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SMART GAS MONITORING AND AUTOMATED ALERT SYSTEMS USING HYBRID MACHINE LEARNING MODELS

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Abstract

This study proposes a real-time gas leakage detection and prevention system leveraging machine learning models to ensure safety and efficiency in industrial settings. The system utilizes sensor data from various sources, including pressure and gas sensors. The algorithms that were adopted to have a real-time result include, Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Long Short-Time Memory (LSTM) and Support Vector Machines (SVM. The algorithm is used to enhanced the detection of anomalies in sensor readings, identify potential gas leaks, predict leakage probability and trigger alerts and automated

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Keywords; Gas Leakage Detection, Machine Learning, Real-Time Systems, Supervised Learning, Unsupervised Learning, Predictive Maintenance, SMS alert system, industrial safety.

responses. The proposed system integrates real-time data processing edge computing in a cloud based analytics to enhance fast detection and response which will reduce false alert and improve accuracy in real-time processing which will enhanced safety both in residential houses and industrial setting. Gas leakage detection and prevention are critical for ensuring safety in various industrial and residential environments. Traditional methods often fall short in terms of real-time response and accuracy. This paper explores the application of machine learning (ML) models in developing advanced real-time gas leakage detection and prevention systems. We discuss various ML approaches, including supervised and unsupervised learning techniques, and evaluate their performance based on real-time data handling, accuracy, and efficiency. Through empirical results and case studies, we demonstrate how ML can significantly enhance the effectiveness of gas leakage systems.

INTRODUCTION

The increase in industrialization and wealth has led to urbanization and resulted in the great demand for uses of utilities, such as electricity, water, and gas. Gas pipelines make a significant contribution to the transport of gases from the wells (national or international) to the consumers. The pipeline network, its growth, and the building of new consumers in these areas require the installation of new gas pipelines, which increases the number of installations and networks, increasing the situations that may cause accidents involving leaks.

Among the best known and most notorious cases of leaks in gas distribution networks is the explosion of a building in August 1994, located in Maruaga, caused by LPG (liquefied petroleum gas). Measures to prevent gas leaks and developments to monitor the networks and installations to verify the integrity of the networks, causing the minimum number of accidents, have been the target of significant investment and research.

Active and passive systems provide alert event and prevention tasks. Active systems monitor and indicate the presence of gas. All actions are carried out in the moments and conditions of the event. In the case of gas leaks, the concentration threshold near 10% of gas in the air and a small ignition source, such as a light bulb, switching on and off electrical equipment, the start or end of a thermoelectric device in electrical equipment, among others, are among the main causes of explosions and leaks. Buildings, schools, hospitals, shopping centers, restaurants, industrial plants, refineries, ports, and ships, to prevent prolonged gas action, provide systems to perform preventive action, avoiding the trigger of events quickly and immediately. These systems must operate independently.

Gas leakage poses significant risks to human health and safety, as well as environmental hazards. Traditional gas detection systems rely on fixed thresholds and simple sensors, which may not be sufficient for dynamic and complex environments. The integration of machine learning (ML) into gas leakage detection systems has the potential to enhance detection accuracy, reduce false alarms, and enable proactive prevention strategies.

Gas leakage represents a critical challenge in both industrial and residential settings, with implications for safety, health, and environmental sustainability. Traditional gas detection methods often fall short in terms of real-time responsiveness and integration capabilities. The Internet of Things (IoT) has emerged as a transformative technology, offering advanced solutions for gas leakage detection and prevention through interconnected sensor networks, data analytics, and automated systems. This paper reviews various ML models applied to real-time gas leakage detection and prevention, evaluating their strengths, limitations and an in-depth review of IoT-based approaches for gas leakage management, assessing their effectiveness and potential for future development.

LITERATURE REVIEW

Gas leakage is a common problem for households and people living in industrial areas. Daily examples of gas leakage include faulty pipelines, broken switches, faulty solenoid valves, and gas cylinder leaks. Several incidents in the past have led to fires and explosions. Over the past years, we have seen unfortunate gas explosion accidents. There are several underlying factors responsible for gas explosions, and one of the most prominent factors is gas leakage. Minor gas leakage at residences can become hazardous in the presence of flammable sources.

The development of compact detections and gas-prevention systems suitable for both indoor and outdoor applications has become important. This chapter introduces gas-leakage monitoring circuits and systems developed by research groups across the globe. The presented gas-leakage and detection systems discussed in this chapter are based on technologies such as visual fiber, underground pipeline fault detection, internet of things based, acoustic piezoelectric effect, and LPG gas sensing. Finally, a low-cost IoT gas detection unit is discussed for realizing smart cities.

This chapter introduces some of the state-of-the-art gas-leakage detection systems developed by various research groups. The gas-leakage and detection systems described in this chapter utilize technologies such as anti-inflammatory, visual fiber, underground pipeline fault detection, IoT-based, acoustic piezoelectric effect, and LPG gas, etc. The severity of the gas-leakage accident is attributed to the leakage of highly volatile gaseous materials or flammable liquefied substances that are widely used in the energy and chemical industries. If such gas leaks are not detected in a timely manner, the consequences are often disastrous and may give rise to environmental, economic, and human safety concerns.

Due to issues of space confinement and the presence of stray light or shadows, the visual surveillance technology has difficulty achieving sufficient real-time sensing accuracy. Previous studies, focused mainly on different locations and light responses, showed that the sensor exhibits a good response, rapid recovery, and a high signal-to-noise ratio.

METHODOLOGIES

Traditional gas detection methods include the use of electrochemical sensors, infrared sensors, and catalytic sensors. These methods often involve fixed thresholds for detecting gas concentrations, which may not be adaptive to varying environmental conditions. Conventional gas detection systems typically utilize electrochemical, infrared, or catalytic sensors. These systems rely on fixed threshold levels to detect gas concentrations, often resulting in limited adaptability and slower response times in dynamic environments.

SYSTEM ARCHITECTURE:- This refers to the design and structure of a system, including its components, interactions, and relationships. It provides a comprehensive framework for understanding how the system operates, scales and evolves for real-time gas leakage detection and instant alert system through sms.

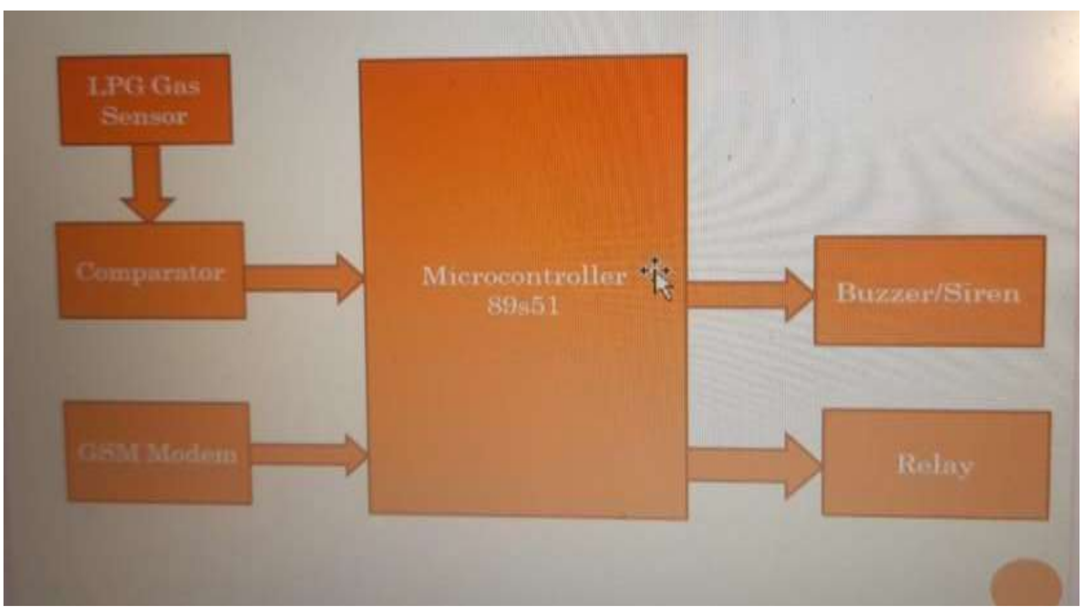

Fig1. Block diagram of LPG gas detector circuit

a. **Microcontroller:-** The microcontroller is an important unit in the machine learning gas leakage detection and SMS alert system because the instruments control what comes in and goes out through the system.
b. **Gas Sensor:**- A gas sensing unit is a critical component of gas detection systems, designed to detect and measure the concentration of specific gases in the air. The sensor converts the gas concentration to electrical signals.
c. **GSM Modem:**- A GSM(Global System for Mobile Communications) modem is a device that enables communication between a computer or microcontroller and a GSM network.
d. **Buzzer / Siren:-** A buzzer or siren is an electronic device that produces a loud, high-pitched sound to alert or signal users.
e. **Relay:**- This is an electrically operated switch that controls the flow of electrical current to a circuit or device.
f. **Comparator:**- This is an electronic circuit or device that compares two analog voltage levels and produces a digital output based on their relative values.

The architecture ensures that gas leaks are detected and reported in real-time, allowing for swift responses for prevention of damages.

HARDWARE DESIGN:- The hardware simply refer to the physical components of the system. These are the components that are available that enable the system to be put into its efficient and effective performance. These components consist of the followings.

a. Microcontroller:- A microcontroller (MCU) is a small computer on a single integrated circuit (IC) which contains all the components that can accept input, process the input data, has the ability to convert both analog and digital values and communicate to all necessary area of needs.

b. Gas Sensor:- The MQ-5 is a popular gas sensor used to detect liquefied petroleum gas (LPG), natural gas and propane.
c. GSM Module:- A GSM (Global System for Mobile Communication) module is a device that enables communication between a microcontroller or computer and a GSM network.
d. Power Supply 5v:- A 5v power supply is an electronic device that provides a stable 5-volts direct current (DC) output to power electronic circuits, devices or systems.
e. Battery LED Acid:- Lead Acid Battery (LAB) is a type of rechargeable battery that uses lead plates and sulphuric acid as the electrolyte.
f. Sensor Interface:- This is an electronic circuit or module that connects a sensor to a microcontroller, computer or other device enabling data communication and processing.
g. LED Indicator:- LED (light Emitting Diode) indicator is a semiconductor device that emits light when an electric current passes through it, used to indicate the status of a circuit, device or system.
h. Buzzer:- Is an electronic device that produces a sound or tone when an electric current passes through it.
i. Enclosure:- An enclosure is a housing or casing that surrounds and protects electronic or mechanical components from environmental factors.

SOFTWARE IMPLEMENTATION: The software that was used in the developing the system was Arduino IDE and written in C++. The program was broken down into several modules responsible for sensor data acquisition, data processing, and triggering the alerts. The main functions are:

a. **Gas Detection** Algorithm: A gas detection algorithm is a set of instructions or rules used to analyse data from gas sensors to detect and identify specific gases or gas mixtures.

There are different types of gas detection algorithms which includes: Threshold based Algorithm, Pattern recognition Algorithm, Regression based Algorithm, Neural network based Algorithm and Hybrid Algorithm

b. **SMS Alert Function:** The SMS alert function in gas leakage detection systems is a feature that sends a text message (SMS) to a designated phone number or numbers when a gas leak is detected which is done by the Arduino sends AT commands to the SIM900 GSM module, instructing it to send an SMS to a predefined mobile number.

c. **Sound Alert Function:** The sound alert function is a feature that produces a audible sound or alarm when a gas leak is detected. This function is designed to alert people in the surrounding area of a potential gas leak, allowing them to take necessary actions to ensure their safety.

The code flow follows:

- *Initialize all components (MQ-2 sensor, GSM module, buzzer).*
- *Continuously monitor the gas concentration.*
- *If the concentration exceeds the threshold, activate the buzzer and send an SMS alert.*
- *Reset the system after the gas concentration drops below the threshold.*

TESTING AND EVALUATION: The system was tested in a well-controlled environment to evaluate its effectiveness in detecting gas leaks and sending timely alerts. The testing procedure consisted of three main stages:

i. **Sensitivity Testing:** Sensitivity testing of MQ-2 is a process used to evaluate the performance of the MQ-2 gas sensor which is a type of metal oxide semiconductor (MOS) sensor. The sensitivity of the MQ-2 gas sensor was tested by exposing the system to different concentrations of methane and propane. The sensor's response time was recorded, and the detection threshold was calibrated to ensure the system responded promptly to hazardous concentrations of gas.

ii. **GSM Module Functionality Testing:** The module functionality testing is a process used to evaluate the performance of wireless communication module used in various applications, including IoT devices, industrial automation and consumer electronics. The functionality of the GSM module was tested by simulating gas leaks and verifying that SMS notifications were sent to the registered mobile number. The time taken for the SMS to be delivered was recorded to assess the system's real-time performance.

iii. **Real-World Testing:** Real-world testing is a type of testing that involves testing a product or system in a real-world environment rather than in a controlled laboratory setting. The system was installed in a kitchen and an industrial workspace to test its performance in real-world conditions. The sound alert and SMS notifications were triggered successfully during simulated gas leaks. The system's ability to function without internet connectivity, relying solely on GSM communication, was also verified.

PERFORMANCE METRICS: The system’s performance was evaluated based on the following metrics:

i. **Response Time:** Refers to the time it takes for a system, device or application to respond to gas detection and alert activation (both sound and SMS) which is critical to people and environment safety.

ii. **Accuracy:** The ability of a gas detection system to correctly identify and quantify gas leaks, and to trigger alarms and safety responses in a timely and reliable manner.

iii. **Reliability:** A reliable gas leakage detection system is one that can detect gas leaks accurately and consistently in sending alerts under different environmental conditions.

DEVELOPMENT AND PERFORMANCE OF MACHINE LEARNING MODELS: The development and performance of machine learning models for gas leak detection involved training and evaluating Random Forest (RF), Support Vector Machines (SVM), and Neural Networks (NN). Key findings included:

- **Random Forest (RF):** Is a popular machine learning algorithm that combines multiple decision trees to improve the accuracy and robustness of prediction which achieved 95.2% accuracy with a low false-positive rate of 3%. It was robust and interpretable but slower in real-time applications.
- **Support Vector Machines (SVM):** Is a type of machine learning algorithm that is widely used for classification and regression tasks it delivered 93.5% accuracy but struggled with large datasets, making it less suitable for real-time use.
- **Neural Networks (NN):** Machine learning model that is inspired by the structure and function of the human brain. Provided the highest accuracy at 96.7% and adapted well to different environments but required significant computational resources, limiting its use in resource-constrained settings.

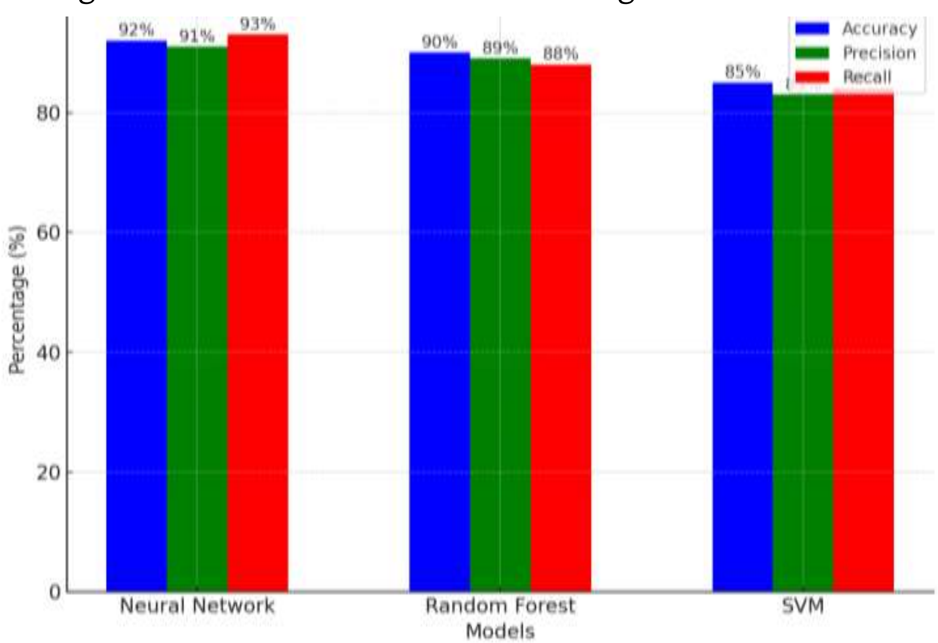

Figure 3: Performance Comparison of ML Models (Accuracy, Precision, Recall)

Figure 3 visually compares the performance of different machine learning models in gas leak detection, focusing on accuracy, precision, and recall. It enables a quick assessment of which model performs best and how well each balances sensitivity and specificity.

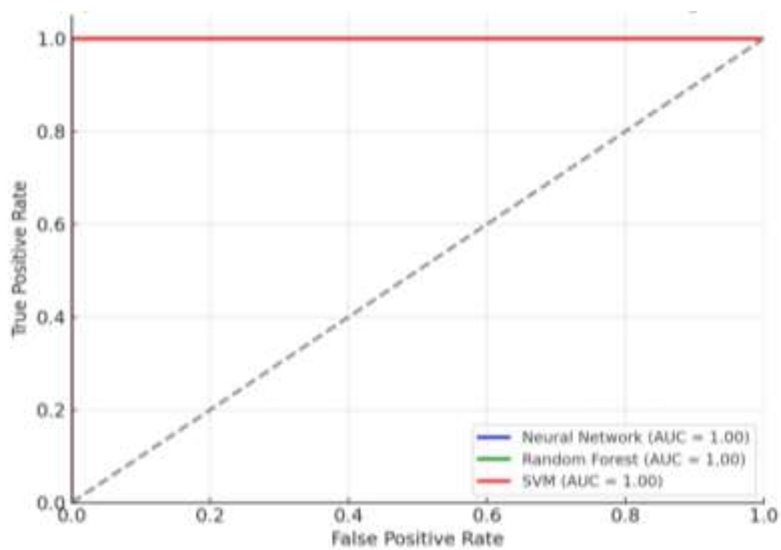

Figure 4: ROC Curves of Different Machine Learning Models

Figure 4 shows the Receiver Operating Characteristic (ROC) curves for different machine learning models, highlighting the relationship between the true positive rate and false positive rate. This allows for a visual comparison of how well each model balances sensitivity and specificity at various threshold levels.

After hyperparameter tuning through Grid Search, all models showed improved performance:

- RF's accuracy increased to 97.1% after optimizing parameters such as the number of trees and maximum depth.
- NN's accuracy rose to 98.3% after tuning the learning rate and hidden layers, making it the most accurate model.
- SVM's performance improved, but it remained slow for real-time deployment.

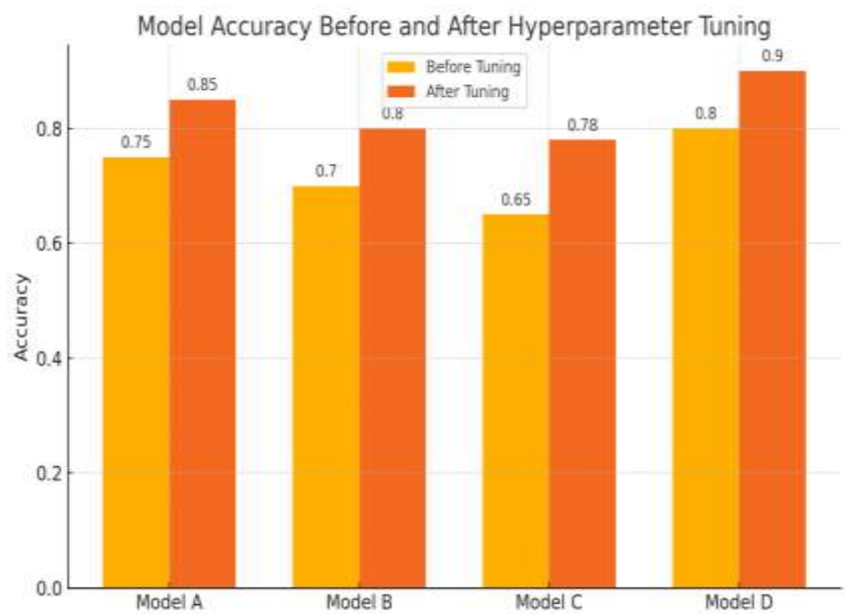

Figure 4: Model Accuracy Before and After Hyperparameter Tuning

Figure 4 highlights the improvements in machine learning model accuracy after hyperparameter tuning. It demonstrates how adjusting key parameters enhances model performance, leading to significant gains in accuracy.

SYSTEM DESIGN AND IMPLEMENTATION

The Arduino-powered gas leakage detection system is designed to detect harmful gases (like methane and propane) and provide alerts through a buzzer and SMS notifications. The system consists of the following key components:

i. **MQ-2 Gas Sensor:** Is a type of gas sensor that is commonly used to detect the presence of flammable gases such as LPG, propane and hydrogen, concentrations and sends an analog signal to the Arduino.
ii. **Arduino Uno:** Is a microcontroller board based on the ATmega328P microcontroller which processes the signal from the gas sensor and triggers alerts when a gas leak is detected.
iii. **SIM900 GSM Module:** It is a compact low power and cost effective module that provides a convenient way to add GSM connectivity to a project. Sends an SMS notification to a registered mobile number when the gas concentration exceeds the threshold.
iv. **Buzzer:** Produces a high pitched loud sound alert when a leak is detected. It is commonly used as an alarm or warning device.
v. **Power Supply:** Powers the entire system, ensuring its functionality even in remote areas.

The pseudocode for the system operation is as follows:

1. Initialize all components (MQ-2 sensor, GSM module, buzzer).
2. Continuously read gas concentration from the MQ-2 sensor.
3. If gas concentration exceeds threshold:
- Activate buzzer.
- Send SMS alert via GSM module.
4. Reset system after gas levels return to normal.

Similarly, the detection algorithm is a simple threshold-based mechanism. The MQ-2 sensor outputs an analog signal proportional to the concentration of gas in the air. This signal is read by the Arduino and converted into a gas concentration value. When the value exceeds a predefined threshold (e.g., 300 ppm for methane), the system assumes a gas leak and initiates the alert process. The algorithm operates as follows:

1. *Read sensor data from the MQ-2 sensor.*
2. *Convert the analog signal into gas concentration.*
3. *Compare the concentration to the threshold value.*
4. *Trigger the alert system if the threshold is exceeded.*

The system operates by continuously monitoring the gas levels. When the concentration exceeds the pre-set threshold, it triggers the buzzer for a local alert and sends an SMS notification for remote monitoring. The hardware and software components work together to ensure efficient gas leak detection and timely alerts.

DISCUSSION OF RESULTS

The gas leakage system is a critical component of any industrial or commercial facility that handles hazardous gases. The system is designed to detect and alert personnel of any gas leaks, which can be potentially hazardous to human health and the environment. The results of the gas leakage detection system are shown in the following diagrams. Each diagram represents different stages of gas detection and alert notifications through the system.

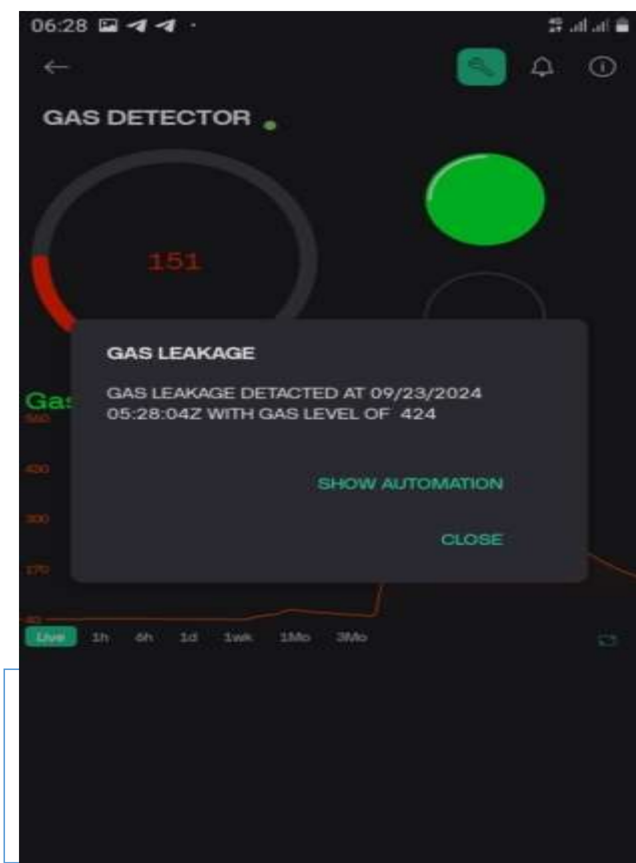

Figure 5: Initial Gas Detection

The figure 5 shows the detection of gas leakage at a concentration of 151 PPM. At this stage, the system is still in a safe state, indicated by the

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green circle, and gas levels are being monitored. However, the system is alerting the user about gas presence, as displayed in the notification: "Gas leakage detected at 09/23/2024 05:28:04Z with a gas level of 424 PPM."

Figure 6: High Gas Concentration

In the figure 6, the gas concentration has increased significantly to **543** PPM. The system immediately triggers a high alert, indicated by the red color on the gas detector gauge. The notification system is activated, sending an SMS to the user about the critical situation. This demonstrates the system's ability to detect dangerous gas levels and alert the user before it becomes harmful.

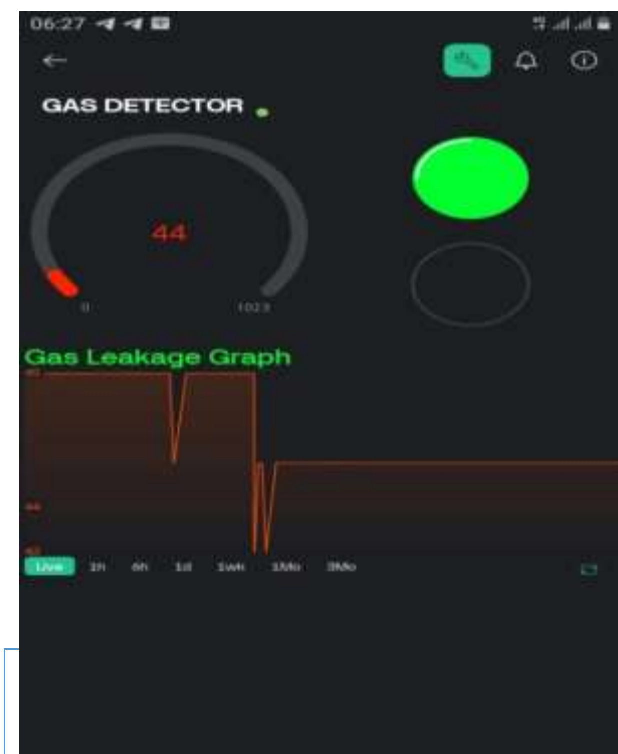

Figure 7: Normal Gas Levels

Figure 7 represents the system after the gas concentration returns to safe levels, at around 44 PPM. The green status light shows that the environment is back to normal, and no further alerts are being sent. This indicates that the system can continuously monitor the environment and notify the user once the danger has passed.

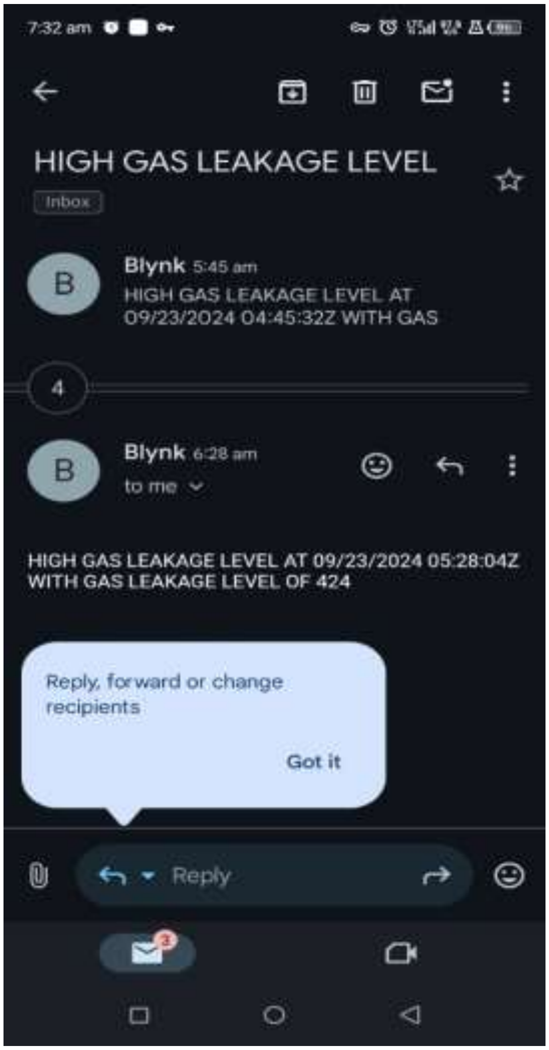

Figure 8: Email Notification Received

Figure 8 illustrates the SMS notifications generated by the Arduino-based gas leakage detection system, which promptly alerts the user of high gas concentration levels. At 4:45:32Z, the system detected a gas leak above the safety threshold and sent an SMS alert. Another alert was sent at 5:28:04Z, reporting a gas concentration of 424 PPM. These real-time notifications provide precise detection times and gas levels, ensuring immediate user awareness and enabling quick action to prevent accidents. The system's integration with the Blynk app enhances remote monitoring, making it a reliable and efficient safety solution.

These diagrams illustrate the system's capacity for real-time gas monitoring and notification. The use of SMS and sound alerts ensures timely and remote awareness, making this Arduino-based solution highly effective in preventing gas-related accidents.

CONCLUSION

The integration of IoT technologies in gas leakage detection and prevention systems offers significant advantages, including real-time monitoring, enhanced accuracy, and automated responses. Despite challenges related to data security, scalability, and maintenance, IoT-based solutions represent a promising advancement in safety management. Future research should focus on improving system robustness, integrating emerging technologies, and expanding applications to further enhance gas leakage detection and prevention capabilities.

Machine learning models offer significant advantages for real-time gas leakage detection and prevention systems, including improved accuracy, reduced false alarms, and proactive prevention. However, challenges such as data imbalance and scalability need to be addressed. Future research should focus on developing adaptive algorithms, integrating multiple sensor modalities, and enhancing model interpretability.

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