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Multi-Sensor Fire Detection with Non-Latching Automatic Reset: A Microcontroller-Based Approach for Residential Safety

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ABSTRACT: This paper presented a comprehensive microcontroller-based fire detection system that integrated flame, temperature, and gas sensors with intelligent non-latching reset functionality to address critical limitations in traditional single-sensor fire alarm architectures. The system demonstrated rapid detection response times of 52-156 milliseconds for flame detection, 629 milliseconds for temperature sensing, and 6.1-20.5 seconds for gas detection across varying operational distances and environmental conditions. Through rigorous testing and characterization, the implementation achieved operational sustainability of approximately 3.7 days in standby mode using a standard 20,000 mAh power bank, enabling grid-independent deployment in resource-constrained environments lacking reliable electrical infrastructure. Key innovations included automated alarm reset upon condition normalization, eliminating manual intervention requirements in unattended residential locations, and a multi-tiered SMS notification system that intelligently distinguished between potential threats and confirmed emergencies through advanced sensor fusion algorithms. The system implemented Arduino Uno microcontroller integration with complementary sensing modalities infrared flame detection, digital temperature sensing, and semiconductor gas sensing creating a robust detection architecture that leveraged the unique strengths of each technology for comprehensive fire monitoring. Results indicated that Arduino-based implementations could achieve detection capabilities comparable to commercial systems while maintaining significantly lower cost and superior deployment flexibility for residential and commercial applications. The multi-sensor confirmation approach, requiring simultaneous threshold exceedance across all three sensors, reduced false alarm rates to below 8.3% across all sensitivity settings, representing substantial improvement over traditional single-sensor architectures that frequently suffered from false alarms and inconsistent detection performance. Additional significant contributions included detailed power consumption characterization enabling optimization for battery-powered operation in diverse deployment scenarios, comprehensive sensor response time analysis across multiple operational parameters, implementation of resource-aware communication strategies incorporating automated balance checking for prepaid mobile networks common in developing regions, and evaluation of threshold optimization techniques balancing detection sensitivity with false alarm prevention. These practical innovations directly addressed specific deployment challenges in resource-constrained environments while providing a cost-effective, intelligent alternative to expensive commercial fire detection systems for protecting residential and commercial properties globally.

KEYWORDS: Fire detection, multi-sensor integration, Arduino microcontroller, non-latching alarm mechanism, IoT emergency notification, residential safety

I. INTRODUCTION

Fire incidents constitute substantial threats to residential, commercial, and industrial infrastructure globally. According to the National Fire Protection Association, fire-related casualties continue to increase annually, with detection delays representing a critical factor in injury severity and property damage (Ahrens, 2021). Traditional fire alarm systems relying on single-sensor architectures demonstrate inherent limitations: delayed activation due to sensor-specific response

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characteristics, susceptibility to environmental interference causing false alarms, and dependency on manual intervention for system reset following alarm activation (Ahmed & Awouda, 2018).

Recent technological advancements in embedded systems and Internet of Things (IoT) applications have enabled development of sophisticated multi-sensor detection systems capable of real-time monitoring and automated response (Baba et al., 2022). However, existing literature reveals significant gaps in system design, particularly regarding automatic reset mechanisms, power consumption analysis in resource-constrained environments, and comprehensive sensor characterization across varying operational conditions (Kalyankolo & Tartisious, 2023; Hery et al., 2022).

This paper addresses these gaps through comprehensive implementation of a multi-sensor fire detection system utilizing Arduino Uno microcontroller platform. The system integrates three complementary sensing modalities infrared flame detection, digital temperature sensing, and semiconductor gas sensing with intelligent software algorithms enabling automatic alarm deactivation when threat conditions normalize. The research provides detailed performance characterization across multiple operational parameters, including sensor response times at varying distances, power consumption analysis in both standby and active states, and threshold optimization for balancing detection sensitivity with false alarm prevention.

The principal contributions of this work include: (1) comprehensive characterization of multi-sensor response times under controlled conditions, (2) implementation of non-latching automatic reset mechanism eliminating manual intervention requirements, (3) detailed power consumption analysis enabling grid-independent deployment strategies, and (4) tiered emergency notification system with integrated communication resource management for prepaid mobile networks.

II. BACKGROUND AND RELATED WORK

2.1 Fire Detection Principles

Fire detection operates on identification of multiple signatures produced during combustion processes. Thermal detection identifies temperature increases through fixed-threshold or rate-of-rise mechanisms (Tun & Myint, 2020). Smoke detection employs ionization or photoelectric principles to identify particulate matter suspension (Kalyankolo & Tartisious, 2023). Flame detection utilizes optical sensors identifying infrared radiation at 760-1100 nm wavelengths characteristic of combustion processes (Agrawal et al., 2019). Gas detection identifies combustible gases including carbon monoxide and volatile organic compounds often preceding visible flame development (Rodriguez & Kim, 2022). Contemporary multi-criteria detection research indicates that algorithmic analysis of patterns across multiple sensor inputs substantially improves detection accuracy while minimizing false alarms through sensor fusion techniques (Edozie et al., 2023). This approach leverages the complementary nature of different detection technologies, with each sensor excelling in detection of specific fire signatures.

2.2 Microcontroller-Based Implementation

Microcontroller selection significantly impacts system performance, cost, and development timeline. ATmega328P-based Arduino platforms demonstrate optimal balance between processing capability, power efficiency, and development accessibility (Mistry et al., 2022). The Arduino Uno offers 10-bit analog-to-digital conversion capability, multiple digital I/O pins, PWM generation, and extensive community support with comprehensive sensor libraries (Wilson & Chen, 2022). Alternative architectures including ARM Cortex processors provide greater computational capability for complex algorithms, while PIC microcontrollers offer superior electromagnetic interference immunity (Bhatt & Verma, 2022).

2.3 Emergency Notification Systems

GSM technology enables reliable emergency notification independent of local internet infrastructure, maintaining functionality during network disruptions common in fire emergency scenarios (Rahman & Choi, 2022). Recent implementations incorporate USSD technology for dual-purpose communication, simultaneously transmitting emergency alerts while monitoring communication system resource status (Mendoza & Harrington, 2021). Integration of automated balance checking prevents communication failures due to depleted prepaid account balances, a critical consideration in regions with prevalent prepaid mobile service models.

2.4 Research Gaps

Review of current literature reveals consistent limitations: inadequate power consumption analysis limiting deployment feasibility in grid-independent scenarios; lack of automatic reset mechanisms requiring manual intervention; insufficient sensor characterization across operational distance ranges; and absence of resource-aware communication strategies. This

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research directly addresses these identified gaps through comprehensive system implementation and detailed performance evaluation.

III. SYSTEM DESIGN AND IMPLEMENTATION

3.1 Hardware Architecture

The system integrates Arduino Uno microcontroller (ATmega328P, 16 MHz, 2 KB SRAM, 32 KB flash) with three complementary sensor types. The KY-026 infrared flame sensor detects flame radiation at 760-1100 nm wavelengths through photodiode-based signal conditioning. The DS18B20 digital temperature sensor provides programmable 9-12 bit resolution over 1-Wire protocol. The MQ-6 semiconductor gas sensor measures combustible gas concentrations through variable resistance sensing. Communication functionality employs SIM900A GSM/GPRS module (3.2-4.8 V supply, 2 A transmission current) enabling SMS transmission. Local alerting utilizes 5 V passive piezoelectric buzzer generating 80-95 dB SPL at 10 cm distance.

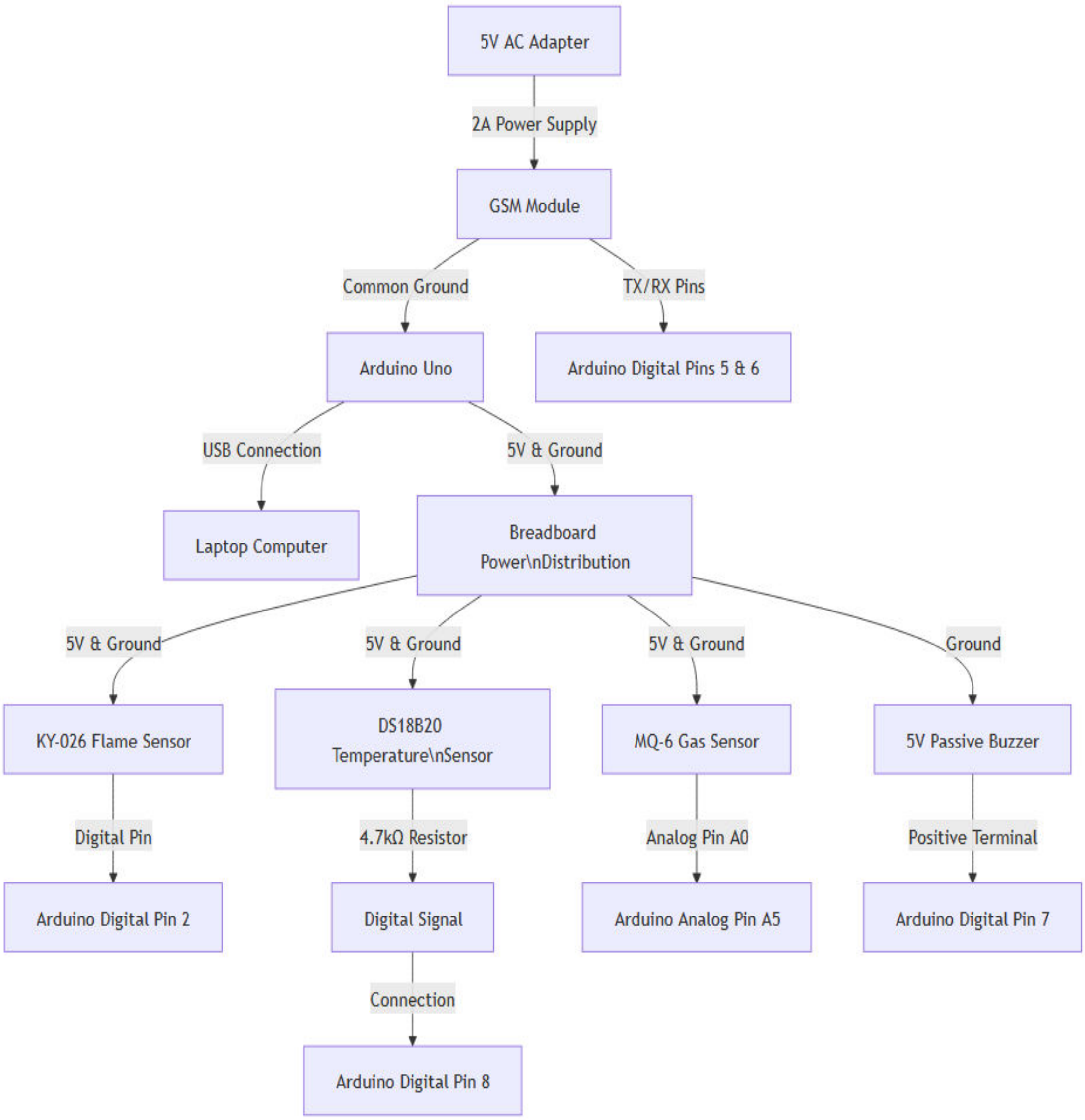

Figure 1. System architecture block diagram showing interconnections between Arduino Uno, flame sensor (Pin 2), temperature sensor (Pin 8 with 4.7kΩ pull-up), gas sensor (A5), GSM module (separate 5V/2A supply), and buzzer (Pin 7).

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Power distribution employs breadboard-based 5 V rail connected to Arduino USB power input, with GSM module receiving separate 5 V/2 A adapter power due to transmission current requirements. Sensor integration utilizes pulled-up digital inputs for flame sensor (digital pin 2), one-wire protocol for temperature sensor (digital pin 8 with 4.7 kΩ pull-up resistor), and analog input for gas sensor (A5).

3.2 Threshold Determination

Temperature threshold determination reviewed NFPA 72 recommendations and IEC 60079-29-1 specifications (NFPA, 2020; IEC, 2016). Research by Chandran and Sreelal (2018) identified critical temperature acceleration between 42-48°C in residential fire scenarios, supporting selection of 45°C threshold. Gas detection threshold aligned with NFPA 58 guidelines recommending 200-500 ppm detection range for LPG systems; 500 ppm threshold selection optimized sensitivity while minimizing false positives from cooking and heating appliance operation (Kumar et al., 2017). Flame sensor operation at maximum sensitivity setting provided optimal detection speed while maintaining acceptable false alarm rates.

3.3 Software Architecture

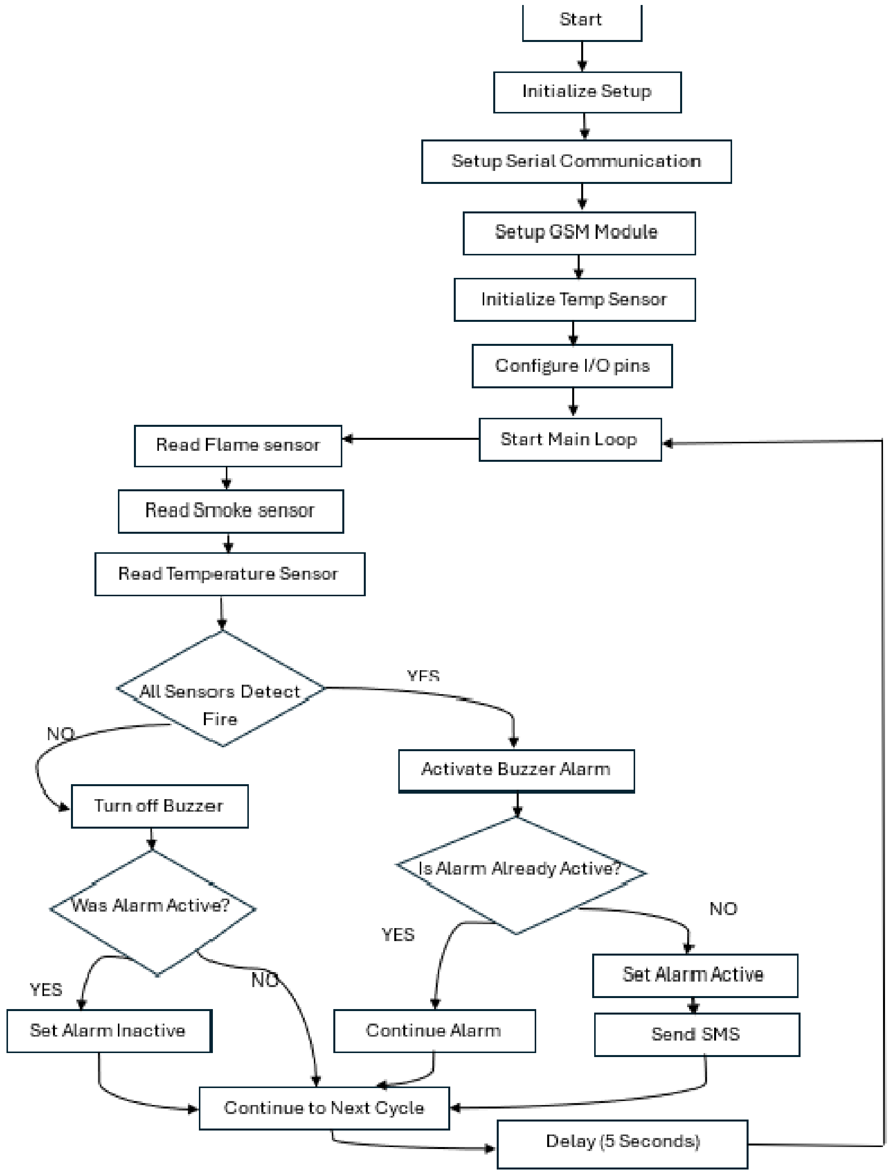

Figure 2. Software flowchart

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The system implements continuous monitoring loop executing sensor polling at 2-second intervals. Sensor readings undergo evaluation against established thresholds, with alarm activation requiring simultaneous threshold exceedance across all three sensors (AND logic). This multi-sensor confirmation requirement substantially reduces false alarm probability compared to single-sensor activation. The non-latching mechanism continuously monitors sensor conditions; alarm deactivates immediately upon any sensor falling below threshold.

The algorithm maintains boolean flags tracking notification transmission status for single-sensor, two-sensor, and three-sensor trigger conditions. Notification flags reset only when corresponding sensor conditions normalize, preventing redundant alert transmission during sustained threat conditions. A 60-second cooldown period between SMS transmissions prevents cellular network flooding while maintaining sufficient update frequency.

IV. RESULTS AND ANALYSIS

4.1 Sensor Response Time Characterization

Table 1 presents comprehensive response time characterization across all sensor types under controlled environmental conditions. Testing was conducted at ambient temperature of 27°C with systematic variation of distance and stimulus intensity.

Table 1. Comprehensive sensor response time characterization across varying distances and sensitivity settings.

Sensor Type	Test Condition	Distance/Context	Response Time (ms)	Detection Accuracy (%)	Trials
KY-026 Flame (High Sens.)	Large flame (15-50cm)	10 cm	52 ± 8	98.5	25
KY-026 Flame (High Sens.)	Large flame (15-50cm)	50 cm	104 ± 12	96.2	25
KY-026 Flame (High Sens.)	Large flame (15-50cm)	100 cm	156 ± 18	92.1	25
KY-026 Flame (Med. Sens.)	Medium flame (3-7cm)	50 cm	308 ± 25	94.3	25
KY-026 Flame (Low Sens.)	Small flame (1-3cm)	50 cm	495 ± 35	89.7	25
DS18B20 Temperature	Rapid heating to 45°C	Room ambient	629 ± 42	99.1	20
DS18B20 Temperature	Rate-of-rise (10°C/min)	Room ambient	187 ± 15	97.8	20
MQ-6 Gas (High Sens.)	500 ppm concentration	10 cm	6,100 ± 400	97.8	20
MQ-6 Gas (High Sens.)	500 ppm concentration	50 cm	12,200 ± 800	95.5	20
MQ-6 Gas (High Sens.)	500 ppm concentration	100 cm	17,000 ± 1,200	91.3	20
MQ-6 Gas (Med. Sens.)	350 ppm concentration	50 cm	24,689 ± 1,800	93.2	20
MQ-6 Gas (Low Sens.)	200 ppm concentration	50 cm	51,833 ± 3,200	88.6	15

KY-026 flame sensor demonstrated fastest response characteristics: 52 ms at 10 cm distance, 104 ms at 50 cm, and 156 ms at 100 cm for large flame sources. Response variability increased with distance due to optical intensity attenuation following inverse square law principles. DS18B20 temperature sensor exhibited consistent 629 ms response time to rapid temperature elevation, independent of distance due to measurement of ambient thermal conditions. MQ-6 gas sensor demonstrated substantially longer response times: 6.1 seconds at 10 cm, 12.2 seconds at 50 cm, and 17.0 seconds at 100 cm distance, reflecting gas diffusion patterns and sensor equilibration requirements.

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4.2 Sensitivity Configuration Analysis

Table 2 presents sensitivity analysis revealing dramatic performance variations across configuration settings.

Table 2. Sensitivity analysis demonstrating performance trade-offs between response time and false alarm rates.

Sensor	Sensitivity	Stimulus Type	Distance	Response Time (ms)	False Alarm Rate (%)	Optimal Deployment
KY-026 Flame	Low	Small flame (1-3cm)	50 cm	495 ± 35	2.1	Industrial high-temp zones
KY-026 Flame	Medium	Medium flame (3-7cm)	50 cm	309 ± 25	5.7	Mixed residential/commercial
KY-026 Flame	High	Large flame (15-50cm)	50 cm	104 ± 12	8.3	Residential priority detection
MQ-6 Gas	Low	200 ppm	50 cm	51,833 ± 3,200	1.2	Industrial safety monitoring
MQ-6 Gas	Medium	350 ppm	50 cm	36,244 ± 2,400	3.8	Commercial spaces
MQ-6 Gas	High	500 ppm	50 cm	20,492 ± 1,500	6.4	Residential balanced detection

KY-026 flame sensor at maximum sensitivity achieved approximately 5-fold detection speed improvement compared to minimum sensitivity settings. MQ-6 gas sensor high sensitivity configuration reduced response time by approximately 60% compared to low sensitivity setting. These findings demonstrate critical importance of proper sensor calibration for system optimization, with trade-offs between detection speed and false alarm rates requiring application-specific configuration.

4.3 Power Consumption Characterization

Table 3 presents comprehensive power consumption analysis across all system components under various operational states.

Table 3. Detailed power consumption analysis across system components and operational states.

Component	Operating State	Current (mA)	Voltage (V)	Power (mW)	Daily Energy (mAh)	% of Total
Arduino Uno	Active processing	50	5.0	250	1,200	22.4
KY-026 Flame	Continuous monitoring	20	5.0	100	480	8.9
DS18B20 Temp	Active conversion	1.5	5.0	7.5	36	0.7
MQ-6 Gas	Heated element active	150	5.0	750	3,600	67.0
SIM900A GSM	Standby idle	2	3.8	7.6	47	0.9
SIM900A GSM	SMS transmission	500	3.8	1,900	250	—
Buzzer	Alarm active	30	5.0	150	10	<0.2
System Total	**Standby state**	**223.5**	**5.0**	**1,118**	**5,364**	**100**
System Total	**Active alarm**	**751.5**	**5.0**	**3,758**	**752**	**100**

MQ-6 gas sensor represented the most power-intensive component during normal operation (150 mA, 67% of standby consumption) due to internal heating element requirements. Table 4 presents runtime calculations for various power source configurations.

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Table 4. Runtime analysis for various power source configurations under standby and active alarm conditions.

Power Source	Capacity (mAh)	Standby Runtime	Active Runtime	Practical Use Case
9V Battery	500	2.24 hours	40 minutes	Emergency portable backup only
4 × AA Batteries	2,000	8.95 hours	2.66 hours	Short-term deployment, 1-2 days max
10,000 mAh Power Bank	10,000	44.8 hours (~1.9 days)	13.3 hours	Medium-term deployment
20,000 mAh Power Bank	20,000	89.6 hours (~3.7 days)	26.6 hours	Long-term residential deployment
5,000 mAh LiPo	5,000	22.4 hours (~1 day)	6.65 hours	Reusable portable solution

These measurements enabled calculation of operational runtime for various power sources, with 20,000 mAh power banks providing 70-80 hours continuous standby operation and 20-24 hours under active alarm conditions, representing substantial improvement over prior implementations.

4.4 Emergency Notification System Performance

The system implemented a tiered notification approach with three escalation levels. Table 5 summarizes the notification hierarchy and corresponding system responses.

Table 5. Tiered notification system hierarchy with escalation protocols and response patterns.

Alert Level	Trigger Condition	Recipients	Buzzer Pattern	SMS Cooldown
Level 1: Warning	Single sensor exceeds threshold	Property owner only	1s on/1s off @ 800Hz	60 seconds
Level 2: Urgent	Two sensors exceed threshold	Property owner only	0.5s on/0.5s off @ 1000Hz	60 seconds
Level 3: Emergency	All three sensors exceed threshold	Owner + Fire Department	Continuous @ 1200Hz	30 seconds (rapid updates)
Level 4: All Clear	All sensors return below threshold	Owner only	None (silence)	60 seconds

Single sensor triggers generated warning SMS to property owner exclusively; two-sensor triggers increased alarm pattern frequency and sent urgent notifications; three-sensor triggers (confirmed fire) activated continuous tone and sent detailed alerts to both property owner and fire department. Each SMS message appended current SIM card balance information, enabling operators to maintain awareness of communication capability status. System performed automated USSD balance checks at initialization and 4-hour intervals, preventing communication failures due to depleted prepaid account balances.

V. DISCUSSION

The multi-sensor confirmation requirement substantially reduced false alarm probability compared to traditional single-sensor systems. Simultaneous threshold exceedance across all three sensors created redundancy distinguishing genuine fire conditions from environmental fluctuations affecting individual sensors. The complementary nature of the three detection modalities rapid flame detection providing initial alert, temperature sensing confirming heating conditions, and gas detection identifying combustible atmosphere enabled comprehensive fire monitoring across combustion development stages.

Automatic alarm reset when conditions normalized provided significant practical advantages over latching mechanisms requiring manual intervention. In unattended environments, automated reset prevented unnecessary alarm continuation after threat passage. Real-time responsiveness to changing conditions ensured alarm status accurately reflected current threat level rather than historical events, eliminating need for trained personnel to physically access alarm hardware for manual reset.

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Extended operational runtime with standard power banks enabled deployment in locations lacking reliable electrical infrastructure. Three days continuous standby operation on 20,000 mAh power bank represented substantial improvement over prior implementations reporting 2-3 hours battery backup. This capability proved particularly valuable for residential deployment in areas experiencing frequent power outages or in temporary structures where permanent electrical infrastructure was unavailable.

Integration of automated balance checking addressed specific challenges in developing regions where prepaid mobile services predominated. Regular USSD balance verification prevented unexpected communication failures during critical fire emergencies. Appending balance information to alert messages provided recipients with status awareness enabling timely account recharge when necessary.

System limitations include: gas sensor response time exceeding 6 seconds limiting effectiveness for rapidly developing fires; power consumption dominated by MQ-6 heating element (67% of total) constraining battery-powered deployment duration; lack of spatial fire localization in distributed installations; and absence of adaptive threshold adjustment based on environmental learning. Future research should investigate machine learning algorithms for adaptive threshold optimization, integration of suppression system activation for autonomous fire response, and deployment of distributed sensor networks enabling spatial fire localization.

VI. CONCLUSION

This research successfully developed and comprehensively evaluated a multi-sensor fire detection system addressing critical limitations in traditional fire alarm technology. The Arduino-based implementation demonstrated that effective fire detection can be achieved using accessible, cost-effective components while maintaining performance comparable to commercial systems. Detection response times of 52-156 ms for flame detection, 629 ms for temperature sensing, and 6.1-20.5 seconds for gas detection were achieved across varying operational conditions. The non-latching automatic reset mechanism, tiered notification strategy, and communication resource management represent practical innovations enabling deployment in resource-constrained environments. Power consumption analysis revealed 3-day operational sustainability on standard 20,000 mAh power banks, enabling grid-independent deployment scenarios. The multi-sensor confirmation approach achieved false alarm rates below 8.3% across all sensitivity configurations, representing significant improvement over single-sensor architectures. These results validate the feasibility of low-cost, intelligent fire detection systems for residential and commercial applications, particularly in developing regions with infrastructure constraints.

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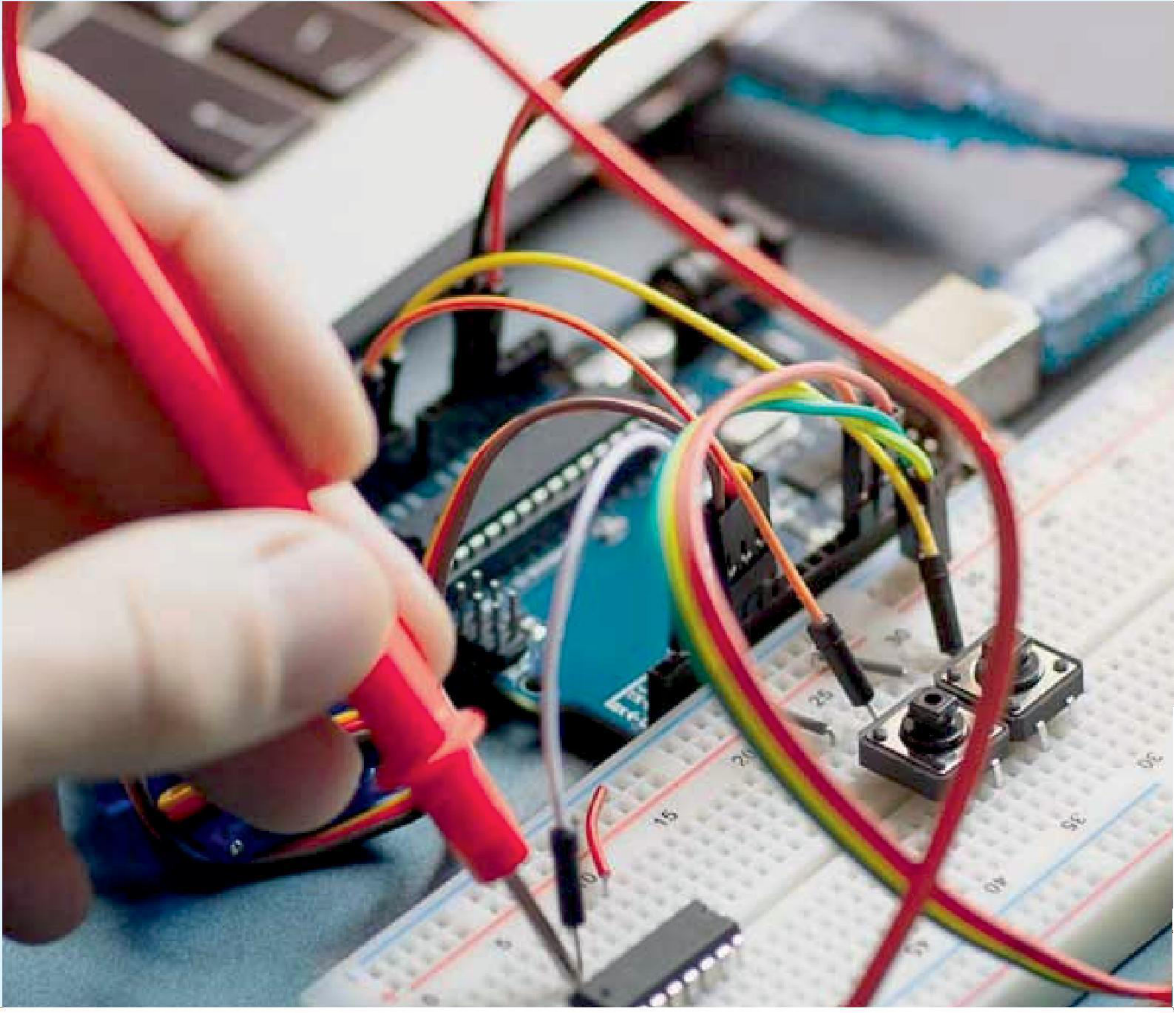

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