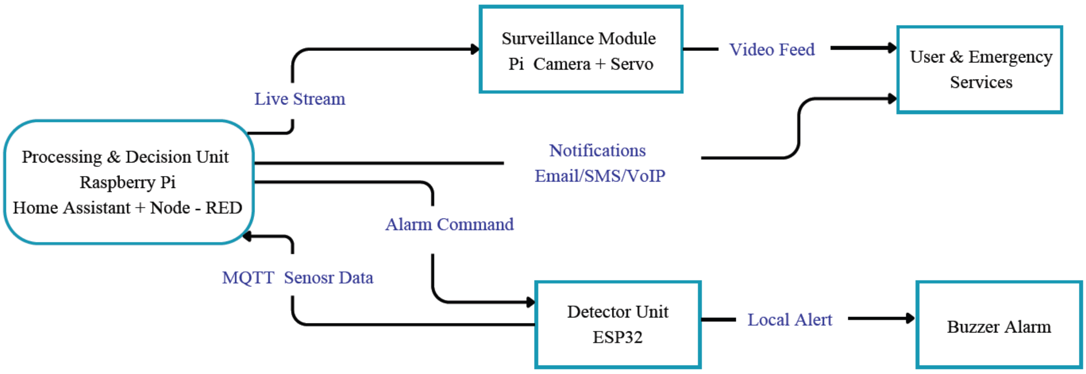

Fig. 1. Overall architecture of the proposed IoT-based smart smoke alarm system

B. Detector Unit Design

The detector unit will detect fire related parameters and will also provide immediate local alarm. Several sensors can be used to optimize their accuracy in detection as well as minimizing false alarms, based on the idea of multi-signature fire detection described in [9].

Ionization smoke detector is applicable in quick apprehension of a fast blaze and the MQ-7 sensor detects the carbon monoxide level which is an essential signal of the imperfect combustion [8]. The sensor of DHT11 offers information on temperature and humidity, which is why it is possible to infer on the environmental context and make the correct choice.

A passive buzzer will be attached to the ESP32 to issue audible alarm on the occurrence of critical thresholds passing or when a remote alarm signal is sent by the processing engine.

Table I: Sensors Used in the Detector Unit

Sensor	Parameter Measured	Purpose
Ionization Smoke Detector	Smoke particles	Early fire detection
MQ-7	Carbon monoxide (ppm)	Combustion confirmation

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DHT11	Temperature (°C), Humidity (%)	Environmental monitoring
Buzzer	Audible alert	Local warning

C. Communication Model

The system uses MQTT-based model of communication to guarantee efficient and reliable transmission of data between distributed parts. On the Raspberry Pi, a Mosquitto MQTT broker is hosted, and it controls the exchange of messages between the ESP32 and Node-RED.

The ESP32 uses defined MQTT topics to publish sensor data esp32/temperature or esp32/humidity and CarbonMonoxide or CarbonMonoxide esp32/detector. Some subscriptions of these topics by a Node-RED subscription include event data generated by the Node-RED, leading to control messages being sent to the topic esp32/alarm when alarm conditions are met.

This scheme of communication is lightweight and reduces the bandwidth consumption and hence it offers scalability reducing it to be an instrument of smart building applications [10], [12].

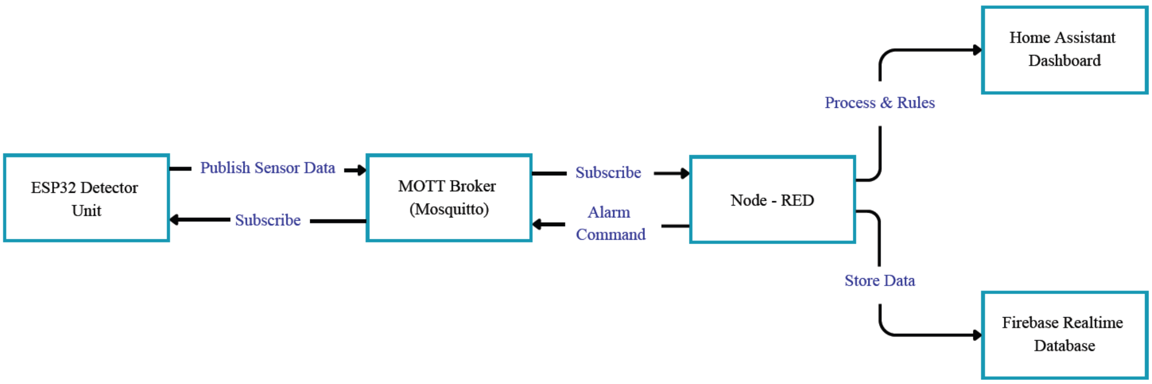

Fig. 2. MQTT-based communication model between ESP32 and Node-RED

D. Processing and Decision-Making Unit

The Raspberry Pi 3 Model B+ is the processing/decision-making unit. Home Assistant has the feature of device integration and automation, whereas node-RED is utilized in data processing, visualizing and executing rules.

The sensor data are shown on a real-time dashboard and is also stored in Firebase Realtime Database to be analyzed in history. The use of threshold-based rules together with multi-sensor validation is used to implement decision logic. An alarm is raised when the sensor reading of two or more of the sensors exceeds specific limits, which further limits the occurrence of false alarms due to steam, cooking fumes, or environmental disturbances [1], [9].

Table II: Threshold Values Used for Fire Detection

Parameter	Threshold Value
Smoke Detector	Triggered
CO Concentration	≥ 35 ppm
Temperature	≥ 49 °C
Humidity	Context-based

E. Surveillance and Localization Module

A Raspberry Pi Zero W is converted to a situational awareness device that then drives a Raspberry Pi Camera Module

v1.3 on servo motors. The camera streamlines the live video deliveries and the user can remotely check the fire status with the assistance of the camera.

DOI: 10.17148/IARJSET.2026.13546

The integration of Inkscape-created digital floor plan is achieved in home assistant. Mappings have been made between each room and detectors and identifying the location of the source of fire. Such information may be especially beneficial when evacuating people and the firefighting process, as it is emphasized in [14].

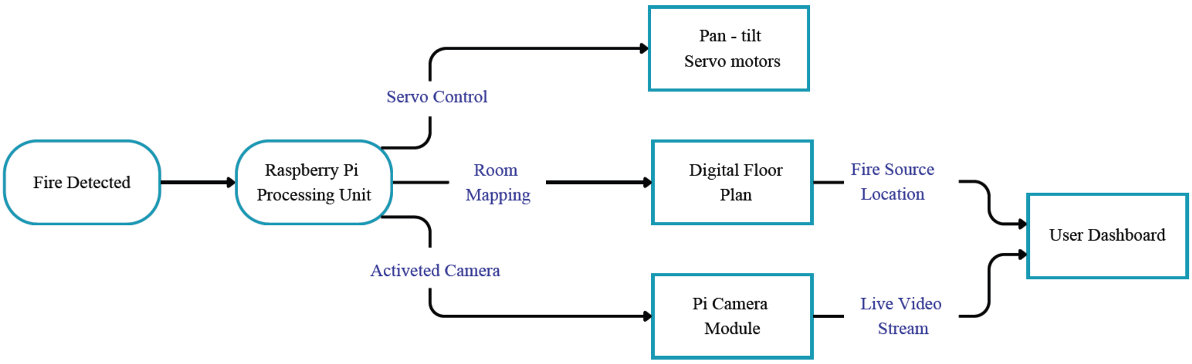

Fig. 3. Integration of live surveillance and floor plan visualization

F. Alert and Emergency Response Mechanism

The system produces multi-level notifications when fire conditions have been identified. The IFTTT platform is used to send the user notifications through email, SMS, and Voice over Internet Protocol (VoIP). In the case of a severe fire, the system sends the GPS position to the nearest fire station automatically and hence responds to the emergency fast.

Such an automated warning system improves the response time and the safety results, particularly when the building is empty [6], [13].

G. System Workflow

The general flow of the system is that at the detector unit, continuous sensor monitoring occurs and then the process continues to work as follows. The sensors transfer the sensor data to the processing unit, which satisfies decision logic to determine if the situation is severe or not. The system triggers a local alarm depending on the conditions that are detected, transmits remote notifications, and triggers emergency procedures.

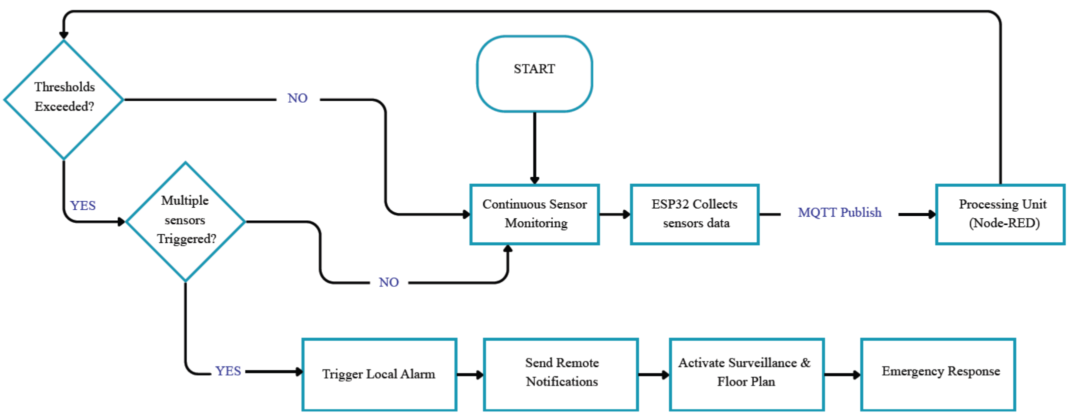

Fig. 4. Flowchart of the proposed smart smoke alarm system

IV. EXPERIMENTAL SETUP AND RESULTS

A. Experimental Setup

The proposed IoT-based smart smoke alarm system was experimentally evaluated in a controlled indoor environment to validate its performance, reliability, and responsiveness. The detector unit comprising the ionization smoke detector, MQ-7 carbon monoxide sensor, DHT11 temperature–humidity sensor, ESP32 microcontroller, and buzzer was installed in a simulated residential room environment.

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Home Assistant (Hass.io), Node-RED, Mosquitto MQTT broker and Firebase Realtime Database were set up on the processing unit made of a Raspberry Pi 3 Model B+. The ESP32 was also used to wirelessly communicate with the Raspberry Pi via the MQTT protocol over a local Wi-Fi network, which is suggested to use in constrained IoT environments [12], [15].

A simulation of controlled fire conditions was done using incense sticks and controlled sources of combustion to produce smoke and carbon monoxide. The false alarm resistance was also tested by the introduction of environmental variations like cooking fumes and steam, previous methods used to investigate fire detection studies [9], [13].

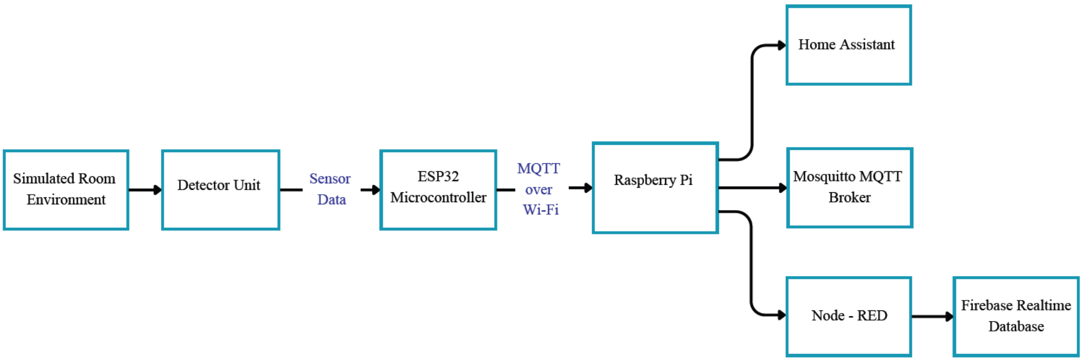

Fig. 5. Block diagram of the proposed smart smoke alarm system

B. Test Scenarios

In order to assess the systems performance of the system in detail, several test scenarios were developed as outlined in Table III.

Table III: Test Scenarios for System Evaluation

Scenario No.	Conditions Simulated	Expected Response
S1	Normal environment	No alarm
S2	Cooking fumes	No alarm
S3	Steam / high humidity	No alarm
S4	Smoke only	Warning notification
S5	Smoke + CO $\geq$ 35 ppm	Alarm activation
S6	Smoke + CO + Temperature $\geq$ 49 °C	Alarm + emergency alert

C. Performance Metrics

The performance measures that were used to evaluate the system include the following used by the majority of fire detection studies [1], [9]:

- Detection Accuracy
- False Alarm Rate
- Response Time
- System Reliability

D. Results and Observations

The experiment outcomes indicate the high detection accuracy of the proposed system and lowering the false alarm by a high margin using multi-sensors fusion has been realized.

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Table IV: Performance Comparison: Traditional vs. Proposed System

Parameter	Traditional Detector	Proposed System
Detection Accuracy	Moderate	High
False Alarm Rate	High	Low
Average Response Time	10–15 s	3–5 s
Remote Notification	No	Yes
Visual Verification	No	Yes

The proposed system was able to distinguish genuine fire hazards and a non-threatening condition in the environment such as cooking smoke and steam. The presence of false alarms was minimized because the sensors required at least several sensor thresholds to be met before an alarm can be activated, which is consistent with literature in the context of multi-signature detection systems [9].

E. Alert Response and Notification Performance

When critical thresholds were exceeded, the system activated the buzzer in the local area and at the same time sent an email, SMS and VoIP call notification to the user through IFTTT. GPS coordinates were sent automatically in case of high-level threatening conditions (CO ≥ 100 ppm and temperature ≥ 49 0 C), which were forwarded to emergency responders.

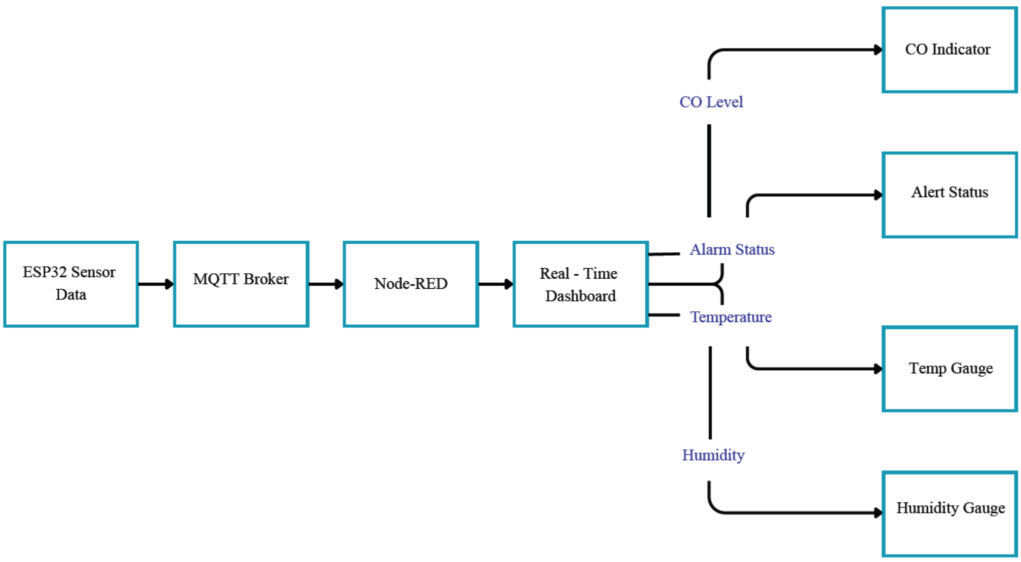

Fig. 6. Node-RED dashboard showing real-time sensor readings and alert status

The average end-to-end alert delivery time, from the time of detection to a user notification, was found to be under five seconds, which by far is much quicker than traditional standalone detectors [6], [13].

F. System Reliability and Data Logging

All sensor data were successfully logged in the Firebase Realtime Database without packet loss during normal network conditions. The MQTT also turned out to be effective when it comes to low-latency data transfer, which validated its applicability in real-time smart fire detection systems [12], [15].

The system had long working periods and was crash-free and data inconsistent in its functionality thus proving to be strong enough to be used in homes and businesses.

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V. CONCLUSION

This paper presented the design and implementation of an IoT-based smart smoke alarm system that prioritizes reliability of fire detection and efficiency in the emergency response in residential and commercial set ups. As compared to the existing standalone smoke detectors, the proposed will be in a position to combine an ionization smoke detector with temperature, humidity, and carbon monoxide sensors allowing multi-sensors fusion to minimize false alarms and enhance accuracy. The experimental findings show that the system is useful in distinguishing the actual fire events and the non-threatening conditions in the environment like cooking fumes and steam. ESP32 and MQTT-based communication guarantees a low Latency and reliable data transmission, and the processing unit is based on Raspberry Pi and thus provide the possibility to visualize the data in real-time and make smart decisions and log the data with the help of Node-RED and Firebase. Visual verification is ensured by the introduction of the live video surveillance with controlled cameraworthy motion of the camera, which enhances the situational awareness of the emergency situation tremendously. Also, the multi-channel alert system of the system such as local alarms, mobile notification, and VoIP-based emergency calls provides user awareness in a timely manner and fast response. Getting GPS coordinates automatically sent to the emergency services in case of critical conditions improves the efficiency of fighting fires and formulation of evacuation plans. In general, the proposed smart smoke alarm system can serve as a reliable and cost-effective solution to the modern fire safety requirements and the requirements that can be scaled to a higher extent. The IoT connectivity, fusion of multi-sensors, and intelligent monitoring makes the system a beneficial addition to the existing technology in fire detection and offers a contribution to the further development of smart building safety and disaster management services and tools.

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