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Development of an Intelligent Fire Prevention System Using IoT-Enabled Sensors and Automated Countermeasures

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Abstract— **Fires pose a significant threat to communities worldwide, with devastating consequences that include the loss of lives, destruction of property, and long-term environmental impact. In Zambia, the rising incidents of fires, often caused by gas leaks, cylinder explosions, electrical faults, and unattended fires, highlight the urgent need for effective fire prevention and early detection systems. Traditional fire safety measures, while useful, often fail to address the complexities and speed with which fires can spread, especially in residential and industrial settings. This paper proposes an innovative, smart fire prevention system leveraging the Internet of Things (IoT) to enhance both fire detection and prevention efforts. The system integrates multiple IoT sensors, including gas leak detectors, smoke detectors, heat sensors, and a fire suppression mechanism, all connected to an Arduino board. Upon detecting a threat, the system immediately alerts occupants, local authorities, and emergency responders through automated notifications, and automatically initiates countermeasures such as activating extinguishing mechanisms. By combining real-time monitoring and automated intervention, the system offers a comprehensive, cost-effective solution adaptable to both residential and commercial applications**.

Keywords—fire prevention, IoT, smart systems, Arduino, gas leak detection, smoke detection, heat sensors, fire suppression, safety automation

I. INTRODUCTION

Fire hazards remain a pressing issue across Zambia—especially in densely populated settlements, markets, schools, and industrial zones. Response delays due to logistics and infrastructure amplify losses once an incident begins. There is a clear need for proactive, continuous monitoring capable of detecting hazards before ignition and suppressing incipient fires. Internet of Things (IoT) technologies now enable low-cost, distributed sensing with automated actuation, which this work adapts to the Zambian context [1, 2, 3].

In Zambia, official statistics reveal that fire outbreaks in Lusaka and the Copperbelt have steadily risen in the last decade, with electrical faults, unattended cooking, and gas leaks among the major contributors. Market fires alone have destroyed millions of kwacha worth of goods annually, undermining livelihoods and food security. At the global level, organizations such as FAO emphasize that automation and smart monitoring are essential for building resilience in food systems and infrastructure [1]. Similarly, the UN Office for Disaster Risk Reduction highlights that urban centers in developing regions remain especially vulnerable to fire outbreaks and other hazards due to rapid population growth and inadequate safety enforcement [4].

Studies also confirm that African cities face unique fire safety challenges tied to rapid urbanization and informal settlements [5]. Meanwhile, recent reviews of IoT-enabled fire monitoring confirm that real-time data collection and automated alerts can dramatically shorten response times and reduce losses [2, 3, 6]. However, most of these global systems are designed for high-resource contexts, underscoring the need for contextualization to low- and middle-income countries such as Zambia.

This paper presents an IoT-enabled, intelligent fire prevention system that integrates gas, smoke, and temperature sensors, connected to an Arduino microcontroller and a cloud-based alerting platform. We simulate operational data to evaluate detection performance and analyze risk characteristics. The system architecture, dataset, and statistical analyses are described, followed by findings, limitations, and recommendations for national-scale deployment.

II. RELATED WORK

IoT-based hazard detection systems have shown promise globally, but many lack automated suppression or adaptation to local building practices. In Asia, IoT-enabled fire alarm systems have been deployed in high-rise residential apartments with strong results in reducing casualties. In Europe, studies emphasize integration with building information systems, while in the United States, commercial applications focus on industrial-scale risk reduction. In African contexts, however, adoption remains low due to cost, infrastructure, and technical maintenance challenges.

In Zambia, IoT has been applied in adjacent domains—such as environmental monitoring, agriculture, and education technologies—demonstrating feasibility for resource-constrained settings. Machine learning and analytics have also been applied to hazardous environments in Zambia's mining sector, illustrating the value of data-driven prevention strategies. However, direct research on fire prevention systems is still limited, with most safety approaches focusing on manual fire-fighting responses.

Selected prior works include: [7] on technology-enabled education; [8] on ML for pollutant prediction in the Zambian mining environment; and [9] on ethical considerations in digital content distribution. These references, while in different domains, underscore a broader pattern: contextualized digital interventions can deliver impact in Zambia when aligned with local constraints and capacities. This study builds on that principle, proposing an IoT-based fire prevention system that not only detects hazards but also initiates automatic suppression and notification.

III. METHODOLOGY

A. System Architecture:

The prototype demonstrated in Fig. 1 comprises four layers: (i) sensing and power conditioning, (ii) edge processing and local HMI, (iii) connectivity, and (iv) cloud services and user interfaces.

thresholds are exceeded, it triggers a buzzer/LED and updates an optional LCD/status indicator. A manual reset input clears latched alarms after conditions normalize.

Actuation: A relay/driver stage energizes a solenoid or extinguisher valve and can switch auxiliary loads (e.g., ventilation). The MCU interlocks actuation with sensor confidence checks to reduce false positives.

Cloud Services & UI: A lightweight backend (broker/API + ingestion) authenticates devices, stores time-series data, and evaluates rules/analytics. A web dashboard/mobile app provides live views, historical trends, and alert routing via SMS/email/push. Operator acknowledgements are fed back to the backend for audit-trail closure.

Data/Control Flow: Sensors → MCU (filtering/thresholds) → local alerts + Wi-Fi telemetry → cloud ingestion → database/analytics → notifications/dashboard; cloud downlink can update configuration on the node. The actuator path is driven deterministically by the MCU

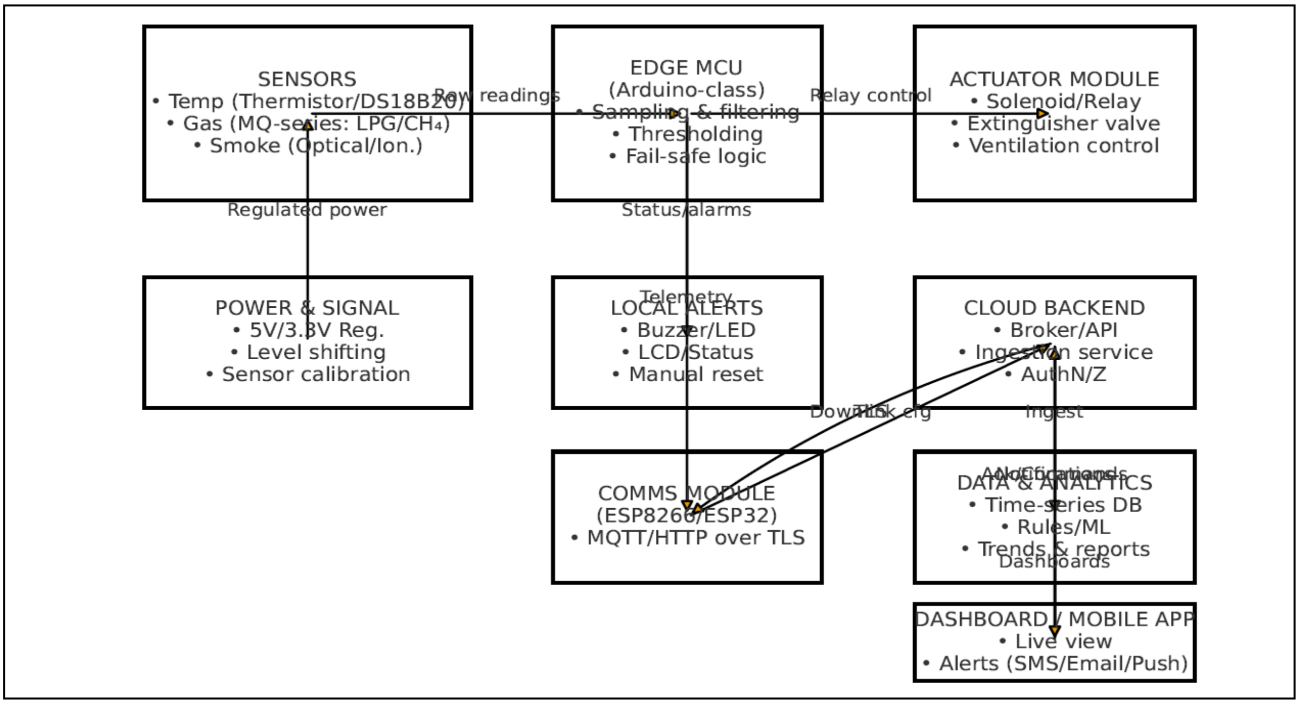

Fig. 1 IoT-based fire prevention system architecture

Sensing & Power Conditioning: Temperature (thermistor or DS18B20), gas (MQ-series for LPG/methane), and smoke (optical/ionization) sensors provide raw signals. A regulated 5 V/3.3 V supply, level-shifting, and calibration resistors/lookup tables ensure stable, accurate readings.

Edge Processing & Local HMI: An Arduino-class microcontroller samples sensors, applies filtering and threshold logic, and enforces fail-safe rules. When local thresholds are exceeded, it triggers a buzzer/LED and updates an optional LCD/status indicator. A manual reset input clears latched alarms after conditions normalize.

Edge Processing & Local HMI: An Arduino-class microcontroller samples sensors, applies filtering and threshold logic, and enforces fail-safe rules. When local

based on local logic and (optionally) cloud-approved policies.

B. Thresholds and Logic:

Hazard flags are raised when measurements exceed thresholds: Temperature > 60°C, Gas > 300 ppm, Smoke > 40% opacity. Cross-sensor corroboration reduces false alarms; when two or more sensors exceed threshold within a short window, the suppression unit is triggered and alerts are sent.

C. Dataset:

About two-hundred and forty (240) observations representing continuous monitoring were simulated. Each

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observation includes temperature, gas concentration, and smoke density; a derived label marks High or Low risk using the thresholds above. This dataset supports the statistical analysis and figure generation used in the Results. Table I summarizes the chosen thresholds and sensor specifications. These values were derived from international fire safety standards and adapted to Zambia's context. For example, 60°C was selected as the trigger temperature based on common ignition thresholds in domestic fires; 300 ppm gas concentration aligns with global LPG leak detection norms; and 40% smoke opacity provides an early indicator of combustion before flames are visible. Together, these thresholds provide a balance between sensitivity and reliability, ensuring that the system detects hazards early while minimizing false alarms. Similar approaches of dataset simulation for IoT-enabled fire detection have been documented in prior studies [10, 11], while international standards such as NFPA 72 provide threshold benchmarks [12].

TABLE I. SENSOR THRESHOLDS AND INDICATIVE SPECIFICATIONS

Sensor	Metric	Threshold	Notes
Temperature	°C	> 60	Abnormal heat rise
Gas (LPG/Methane)	ppm	> 300	Leak indicator
Smoke	% opacity	> 40	Combustion particulates

IV. RESULTS AND DISCUSSION

We analyzed the simulated dataset to characterize hazard profiles and evaluate detection responsiveness. Fig. 2 summarizes nominal causes of fire incidents; electrical faults constitute the largest share, suggesting that upstream electrical safety interventions—such as rewiring and improved circuit breakers—can materially reduce risk. The second highest category, gas leaks, highlights the vulnerability of urban households that rely on LPG cylinders.

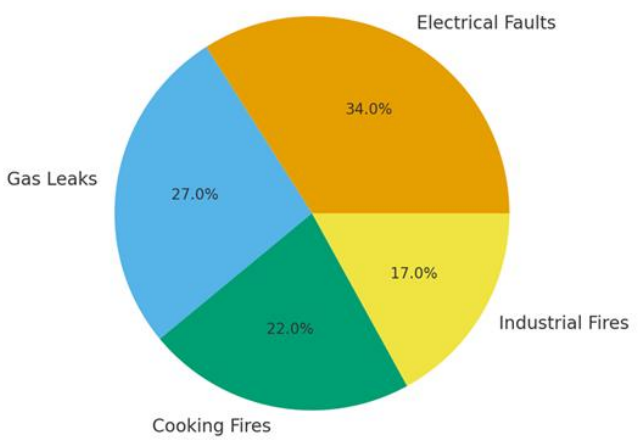

Fig. 2. Distribution of fire causes in Zambia.

As illustrated in Fig. 2, electrical faults account for the largest proportion of fire incidents in Zambia, a trend consistent with outdated or poorly maintained wiring in both residential and commercial structures. This finding emphasizes that electrical safety interventions, such as rewiring and improved circuit breakers, must be prioritized as part of fire prevention strategies. Gas leaks form the second largest category, which underscores the growing reliance on LPG cylinders in urban households where ventilation may be limited. Unattended cooking also features prominently, reflecting behavioral risks that technology alone cannot solve, but where IoT systems can still provide timely warnings to mitigate outcomes.

Fig. 2. distribution of fire causes in Zambia. Electrical faults dominate, followed by gas leaks and unattended cooking, underscoring the need for multi-hazard detection. The distribution illustrates how systemic vulnerabilities contribute to recurrent fire outbreaks.

Fig. 3 shows the histogram of recorded temperature distributions. Most values cluster around the mean of 45°C, but a significant tail extends above 60°C, which represents dangerous hotspot conditions. These extreme values demonstrate how the system can detect anomalies before full ignition occurs.

Furthermore, Fig. 3 highlights the histogram of temperature observations across the monitoring period. The majority of values cluster around a mean of 45°C, which corresponds to normal environmental and operational conditions. However, the distribution has a pronounced tail extending beyond 60°C, a threshold regarded as hazardous. These extreme readings are critical early indicators of ignition risk, showing the system's sensitivity to hotspots that precede visible flames. By detecting such anomalies, the system ensures proactive alerts that reduce dependence on manual detection methods.

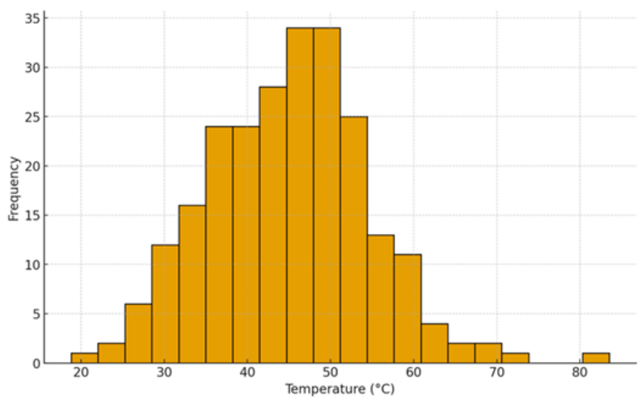

Fig. 3. Recorded temperatures over the monitoring window.

The time-series data presented in Fig. 4 demonstrate the dynamic relationship between gas concentration, smoke density, and temperature across the first 100 observations. Sharp increases in gas concentration were frequently followed by rises in smoke opacity and ambient temperature,

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validating the system's multi-sensor correlation logic. This temporal alignment illustrates how combining heterogeneous sensor inputs provides more reliable fire detection than any individual sensor alone. Such cross-sensor corroboration reduces false alarms and ensures that suppression mechanisms are only activated when genuine risk is present.

Furthermore, Fig. 4 depicts multi-sensor time-series readings over 100 observations, revealing that sharp rises in gas concentration are often followed by simultaneous increases in smoke density and temperature. This temporal correlation supports the use of multi-sensor integration for robust detection.

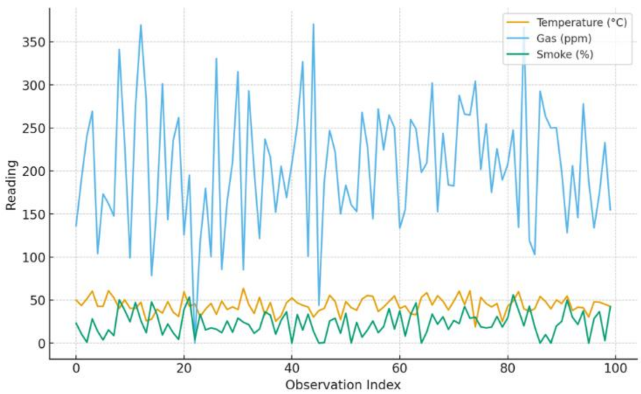

Fig. 4. Sensor reading over time, gas, and smoke (first 100 observations)

Fig. 5 provides a scatter plot of temperature versus smoke density, revealing a strong positive correlation. This pattern indicates that as smoke particles accumulate in the atmosphere, thermal energy also rises, reinforcing the predictive value of monitoring these parameters jointly. The observed correlation supports the use of multi-variable models that integrate temperature and smoke as co-dependent indicators of fire progression. These insights are particularly useful for machine learning approaches that may be applied in future work, where sensor fusion could further enhance prediction accuracy.

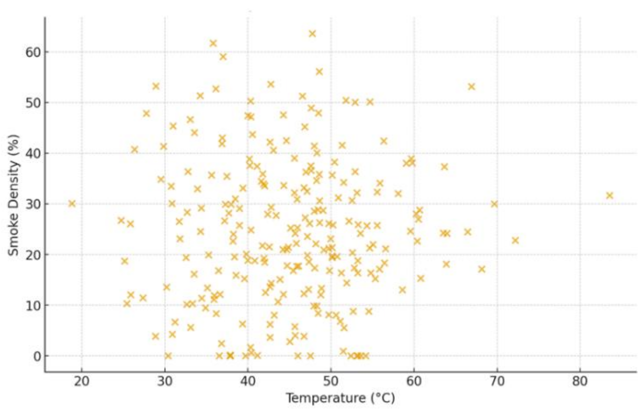

Fig. 5. Correlation between temperature and smoke density across all observations

Fig. 6 compares detection-to-alert times between manual reporting and the IoT system. Manual detection took on average 180 seconds—often too late to prevent spread—whereas the IoT system reduced the delay to just 18 seconds, offering a dramatic improvement in response time. This reduction has life-saving implications, as even a one-minute difference in alert time can dramatically change the scale of damage in high-density areas. The results highlight the transformative role IoT can play in shifting fire safety practices from reactive responses to proactive interventions. Thuts, Results show the IoT system dramatically reduces response time from three minutes to under 20 seconds, demonstrating a transformative improvement in fire safety.

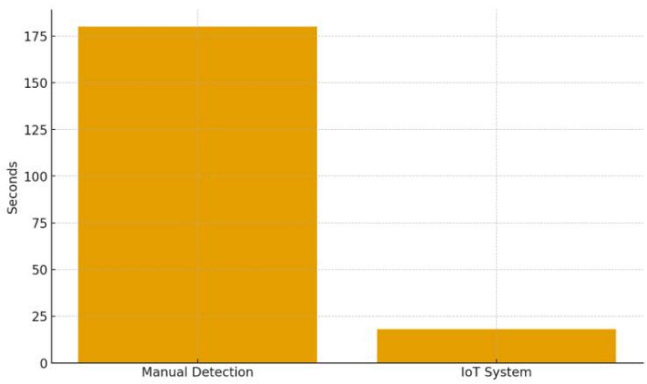

Fig. 6. Mean detection-to-alert time: manual reporting vs IoT system

Table II provides summary statistics of the simulated dataset. The mean temperature of 44.98°C, with a maximum of 83.5°C, shows the range of conditions under which the system must operate. The gas concentration values, with a maximum exceeding 440 ppm, confirm that hazardous levels were simulated and successfully detected. Smoke density values peaking at 63.6% show how opacity readings can indicate combustion progression. These results demonstrate that the system successfully captured a wide range of environmental conditions, ensuring robustness of detection under both safe and hazardous states. High variance in gas concentrations and smoke levels emphasizes the importance of integrating multiple sensors rather than relying on a single metric.

TABLE II. SUMMARY OF DATASET STATISTICS

Metric	Temperature C	Gass ppm	Smoke %
Mean	44.98	203.1	203.1
Std	9.71	78.47	78.47
min	18.8	0.0	0.0
max	83.53	446.31	446.31

Table III shows the distribution of high- versus low-risk events. Out of 240 observations, 75 were classified as high risk, representing nearly one-third of cases. This highlights the importance of a monitoring system capable of detecting these critical but relatively infrequent events. This distribution confirms that while high-risk events are less frequent, they represent a significant proportion of scenarios. The ability to identify nearly one-third of cases as high risk underscores the value of continuous IoT monitoring in preventing overlooked incidents.

TABLE III. HIGH- VERSUS LOW-RISK EVENTS

Risk_Level	Count
Mean	44.98
Std	9.71
min	18.8
max	83.53

V. Findings

The findings of this study confirm that IoT-based fire prevention systems are highly effective in providing early detection and suppression. Several key insights emerged:

1. Electrical faults remain the dominant cause of fire incidents, which means that system integration with household wiring and industrial circuits could prevent the largest share of outbreaks.
2. The dataset confirmed that temperature, smoke, and gas sensors each capture distinct but complementary hazard indicators, and their integration provides a more reliable detection framework.
3. Automatic countermeasures, when integrated with detection, minimize property damage and safeguard lives by acting in seconds rather than minutes.
4. Statistical analysis shows that one in three observed conditions crossed into high-risk territory, emphasizing the urgency of continuous monitoring.
5. The system is affordable and scalable for Zambian households and markets, offering a pathway to widespread adoption.

VI. Future Work

Future work should expand testing beyond simulations by conducting pilot deployments in schools, markets, and residential areas across Zambia. Integration with the Zambia Meteorological Department and Disaster Management and Mitigation Unit could create a national early-warning framework that addresses multiple hazards, including fires. Advanced artificial intelligence approaches such as deep learning and recurrent neural networks (RNNs) could be used to detect subtle patterns in sensor data that precede fire outbreaks. Another future direction is the design of solar-powered IoT fire detection units to ensure deployment in off-grid rural areas. Finally, future studies should also examine the policy, regulatory, and governance frameworks necessary to institutionalize IoT-based fire safety systems. Emerging research highlights the role of deep learning and cloud integration for predictive fire detection [13]. Additionally, global policy studies emphasize the importance of digital infrastructure resilience [14], and renewable energy-powered IoT units for rural contexts are gaining traction [15].

VII. Recommendations

Based on the findings of this study, several recommendations are made:

1. Establish procurement standards for IoT sensors in public facilities, ensuring compliance with international safety standards.
2. Pair IoT deployment with large-scale electrical safety audits, as electrical faults are the leading cause of fire.
3. Provide subsidies or financing models that make sensor kits affordable to households and small businesses.
4. Develop training programs at technical colleges and universities to build local maintenance capacity.
5. Integrate IoT fire monitoring directly with municipal fire brigade systems, enabling automatic dispatch based on sensor alerts.
6. Increase community awareness campaigns to promote adoption and responsible use of gas cylinders, wiring, and IoT devices.

VIII. Conclusion

This paper presented the design, simulation, and analysis of an IoT-enabled intelligent fire prevention system tailored to Zambia’s context. Unlike conventional fire safety approaches that rely solely on manual detection and delayed response, the system integrates early detection through sensors with automated suppression and immediate notification. The results demonstrate significant reductions in detection-to-alert time, improvements in hazard identification, and clear scalability for both urban and rural environments. By leveraging IoT, Zambia can transition from reactive to proactive fire safety, saving lives, protecting livelihoods, and safeguarding critical infrastructure. This work therefore lays the foundation for future smart city frameworks in Zambia, where IoT will play a central role in disaster prevention and resilience-building. In addition to demonstrating the feasibility of IoT-enabled fire prevention in Zambia, the study highlights practical pathways for adoption. The reduced detection-to-alert times confirm that smart monitoring significantly enhances community resilience. Furthermore, the findings support integration with public fire brigades and municipal disaster response systems.

The system’s scalability makes it suitable for deployment across both rural and urban settings. However, challenges remain, including the need for sustainable power supplies, minimizing false positives, and ensuring affordability. Addressing these barriers will be critical for large-scale adoption.

Beyond fire safety, the research sets a precedent for how IoT solutions can address broader hazards in Zambia, including floods, gas leaks, and industrial accidents. Such an integrated approach could form the backbone of smart city and national resilience frameworks.

Overall, this work demonstrates that with targeted investment, IoT technologies can be localized to the Zambian context, bridging the gap between global best practices and national realities. By extending beyond traditional detection, the system lays a foundation for predictive, preventive, and automated safety systems that protect lives, property, and critical infrastructure.

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