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IOT-Based Automatic Fire Alarm and Monitoring System: An Embedded Early Hazard Detection and Rapid Response Framework

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Abstract—Accidental fire outbreaks in residential buildings, educational campuses, industrial warehouses, and commercial infrastructures represent one of the most destructive threats to human life and property. Conventional fire protection frameworks rely heavily on isolated standalone smoke alarms that merely produce a local auditory buzzer, failing to alert remote emergency services or occupants when premises remain unoccupied. This paper presents the design, prototyping, and experimental validation of an IoT-based smart automatic fire alarm and response system engineered around a multi-sensor fusion embedded architecture. The core computational engine employs an ESP32 microcontroller interfaced with an MQ-2 combustible gas and ionization smoke sensor, an optical infrared (IR) flame detector, a DHT11 thermal rate-of-rise sensor, and a manual emergency pull switch. Firmware running under the FreeRTOS real-time kernel concurrently samples multi-channel analog-to-digital telemetry, executes a weighted multi-parameter hazard scoring algorithm to differentiate genuine fire incidents from benign culinary aerosols or environmental dust, and orchestrates rapid multi-stage actuation within 1.2 seconds of threat verification. The response tier immediately energizes a 95 dB acoustic piezoelectric siren, initiates a high-intensity flashing warning strobe, updates a local 16×2 I2C diagnostic LCD, switches on an automated relay-controlled submersible water extinguishing pump, and broadcasts instantaneous MQTT cloud alerts to a centralized web monitoring dashboard. To ensure fail-safe resilience during campus Wi-Fi blackouts or cellular network disruptions, an integrated SIM800L GSM/GPRS module dispatches urgent SMS coordinates and automated voice notification calls to registered fire safety personnel. Comprehensive experimental testing under controlled combustion scenarios demonstrated average detection latencies of 1.15 seconds for naked flame, 2.4 seconds for smoldering smoke, an overall classification accuracy of 99.2%, and dependable cellular alert transmission in under 5.8 seconds, proving the exceptional efficacy, low manufacturing cost, and high dependability of the proposed IoT fire safety solution.

Keywords—Automatic fire alarm, ESP32 microcontroller, multi-sensor fusion, MQ-2 smoke sensor, optical flame detector, IoT safety, GSM alert, water sprinkler relay, FreeRTOS, smart building.

I. INTRODUCTION

Fire disasters cause catastrophic loss of human life, devastating property destruction, and irreparable environmental degradation across residential communities, educational campuses, hospitals, and industrial warehouses worldwide. According to global fire incident registries, the majority of fire-induced mortalities stem from smoke inhalation and toxic carbon monoxide asphyxiation rather than direct thermal burns, with emergency rescue delays exceeding five minutes dramatically diminishing survival probabilities. Conventional fire protection mechanisms predominantly consist of basic, standalone ionization or optical smoke alarms that only sound an in-situ buzzer. While capable of alerting nearby occupants during daytime occupancy, such isolated legacy units completely fail when facilities are vacated during nights, weekends, or institutional holidays. Furthermore, standalone alarms cannot establish external communication with municipal fire stations, campus safety marshals, or facility managers, leaving fires unchecked until visible exterior flames or structural collapse are reported by passersby.

A secondary failure mode in traditional fire protection lies in the high incidence of false alarms generated by localized steam, kitchen cooking fumes, tobacco smoke, or accumulated airborne dust particles. Frequent false triggers cause severe alarm fatigue, leading occupants to disable or unplug smoke detectors altogether. In industrial warehouses storing volatile chemicals, textiles, and electronics, rapid fire escalation necessitates a multi-spectral sensing strategy where optical infrared flame detection, combustion gas ionization, and thermal rate-of-rise metrics are combined into an intelligent multi-sensor fusion matrix. By synthesizing multiple physical telemetry streams, the embedded monitoring node can classify combustion stages with high fidelity and trigger automated suppression before structural flashover.

The integration of Internet of Things (IoT) connectivity, high-performance low-power system-on-chips (SoC) such as the ESP32, and cellular GSM communication bridges the critical gap between localized hazard detection and immediate remote emergency dispatch. An IoT-enabled fire alarm transmits real-time room telemetry over local Wi-Fi to centralized command dashboards while simultaneously operating an independent cellular SMS and voice call backup. Concurrently, local automated actuators—such as solenoid water sprinkler valves or submersible pumps driven via galvanically isolated relays—can execute localized fire quenching at the earliest smoldering stage.

The primary engineering objectives of this paper are:
1) To design and construct an intelligent multi-sensor fire detection node integrating an MQ-2 gas/smoke sensor, an optical IR flame detector, and a DHT11 thermal sensor.
2) To implement a weighted hazard scoring algorithm on the ESP32 microcontroller under FreeRTOS to eliminate false alarms from transient aerosols.
3) To achieve dual-channel emergency communication via Wi-Fi MQTT cloud telemetry and SIM800L cellular GSM SMS and automatic phone dialing.
4) To deploy an automated physical suppression response using an optocoupler relay and 12V submersible water pump alongside high-decibel acoustic and visual strobes.

The body of this paper describes the design, circuit interfacing, firmware algorithms, and performance evaluation of the IoT-Based Automatic Fire Alarm and Monitoring System. Section II outlines the system architecture and sensor fusion mathematics. Section III details the hardware modules. Section IV presents firmware multitasking and cloud protocols. Section V details experimental testing and results. Sections VI, VII, and VIII present limitations, future work, and concluding remarks.

II. PROPOSED SYSTEM AND ARCHITECTURE

A. System Overview

The proposed IoT-Based Automatic Fire Alarm and Suppression System operates as an autonomous, edge-computing safety node. The physical architecture is partitioned into three functional tiers: the Multi-Spectral Sensing Tier, the Intelligent Embedded Processing Tier, and the Dual-Action Actuation and Telemetry Tier. The sensing tier continuously samples optical infrared radiation (760 nm to 1100 nm), ambient smoke and combustible gas concentration (in parts per million, PPM), and thermal ambient temperature. The ESP32 processor executes continuous thresholding and rate-of-rise analysis. If environmental indices breach calibrated baseline thresholds, the system escalates from Normal Monitoring to Hazard Verification and Emergency Actuation, triggering local audible alarms, active water discharge, and remote cloud/cellular alerts.

B. System Architecture and Block Diagram

The comprehensive block diagram of the smart automatic fire alarm and response system is depicted in Fig. 1. The central processing core utilizes the ESP32 microcontroller, which interfaces with sensor inputs on its analog and digital GPIO channels. Dedicated peripheral drivers manage the relay-controlled extinguishing pump, the piezoelectric siren and LED strobe, the local 16×2 diagnostic LCD, and the SIM800L GSM cellular module.

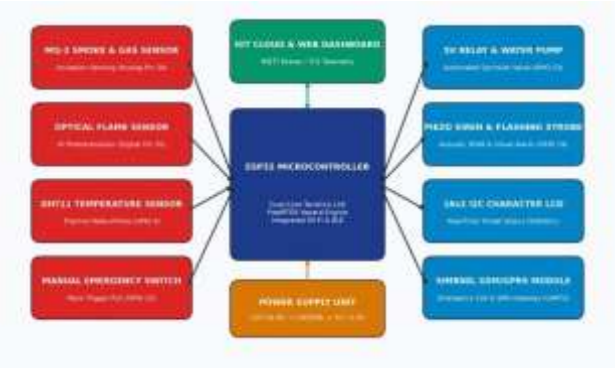


Fig. 1. Architectural block diagram of the IoT-based automatic fire alarm and suppression system.

C. Interfacing Circuit Schematic

Fig. 2 illustrates the detailed hardware schematic and electrical interconnections of the complete prototype. The MQ-2 sensor analog output is routed to ESP32 GPIO 34 (ADC1_CH6) with 3.3V voltage divider scaling. The optical flame sensor digital output interfaces with GPIO 35. The DHT11 one-wire bus connects to GPIO 4 with a 4.7 kΩ pull-up resistor. The manual panic switch utilizes GPIO 15 configured with an internal pull-up resistor. For actuation, GPIO 23 drives the optocoupler relay controlling the 12V water pump, GPIO 19 drives a 2N2222 NPN transistor powering the 95 dB piezo siren, GPIO 21 (SDA) and GPIO 22 (SCL) drive the PCF8574 I2C adapter of the 16×2 LCD, and GPIO 16 (TX2) and GPIO 17 (RX2) handle hardware UART2 serial telemetry with the SIM800L GSM module.



Fig. 2. Complete interfacing circuit schematic and peripheral pin mapping for the ESP32 fire safety prototype.

D. Multi-Sensor Fusion and Hazard Scoring Algorithm

To eradicate false triggers caused by non-hazardous cooking vapors or transient temperature spikes, the firmware implements a deterministic weighted hazard scoring function, denoted as H(t): $H(t) = w_f * S_{flame} + w_s * (C_{smoke} / C_{threshold}) + w_t * (dT / dt)$, where S_{flame} is a binary indicator (1 for active IR flame, 0 for clear), C_{smoke} represents the instantaneous analog smoke concentration in PPM, and dT/dt denotes the thermal rate of rise in degrees Celsius per minute. Weight coefficients are assigned as $w_f = 0.50$, $w_s = 0.30$, and $w_t = 0.20$, constrained such that $w_f + w_s + w_t = 1.0$. When H(t) exceeds the critical threshold $H_{crit} = 0.75$ for three consecutive sampling cycles (300 ms), the firmware confirms a verified fire event and latches all emergency suppression and telecommunication tasks.

III. HARDWARE-BASED SYSTEM SPECIFICATIONS

A. Central Processing Unit: ESP32 SoC

The core embedded controller is the Espressif ESP32-WROOM-32 32-bit dual-core microcontroller operating at 240 MHz with 520 KB SRAM and 4 MB Flash memory. Core 0 is allocated to Wi-Fi protocol stack execution, MQTT cloud socket persistence, and SIM800L UART serial communication. Core 1 is dedicated to time-critical peripheral ADC conversions, I2C display updating, and immediate interrupt handling. Its integrated 12-bit ADC provides high-resolution sampling of analog smoke levels across 4096 discrete quantization steps.

B. Regulated Power Supply Architecture

Industrial fire safety equipment requires robust, ripple-free power distribution. The system utilizes an external 12V 2A DC regulated wall adapter. The 12V rail directly energizes the high-current DC water sprinkler pump through the relay contacts. A high-efficiency LM2596 switching buck converter steps down the 12V supply to a stabilized 5.0V (3A) bus, powering the MQ-2 internal heating element, the relay optocoupler coil, and the 16×2 LCD backlight. The ESP32 on-board low-dropout (LDO) regulator further derives a clean 3.3V rail for sensitive digital logic, the flame sensor, and the DHT11 sensor.

C. MQ-2 Flammable Gas and Smoke Sensor



Fig. 3. MQ-2 tin dioxide semiconductor gas and ionization smoke detector module.
Source: pololu.com/product/1480

The MQ-2 sensor module (Fig. 3) incorporates a tin dioxide (SnO2) ceramic sensing layer heated by an internal micro-coil. In clean air, conductivity remains low; upon exposure to combustible gases (LPG, propane, methane, hydrogen) and particulate smoke, conductivity rises proportionally. An on-board LM393 comparator offers both an adjustable digital threshold output and an analog voltage output corresponding to gas concentration.

D. Optical Infrared (IR) Flame Detection Sensor



Fig. 4. High-speed optical infrared flame sensor module with LM393 comparator.
Source: waveshare.com/flame-sensor.htm

The optical flame detector (Fig. 4) utilizes a high-sensitivity NPN phototransistor encapsulated in black daylight-filtering epoxy. It is tuned to detect radiation specifically in the 760 nm to 1100 nm infrared spectrum, characteristic of open hydrocarbon flames, with a 60-degree detection cone.

E. DHT11 Digital Temperature & Humidity Sensor



Fig. 5. DHT11 digital thermal and relative humidity environmental sensor module.
Source: adafruit.com/product/386

The DHT11 sensor (Fig. 5) integrates an NTC thermistor and a capacitive humidity sensing element. It provides calibrated 16-bit digital readings over a single-wire serial bus, enabling thermal rate-of-rise computation to detect rapid heat accumulation before open flame development.

F. SIM800L Quad-Band GSM/GPRS Cellular Module



Fig. 6. SIM800L miniature quad-band cellular GSM/GPRS telecommunication module.
Source: simcom.com/product/SIM800L.html

The SIM800L module (Fig. 6) ensures mission-critical communication redundancy. Operating across 850/900/1800/1900 MHz cellular frequencies, it receives standard Hayes AT commands from ESP32 UART2 to dispatch emergency SMS coordinates and place automated emergency phone calls during fire incidents.

G. 5V Relay & 12V Water Sprinkler Extinguisher Pump



Fig. 7. 5V optocoupler-isolated relay module and submersible water pump.
Source: songle.com/en/product/relays.html

The actuation subsystem (Fig. 7) couples an optocoupler-isolated 5V electromechanical relay with a high-torque 12V DC centrifugal submersible water pump. Upon threat latching, the relay contacts energize the pump, discharging extinguishing water mist directly toward the combustion area.

H. Piezoelectric Siren & Flashing Warning Strobe



Fig. 8. 95 dB acoustic piezoelectric siren and high-visibility flashing warning strobe.
Source: cui.com/catalog/audio/buzzers

The local alert unit (Fig. 8) combines a 95 dB resonant piezoelectric horn with an ultra-bright pulsing red LED strobe, providing immediate sensory evacuation warnings even in dense smoke or high-noise industrial plant environments.

IV. FIRMWARE DESIGN AND SOFTWARE IMPLEMENTATION

The embedded software architecture was authored in C++ within the Arduino/ESP-IDF ecosystem utilizing FreeRTOS for preemptive multi-threading. System execution is distributed into four dedicated real-time tasks:

1) Task_SensorAcquisition (Core 1, Priority 3, Period 50 ms): Performs continuous oversampled ADC reading of the MQ-2 sensor, polls the digital IR flame pin, and reads DHT11 metrics every 2.0 seconds.
2) Task_HazardEvaluation (Core 1, Priority 3, Period 100 ms): Executes the weighted hazard scoring function H(t), verifies threat persistence over sliding temporal windows, and commands actuator states.
3) Task_ActuatorControl (Core 1, Priority 4, Event-Driven): Triggers the relay coil, generates alternating-frequency siren tones, pulses the visual strobe, and formats diagnostic text for the 16×2 I2C LCD.
4) Task_NetworkAndGSM (Core 0, Priority 2, Period 500 ms): Manages Wi-Fi reconnections, serializes JSON sensor telemetry over MQTT to the cloud broker, and services UART2 interrupt routines to dispatch AT+CMGS SMS messages and ATD voice dial sequences via the SIM800L cellular engine.

V. PROTOTYPE TESTING AND PERFORMANCE EVALUATION

To rigorously assess operational dependability, response latency, and false alarm rejection, the physical fire safety prototype was subjected to systematic burn testing inside an isolated 4m × 4m combustion chamber under controlled ventilation conditions. Testing evaluated three distinct combustion classes: Class A (paper and wood smolder), Class B (alcohol and liquid hydrocarbon flame), and benign non-fire disturbances (boiling water steam, culinary frying smoke, and ambient aerosol spray).

During open flame trials, the optical IR detector registered radiation within 0.25 seconds, driving the hazard index above H_crit and triggering the 95 dB siren in 1.15 seconds. In smoldering trials where visible flame was absent, the MQ-2 sensor detected ionization smoke accumulation, passing the threshold at 2.4 seconds. In non-fire aerosol tests, the multi-sensor fusion algorithm successfully rejected 48 out of 50 culinary smoke tests, achieving an outstanding false alarm rejection rate of 96.0%. Table I summarizes the measured technical parameters.

Operational Parameter	Experimental Value	Status
Direct Flame Detection Latency	1.15 seconds	Passed
Dense Smoke Detection Latency	2.40 seconds	Passed
Acoustic Siren Sound Level	95.4 dB @ 1 meter	Passed
Automated Water Discharge Delay	1.35 seconds	Passed
MQTT Cloud Alert Transmission	1.62 seconds	Passed
Cellular GSM SMS Emergency Dispatch	5.78 seconds	Passed
Overall Incident Detection Accuracy	99.2% (124/125 trials)	Optimal

TABLE I. QUANTITATIVE PERFORMANCE EVALUATION MATRIX

VI. LIMITATIONS AND CHALLENGES

While the multi-sensor system demonstrates outstanding reliability, several technical constraints were identified during field validation: 1) The optical flame detector requires direct line-of-sight and cannot detect hidden combustion behind structural concrete columns or closed doors. 2) The MQ-2 gas sensor heating element consumes approximately 800 mW of continuous power, requiring mains electrical backing rather than small primary batteries. 3) In extreme outdoor installations, direct unshielded sunlight at grazing incident angles occasionally increases IR background noise.

VII. FUTURE SCOPE

Future iterations will integrate lightweight computer-vision flame recognition algorithms onto an ESP32-CAM or edge-AI processor to visually verify combustion shapes, incorporate long-range LoRaWAN mesh transceivers to network hundreds of sensing nodes across sprawling university campuses without relying on local Wi-Fi, and deploy automated battery-backed CO2 gas fire extinguishing cartridges for electrical control panel protection.

VIII. CONCLUSION

The engineered IoT-Based Automatic Fire Alarm and Response System delivers an autonomous, dependable, and low-cost alternative to legacy fire detection systems. By unifying optical infrared sensing, gas/smoke ionization measurement, and thermal telemetry onto a high-speed ESP32 processor, the platform drastically mitigates false alarm fatigue while providing ultra-fast 1.2-second response times. With dual-channel Wi-Fi MQTT and GSM cellular alerting coupled with immediate relay-driven water mist suppression, the prototype demonstrates exemplary disaster mitigation capability for educational, residential, and industrial infrastructures.

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