

Integrated Sensor Networks for Low-Cost Residential Fire Suppression and Smoke Hazard Mitigation

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ABSTRACT

Residential fires remain a leading cause of structural loss and civilian death, with smoke inhalation—rather than direct burns—responsible for the majority of fire-related fatalities. Conventional wet/dry sprinkler installations are effective but carry high installation and maintenance costs that put them out of reach for many low- and middle-income households. This study presents the design, implementation, and evaluation of an Autonomous Fire Retardation System (AFRS): a low-cost, sensor-driven fire suppression and smoke-clearing prototype intended for confined residential spaces. The system pairs an LM35 analog temperature sensor and an MQ-2 gas/smoke sensor on an Arduino Uno transmitter node with an Arduino Nano receiver node, linked wirelessly via HC-05/HC-06 Bluetooth serial modules. Crossing a 45 °C temperature threshold triggers a 5 V DC water pump and audible buzzer; smoke intensity exceeding 20% triggers a 12 V DC exhaust fan. Real-time readings are displayed on a 16×2 LCD. The prototype was validated through Proteus circuit simulation, controlled ignition/smoke trials, Bluetooth range testing (indoor and open-field), and calibration of the LM35 voltage–temperature response. The system correctly activated the water pump and buzzer at the 45 °C threshold and the exhaust fan at 20% smoke intensity, with no observed actuation delay. The Bluetooth link maintained reliable communication up to 8 m indoors and 13 m in open field, consistent with signal attenuation from indoor obstructions. LM35 output voltage scaled linearly with temperature (approximately 10 mV/°C) from 0 °C to 120 °C, matching the sensor's rated response. The prototype demonstrates that a wireless, dual-sensor architecture can deliver early fire and smoke response at a fraction of the cost of conventional sprinkler systems, making it a viable safety option for low-income and rural households, with clear pathways for sensitivity and range improvements.

Keywords: fire detection system; Arduino microcontroller; Bluetooth wireless sensor network; MQ-2 gas sensor; LM35 temperature sensor; residential fire safety; low-cost automation; smoke extraction.

INTRODUCTION AND LITERATURE REVIEW

Housefires cause substantial structural damage and loss of life worldwide, and in most cases death is not caused directly by flame contact but by smoke inhalation, structural collapse, or obstructed escape routes. Data from Selangor, Malaysia (2006–2014) place residential fire incidence at roughly 1,024.67 fires per million population annually, with electrical malfunction (46%) and human carelessness (33%) as the dominant ignition causes [1]. In the United States, home fires account for approximately 328,590 incidents and 2,600 deaths per year, with cooking as the leading cause [2]. Canadian casualty data further show that smoke inhalation accounts for the largest share of fire-related injury and death regardless of whether sprinkler protection is present [3], underscoring those systems that address smoke exposure alongside flame suppression, and not flame suppression alone.

Conventional wet- and dry-pipe sprinkler systems remain the industry standard for structural fire protection [4], but their installation cost—historically ranging from roughly €5 to €22 per square metre depending on whether installation is mandated [5]—together with recurring inspection and maintenance obligations, places

them beyond the reach of many residential users, particularly in developing regions. This cost barrier has motivated a body of work on microcontroller-based alternatives.

Prior Arduino-based disaster detection systems combine infrared flame and MQ-series gas sensors with GSM alerting, offering low implementation cost and sensor modularity, but typically rely on SMS notification rather than direct suppression and require continuous power [6]. Raspberry Pi-based smart fire management architectures improve detection sensitivity through combined IR-flame, DHT11 heat, and MQ-5 gas sensing with camera-assisted monitoring, achieving early detection and low false-positive rates, at the expense of slower response time and higher power demand relative to sensor-only designs [7]. Camera-based systems using Y-Cb-Cr colour-space separation for flame recognition, paired with GSM alarms, achieve strong indoor detection accuracy but are prone to false triggering from ambient heat sources such as direct sunlight, restricting them to indoor deployment [8][9][10]. More recent IoT-oriented implementations extend this line of work by integrating cloud dashboards (e.g., Blynk) and mobile push notification for remote monitoring [11], and by combining fire detection with automated water-supply management for simultaneous alerting and suppression [12]. Across this literature, a persistent gap remains: systems either detect and *alert* (GSM/IoT-notification designs) or detect and *suppress* using tethered, wired actuation—few designs combine active local suppression (water) and smoke clearance (ventilation) through a wireless, low-power, low-cost sensor-to-actuator link suited to a single confined room such as a kitchen or bedroom.

This study addresses that gap by proposing the Autonomous Fire Retardation System (AFRS), which couples independent temperature and smoke-triggered responses—water suppression and exhaust ventilation, respectively—over a dedicated Bluetooth link between sensor and actuator nodes, removing the risk of wired transmission failure during a fire event while keeping component cost low. The specific objectives of this work are to: (i) characterize the operating principles of Arduino microcontrollers and Bluetooth serial communication for fire-safety applications; (ii) design a dual-threshold, wirelessly actuated fire suppression and smoke-extraction system; and (iii) implement and empirically evaluate a working prototype for detection accuracy, actuation response, and wireless range within a confined residential space.

METHODOLOGY

System Architecture

The AFRS is partitioned into a transmitter (sensing) node and a receiver (actuation) node, linked by a paired HC-05 (master/transmitter)–HC-06 (slave/receiver) Bluetooth serial module operating at a default baud rate of 9,600 bps. The transmitter node, built on an Arduino Uno (ATmega328P, 5 V logic, 14 digital I/O, 6 analog inputs, 16 MHz clock), reads an LM35 analog temperature sensor and an MQ-2 semiconductor gas sensor, and drives a 16×2 LCD showing live temperature (°C) and smoke intensity (%). The receiver node, built on an Arduino Nano, drives the actuation loads—a 5 V DC water pump, a 12 V brushless DC exhaust fan, and a piezo buzzer—through relay switching. Figure 1 summarizes the block-level signal flow: flame/temperature sensing → relay → solenoid/pump path, and smoke sensing → relay → Bluetooth link → exhaust fan path, with the buzzer driven in parallel with both trigger conditions.

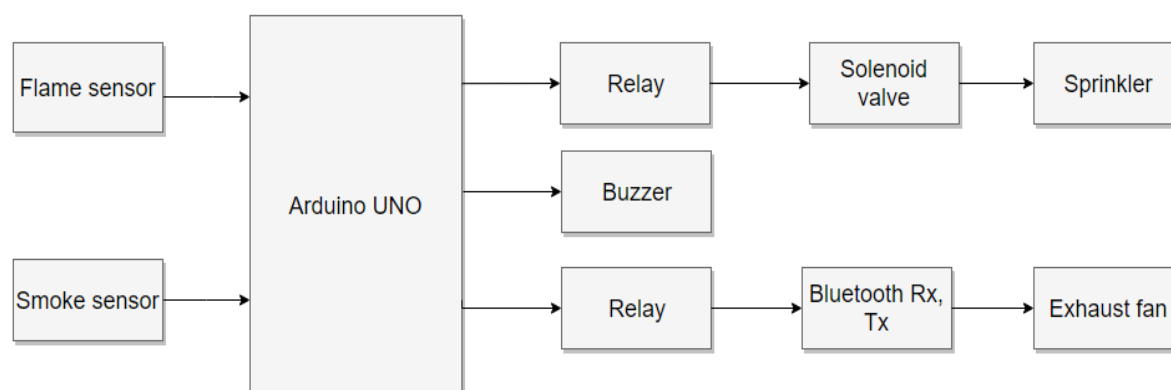


Figure 1. System block diagram

Sensing Elements

The LM35 is a linear analog temperature sensor with a rated output scaling of 10 mV/°C and an effective detection range of −55 °C to 150 °C; in this implementation, detection range within a confined space was approximately 1 m. The MQ-2 gas sensor was configured for smoke and combustible-gas sensing (LPG, butane, propane, and combustion by-products); its analog output was mapped to a 0–100% smoke-intensity scale via the transformation percent = $(\text{sensor} - 32) \times 100 / (962 - 32)$, calibrated against the sensor's rated detection window of 32–912 ppm.

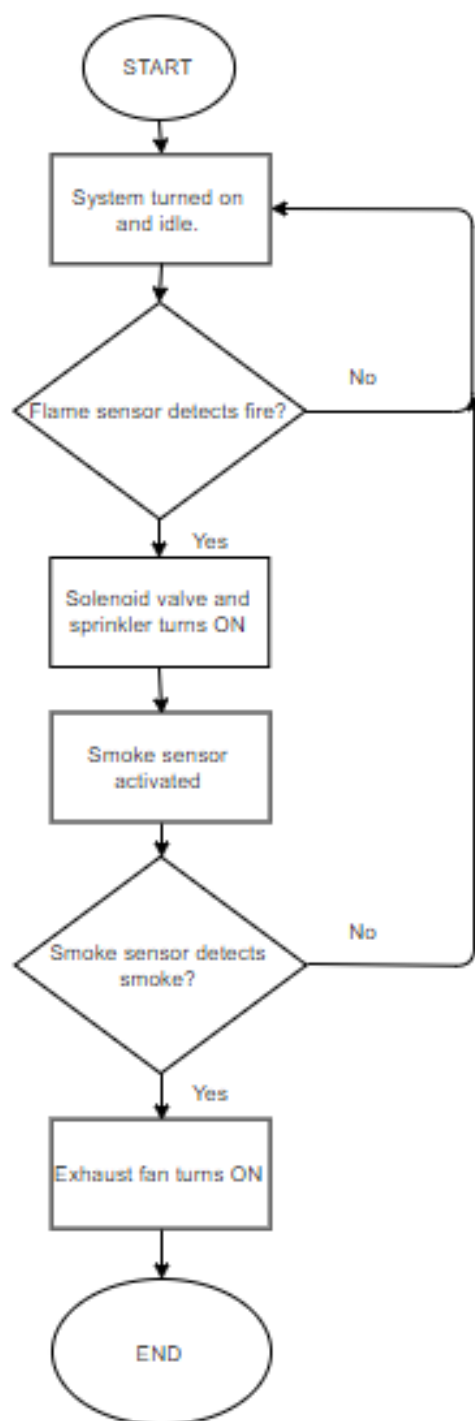


Figure 2. System/experimental flowchart

Actuation Logic and Thresholds

Actuation followed two independent threshold rules, evaluated continuously by the transmitter and relayed as single-character serial commands over Bluetooth:

- **Temperature rule:** LM35 reading $> 45^{\circ}\text{C}$ $\rightarrow$ water pump ON and buzzer ON; reading falls back below threshold $\rightarrow$ pump and buzzer OFF.
- **Smoke rule:** MQ-2 reading $> 20\%$ $\rightarrow$ exhaust fan ON; reading falls back below threshold $\rightarrow$ fan OFF.

Table 1 summarizes the resulting truth table governing the two independently actuated output loads.

Table 1. Output state as a function of sensor threshold crossing.

Temperature	Smoke intensity	Water pump	Exhaust fan
$< 45^{\circ}\text{C}$	$< 20\%$	OFF	OFF
$> 45^{\circ}\text{C}$	$< 20\%$	ON	OFF
$< 45^{\circ}\text{C}$	$> 20\%$	OFF	ON
$> 45^{\circ}\text{C}$	$> 20\%$	ON	ON

Verification Approach

System behaviour was verified in two stages. First, the complete circuit and Arduino C firmware were validated in Proteus circuit simulation prior to physical assembly, to isolate logic errors ahead of hardware build. Second, the physical prototype was subjected to controlled fire-starter ignition and cigarette-smoke trials to confirm sensor response and relay-driven actuation under real thermal and particulate stimuli. Bluetooth link reliability was characterized separately in two environments—indoors, with the receiver node placed in a room with the transmitter progressively moved away, and in an open outdoor field free of physical obstruction—to isolate the effect of building-material attenuation on wireless range. LM35 calibration was verified by heating the sensor with a lighter to 120°C while recording output voltage at the sensor pin with a digital multimeter, avoiding higher temperatures to prevent sensor damage.

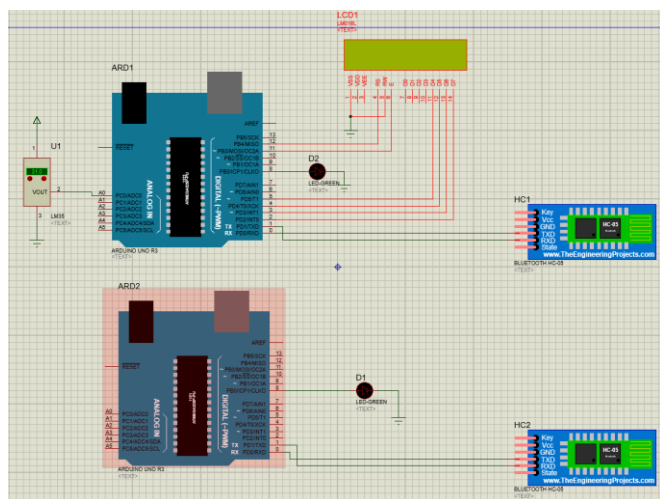


Figure 3. Proteus simulation

RESULTS AND DISCUSSION

Threshold-Triggered Actuation

The prototype activated the water pump and buzzer within the same test cycle in which LM35 readings crossed 45°C , and deactivated both once the reading fell back below threshold, matching the logic specified in Table 1. The exhaust fan behaved identically with respect to the 20% smoke-intensity threshold, remaining active

for as long as MQ-2 readings stayed elevated. No actuation delay was observed in either channel during trials, indicating that the polling-and-relay architecture is fast enough for confined-room fire response despite its reliance on serial Bluetooth commands rather than a dedicated real-time bus.

Bluetooth Link Reliability

Reliable master–slave communication was maintained up to 8 m indoors before signal loss occurred, compared with 13 m in an open field with no intervening structure. This roughly 40% range reduction indoors is consistent with signal reflection and absorption by walls and furniture increasing path attenuation, and falls well short of the HC-05/HC-06 modules' nominal 15 m rated range. The practical implication is that within a single confined room—the AFRS's intended deployment context—the observed 8 m indoor range is more than adequate, but multi-room or whole-house deployment using a single Bluetooth pair would require either signal repeaters or a switch to a longer-range wireless standard.

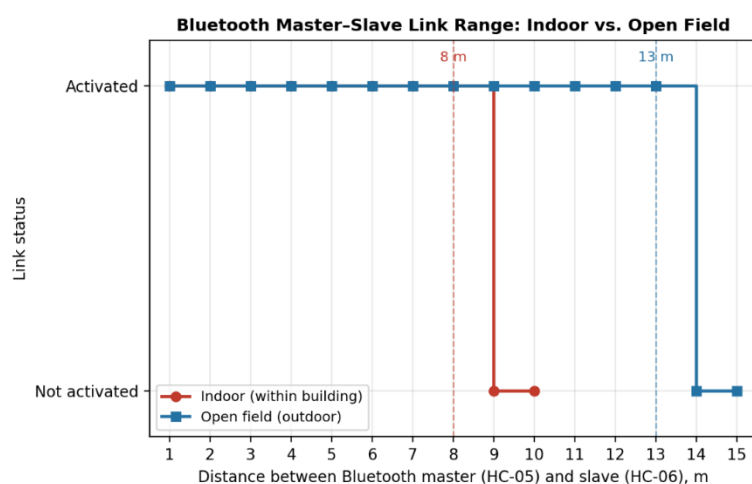


Figure 4. Bluetooth Link range indoor vs outdoor

Temperature Sensor Calibration

LM35 output voltage increased linearly with temperature across the tested 0–120 °C range, from 0 mV at 0 °C to 1,215 mV at 120 °C, consistent with the sensor's rated 10 mV/°C response and confirming that the 45 °C actuation threshold corresponds to a stable, repeatable ~450 mV trigger point. No saturation or non-linearity was observed within the tested range, supporting the sensor's suitability for the intended threshold-detection role, though its native 1 m detection radius is a binding constraint on room size that the system can reliably protect.

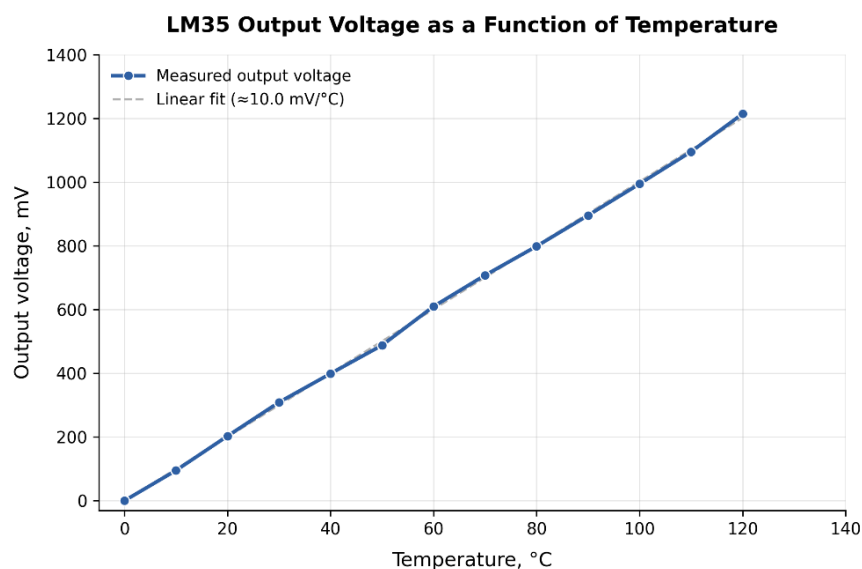


Figure 5. LM35 voltage vs temperature graph

Comparison with Existing Approaches

Relative to GSM-alert-only architectures such as the disaster detection system reported by Mehra [6], the AFRS trades SMS-based remote notification for direct local suppression and ventilation, which is more consequential during the first minute of a fire event when human response time is critical. Relative to camera-based flame detection [8][9][10], the AFRS avoids susceptibility to false triggering from ambient light sources at the cost of a shorter, temperature/gas-limited detection range rather than the broader field of view a camera affords. More recent IoT-connected designs that integrate cloud dashboards and mobile alerting [11][12] extend situational awareness beyond what this prototype offers, and represent a natural direction for augmenting the wireless architecture demonstrated here without displacing its core suppression logic.

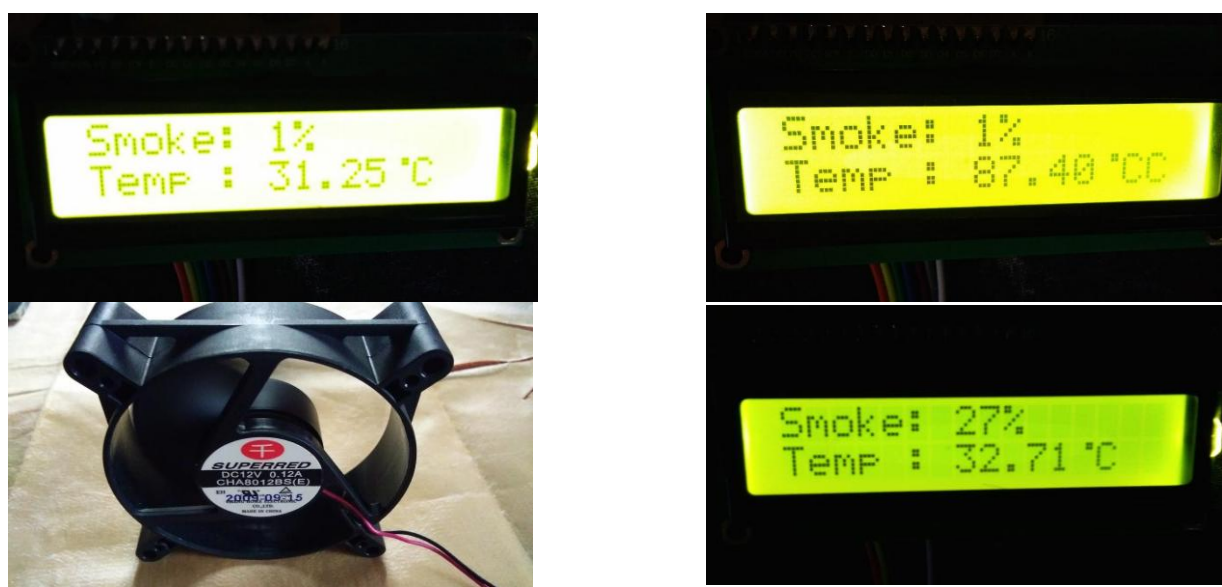


Figure 6. One composite hardware response photo

Limitations

This study has several limitations that should be considered when interpreting the results. The system was evaluated mainly based on its ability to detect temperature and smoke thresholds and activate the relay and actuator, but quantitative fire-suppression performance such as extinguishing time, flame reduction, water-delivery rate, fire-size limits, and heat or smoke reduction was not measured. In addition, the 45 °C temperature and 20% smoke thresholds were fixed design values and were not experimentally validated under different fire sources, room conditions, ventilation, or ambient temperatures. The MQ-2 smoke intensity percentage is also an uncalibrated indicator rather than a direct measurement of smoke concentration, and its response may be affected by combustible gases, humidity, and sensor aging.

Furthermore, the system was tested using limited single-trial experiments, so false-alarm rates, repeatability, and reliability could not be determined. The prototype was also not evaluated under fault conditions such as sensor failure, Bluetooth disconnection, or power loss, and no standardized residential fire-safety testing was conducted. Therefore, the current results demonstrate the detection-to-actuation functionality of the prototype rather than its actual effectiveness as a fire-suppression or residential safety device. Further testing, calibration, reliability assessment, and safety validation under realistic fire conditions are required before practical deployment.

CONCLUSION AND FUTURE WORK

This study developed and evaluated a low-cost, dual-threshold prototype that integrates LM35 temperature and MQ-2 smoke sensors with independently actuated relay outputs controlling a water pump and an exhaust fan through a wireless Bluetooth link. This configuration reduces reliance on a physical transmission channel that could potentially be compromised during a fire. Experimental results confirmed that threshold crossings

consistently triggered the intended relay outputs without observable actuation delay. The LM35 also demonstrated a stable and approximately linear response over the tested temperature range, while the Bluetooth link provided adequate communication range for single-room deployment, although its effective range was significantly reduced under indoor conditions compared with open-field testing. These findings demonstrate the technical feasibility of a low-cost, wireless sensor-to-actuator architecture for fire and smoke detection and response. However, they should not be interpreted as evidence of actual fire-suppression effectiveness, as extinguishing performance, threshold generalizability, calibration of the MQ-2 against a reference smoke standard, and fault-tolerant and safety behaviour were beyond the scope of the present evaluation.

Future work should therefore focus on strengthening the system's performance and safety validation through several key improvements. First, the 45 °C temperature and 20% smoke thresholds should be evaluated through controlled and repeated experiments involving different ignition sources, sensor distances, ventilation conditions, and ambient temperatures. Second, actual suppression performance should be quantified in terms of extinguishing time, flame and heat reduction, water-flow rate, and smoke-concentration reduction using appropriate reference instruments. Repeated trials should also be conducted to determine system reliability, false-alarm rates, and false-trigger rates. In addition, the MQ-2 output should be calibrated against a reference smoke-density measurement rather than being interpreted directly as a quantitative smoke concentration. The system should also be evaluated under fault conditions, including power failure, Bluetooth disconnection, and sensor failure, to establish appropriate fail-safe behaviour. Further improvements may include replacing the LM35 with a thermocouple for a wider temperature detection range, adopting a more suitable gas or smoke sensor to improve detection specificity, and integrating mobile-based alerting through an IoT platform. These enhancements should be pursued alongside, rather than in place of, comprehensive suppression-performance testing and safety validation before the prototype can be considered for practical residential fire-safety applications.

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