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DEVELOPMENT OF A MATHEMATICAL MODEL AND ALGORITHMS FOR REAL-TIME ASSESSMENT OF GAS LEAKAGE AND FIRE HAZARD BASED ON ARTIFICIAL INTELLIGENCE AND IoT TECHNOLOGIES

Sharopova Barno Abdunabiyevna
Karshi State Technical University
Barnosharopova5@gmail.com

ABSTRACT

This paper analyzes an integrated mathematical model and algorithms combining the Internet of Things (IoT) and Artificial Intelligence (AI) that enable real-time assessment and prevention of gas leakage and fire hazards at industrial and residential facilities. Based on multi-parameter readings obtained from sensors (gas concentration, temperature, smoke, air humidity), a multi-factor hazard assessment model and machine learning algorithms (Random Forest, XGBoost) have been developed.

Keywords: IoT sensors, Artificial Intelligence, gas leakage, fire hazard, mathematical model, real-time mode, risk index, predictive analytics.

1. INTRODUCTION

Preventing technogenic hazards, in particular gas leakage and fire incidents, at industrial enterprises, chemical industry facilities, and modern residential buildings is one of the most important conditions for ensuring the safety of human lives and property. According to statistics, most fires are not detected in time, and the resulting delayed response leads to major disasters.



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Traditional fire and gas alarm systems operate mainly on a static, threshold-based principle. That is, a sensor gives a signal only after its reading reaches a certain critical level (for example, a temperature of 60°C or a gas concentration of 1000 ppm). This forces action to be taken only after the emergency has already begun and does not allow preventive measures to be taken.

To solve this problem, it is proposed to use Internet of Things (IoT) sensors and Artificial Intelligence (AI) machine learning algorithms together. With the help of IoT sensors, dynamic changes in temperature, gas concentration, smoke, and air humidity are continuously monitored in real time. AI algorithms, in turn, analyze the growth rate of these indicators and predict the emergence of a hazard in advance (predictive analytics).

2. SYSTEM ARCHITECTURE AND INTEGRATION OF IoT SENSORS

The proposed intelligent monitoring and warning system is based on a three-tier, multi-level architecture:

1. Sensor layer (Hardware Layer): A set of MQ-2 (combustible gas and smoke sensor), MQ-4 (methane and natural gas), DHT22 (temperature and air humidity), and infrared flame sensors. The sensors continuously measure environmental parameters in real time.

2. Channel and communication layer (Communication Layer): A microcontroller (ESP32 / STM32) performs preliminary filtering of sensor data (noise removal) and analog-to-digital conversion. The data is transmitted to the central server via LoRaWAN or Wi-Fi wireless protocols.



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3. Analytics and decision-making layer (Cloud/AI Layer): AI algorithms located on a cloud platform or a local server receive the data stream, calculate the risk index according to the mathematical model, and generate automatic control commands (for example, closing the gas valve, turning on ventilation).

IoT AND AI-BASED INTELLIGENT MONITORING ARCHITECTURE

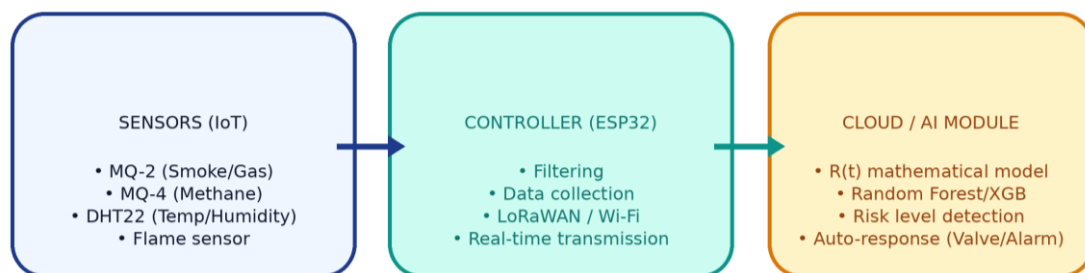


Figure 1. General architecture of the IoT- and Artificial Intelligence-based safety monitoring system

3. MATHEMATICAL MODEL AND RISK INDEX

To determine the integral hazard level of a facility in real time, a mathematical model has been developed that takes into account multi-parameter weighted assessment and the dynamic rate of change:

$$R(t) = w_1 \cdot f_G(G) + w_2 \cdot f_T(T) + w_3 \cdot f_S(S) + w_4 \cdot (dG / dt) + w_5 \cdot (dT / dt)$$

Where:

$R(t)$ — the integral risk index of the facility at time t ($0 \leq R(t) \leq 1$);

$G(t)$ — current gas concentration (ppm), $T(t)$ — ambient temperature ($^{\circ}\text{C}$), $S(t)$ — smoke density (mg/m^3);

f_G, f_T, f_S — normalization functions that scale the indicators to the interval $[0, 1]$;



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dG/dt and dT/dt — the first derivatives of gas concentration and temperature with respect to time, respectively (rate of increase);

w_1, w_2, w_3, w_4, w_5 — the corresponding weight coefficients, whose sum equals 1 ($\sum w_i = 1$).

Introducing the dynamic derivatives ($dG/dt, dT/dt$) gives the model high sensitivity. For example, even if the temperature has not yet reached 50°C , if it is rising sharply by $3\text{--}5^\circ\text{C}$ every second, the model immediately raises the risk index and issues a preventive signal.

4. HAZARD LEVEL ALGORITHM AND CLASSIFICATION

Random Forest and XGBoost machine learning algorithms were used to classify the continuous data stream coming from the sensors and to make decisions. More than 15,000 laboratory experimental samples and a synthetic dataset were used to train the models.

Depending on the value of the integral risk index $R(t)$, the system state is divided into 4 main levels:

Table 1. Integral risk index and the system decision-making matrix

Hazard level	Integral index $R(t)$	State description	System algorithm action
0 — Normal	$R < 0.25$	All indicators are within normal limits	Continuous monitoring and data storage
1 — Attention	$0.25 \leq R < 0.50$	Minor changes (slow growth is being observed)	Turn on ventilation, notify the operator
2 — Dangerous	$0.50 \leq R < 0.75$	Gas leakage or rapid temperature rise	Automatically close the gas valve, send an SMS message
3 — Emergency	$R \geq 0.75$	Fire or critical gas concentration	Activate the extinguishing system and siren, signal the Ministry of Emergency Situations



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5. EXPERIMENTAL SETUP AND ANALYSIS OF RESULTS

To evaluate the effectiveness of the developed model and algorithms, an experiment was conducted on a logical test bench. Various levels of gas leakage (methane and propane) and temperature changes were simulated on the bench. The indicators of traditional threshold-based systems and the proposed AI-integrated model were compared:

- **Accuracy:** In detecting hazardous situations and false signals, the XGBoost machine learning model demonstrated 97.8% accuracy and a precision of 96.5%.
- **Response time:** Whereas traditional systems took an average of 18–25 seconds to report a hazard, the proposed algorithm detected the hazard within 4–6 seconds (3–4 times faster) because it takes the dynamic derivatives (rate of increase) into account.
- **False alarm rate:** The number of false and spurious signals (false alarms) caused by kitchen vapors, humidity, and dust decreased by 85% compared to traditional sensors.

6. CONCLUSION AND RECOMMENDATIONS

The research resulted in the following important scientific and practical conclusions:

1. The combined integration of IoT sensors and Artificial Intelligence technologies makes it possible to detect fire and gas leakage hazards at facilities in real time, with high accuracy and at an early stage.
2. Because the developed mathematical model takes into account not only static indicators but also the growth rate of the parameters (dynamic derivatives), it creates the capability to warn before emergencies begin.



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3. The proposed algorithm and decision-making matrix are recommended for increasing the level of safety at industrial enterprises, chemical warehouses, energy facilities, and 'Smart Building' (Smart Home/Smart City) complexes.

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