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DEVELOPMENT AND TESTING OF A SEISMIC-RESPONSIVE IOT-BASED SAFETY SYSTEM FOR GAS DISTRIBUTION NETWORKS

Florin-Bogdan MARIN[1,2], Cristina-Daniela STAICU (MĂRIAN)[1], Mihaela MARIN[1,2]
[1] "Dunarea de Jos" University of Galati, Romania
[2] Interdisciplinary Research Centre in the Field of Eco-Nano Technology and Advance Materials CC-ITI, Faculty of Engineering, "Dunarea de Jos" University of Galati, Romania, 47 Domnească Street, RO-800008, Galaţi, Romania
e-mail: flmarin@ugal.ro

ABSTRACT

This paper presents the design and experimental evaluation of a smart safety system intended to mitigate seismic risks in urban gas distribution infrastructure. The proposed solution integrates an ESP32 microcontroller with an MPU6500 inertial sensor to detect ground vibrations associated with seismic activity. Upon exceeding a calibrated threshold, the system autonomously triggers the closure of a solenoid valve, thereby halting gas flow and reducing the risk of leaks or explosions. Sensor data is transmitted wirelessly using MQTT protocols to a cloud-based interface for real-time monitoring and logging. The prototype demonstrates rapid actuation, low latency, and high sensitivity to motion events, confirming its suitability for scalable deployment in residential or municipal gas pipeline networks. The implementation relies on low-cost hardware, open-source software, and edge processing to ensure both affordability and autonomous operation in critical infrastructure applications.

KEYWORDS: smart safety system, seismic detection, ESP32, MPU6500, solenoid valve, gas pipeline

1. Introduction

Natural gas distribution systems are critical infrastructure that require reliable monitoring and fast response mechanisms to mitigate hazards such as leaks, overpressure, and structural damage caused by seismic activity. Traditional supervisory systems based on SCADA or manual inspection often suffer from limited scalability, delayed reaction times, and high implementation costs, particularly in distributed urban settings [1-2].

With the rapid development of wireless communication technologies and the Internet of Things (IoT), new opportunities have emerged for decentralized, cost-effective safety monitoring [3], [4]. IoT-based solutions leverage embedded sensors, edge computing, and real-time telemetry to provide intelligent decision-making capabilities directly at the point of risk [5-7]. These systems have been successfully deployed in smart grid monitoring [8], environmental sensing [9], and pipeline integrity evaluation [10].

Seismic-induced failures in gas pipelines represent a major safety concern in densely populated areas, particularly where infrastructure is aging or insufficiently reinforced [11-12]. The integration of vibration sensors and microcontrollers allows the implementation of early warning mechanisms capable of autonomous actuation during ground motion events [13-14]. Accelerometers such as the MPU6050 and MPU6500, when interfaced with microcontrollers like the ESP32, offer an accessible platform for detecting acceleration anomalies and issuing control commands [15]. Recent studies have highlighted the benefits of combining vibration detection with gas flow control using electromagnetic shutoff valves in distributed networks [16-17]. This approach has proven effective in reducing response time and avoiding catastrophic failures caused by undetected leaks or delayed interventions [18]. Moreover, the rise of cloud-based dashboards and real-time data streaming protocols such as MQTT further enhances system visibility and user interaction [19]. Advanced implementations include edge computing strategies

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that minimize dependence on central servers and enable fast local decision-making [20]. Additionally, sensor fusion techniques improve accuracy in vibration recognition by filtering noise and correlating motion signals with environmental data [21].

This paper proposes a seismic-responsive gas safety system using an ESP32 microcontroller, an MPU6500 accelerometer, and a solenoid valve actuator. The system is designed to detect ground motion events exceeding a predefined threshold and autonomously interrupt gas flow, while simultaneously sending alerts to a cloud-based monitoring platform. The objective is to validate the feasibility of such a solution under laboratory-simulated seismic conditions, demonstrating its applicability to urban gas distribution networks.

2. Experimental procedure

To evaluate the seismic-responsive safety system for gas distribution pipelines, an experimental setup was developed using low-cost and easily integrable components. The architecture was centered around the ESP32 microcontroller, selected for its dual-core processing, integrated wireless communication capabilities, and support for real-time sensor data handling. Vibration detection was performed by an MPU6500 inertial measurement unit, which integrates a 3-axis accelerometer and a 3-axis gyroscope. The sensor was configured to detect acceleration events in the ±2 g range, which corresponds to low-to-moderate seismic activity. Communication between the sensor and microcontroller was achieved through the I²C protocol, and a basic signal processing algorithm—based on a moving average filter—was applied to eliminate transient noise. When the acceleration exceeded a threshold of 0.3 g in any axis, the microcontroller executed a predefined response routine. This included triggering a 12V DC solenoid valve via a relay module, which was electrically isolated using an opto-coupler to prevent interference. The actuation served to simulate the automatic shutdown of gas flow in the event of an earthquake-induced structural disturbance. In parallel, the ESP32 transmitted the event via the MQTT protocol to a cloud-based monitoring dashboard, ensuring remote visibility. Event data was logged locally and visualized using Grafana through integration with InfluxDB, allowing for real-time diagnostics and post-event analysis.

Mechanical perturbations were manually induced on the platform in order to replicate seismic conditions. These included direct tapping, controlled shaking, and tilt simulation. Each experiment was repeated ten times to verify consistency and repeatability. The response time from event detection to actuation was measured using a logic analyser and was confirmed to be under three seconds in all valid test cases. The system was powered by a stabilized 12V DC source, with internal regulation providing 5V to the sensor components. To ensure continuous reliability, a watchdog routine was implemented in the firmware to automatically reset the device in case of execution faults. This fully self-contained setup allowed accurate simulation of seismic-induced risks and enabled detailed assessment of system responsiveness, sensitivity, and operational stability under fault conditions. The low-power design, real-time actuation, and wireless reporting demonstrate its potential for real-world deployment in distributed gas safety networks.

3. Results and discussions

To validate the behavior of the prototype under simulated seismic scenarios, a series of controlled tests was conducted in which mechanical vibrations were applied to the sensor platform. The system consistently responded when the acceleration measured by the MPU6500 exceeded the 0.3 g threshold. Upon detection, the ESP32 microcontroller activated the electromagnetic relay, triggering the immediate closure of the gas valve.

Figure 1 illustrates the complete experimental setup, showing the integration of key components: the ESP32 board (1), the solenoid valve actuator (2), the vibration sensor (3), and the smartphone interface (4). This figure provides a clear overview of the system architecture designed for pipeline fault detection.

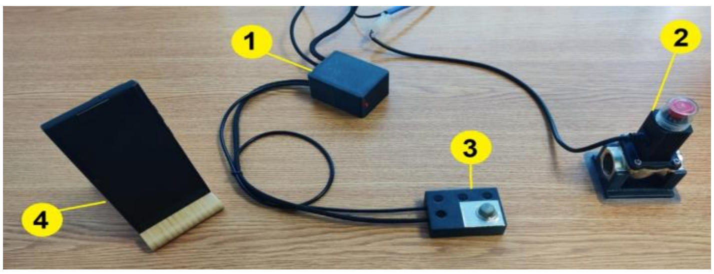

Fig. 1. *Experimental setup for testing the fault detection system in a natural gas pipeline*

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Figure 2 shows the test configuration during simulated vibration, with the control unit in operation and the valve ready for actuation. The internal structure of the control module integrates three key elements. (1) represents the dual relay system responsible for managing the electrical isolation and actuation of the solenoid valve during emergency scenarios. This configuration enables safe control of high-current circuits triggered by the detection algorithms. (2) is the wiring bundle that connects power lines, sensors, and control interfaces, ensuring stable signal flow and system integrity. (3) denotes the ESP32-based microcontroller, which performs all real-time processing, data acquisition from sensors, and wireless transmission through its integrated Wi-Fi connectivity. This architecture allows for autonomous response and remote supervision within the gas safety system.

Across all 10 test cycles, a consistent system response was observed. The average response time from detection to valve actuation was approximately 2.6 seconds, with minimal variation.

Figure 4 documents the system's state immediately after triggering, Figure 5 presents a dashboard screenshot displaying live valve status and alert conditions. Data was also logged to InfluxDB and visualized through Grafana, enabling retrospective analysis.

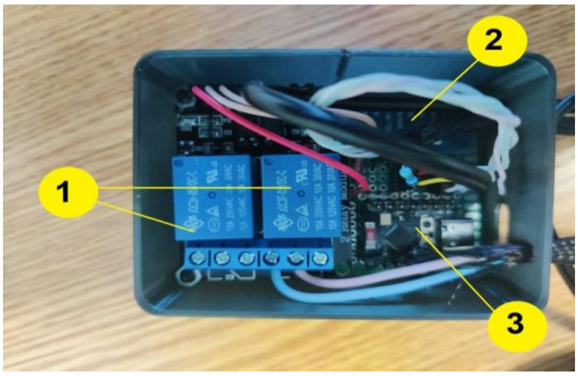

Fig. 2. *Control unit of the seismic safety system*

Figure 3 depicts the system in standby mode, with no seismic activity detected. The internal layout of the gas detection unit includes two key components. The first component (1) consists of a gas diffusion chamber equipped with a mesh cover and structural support, which ensures controlled air exchange while protecting the internal electronics from dust and mechanical damage. The second component (2) is the MQ-series gas sensor module, responsible for detecting combustible gases such as methane. It is mounted on a printed circuit board and connected to the system's microcontroller, enabling real-time monitoring of gas concentration and automatic triggering of safety protocols when predefined thresholds are exceeded.

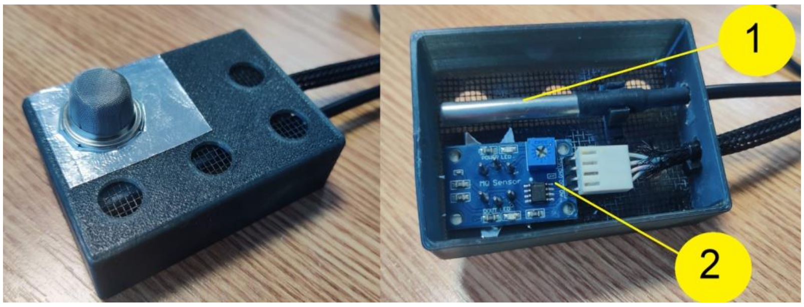

Fig. 3. *Sensor unit of the seismic detection system*

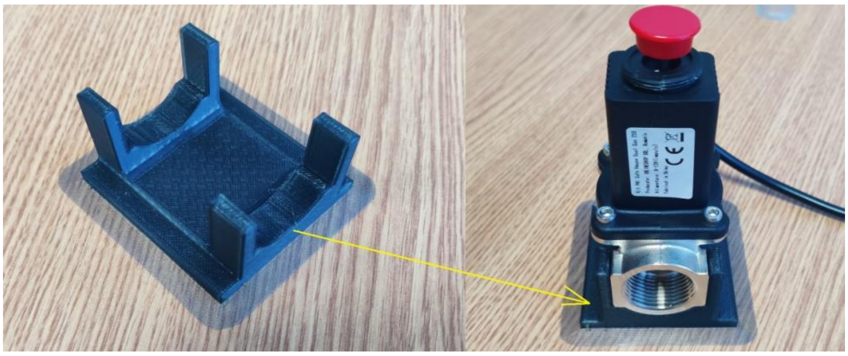

Fig. 4. *PNI Safe House Dual Gas 250 solenoid valve used for automatic gas shutoff*

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Fig. 5. *Arduino IoT interface displaying operational parameters of the natural gas pipeline fault detection system*

To evaluate the responsiveness of the seismic detection system, multiple vibration events were simulated using a controlled mechanical excitation setup. During testing, the MPU6500 sensor recorded continuous acceleration data, which was transmitted in real time to the IoT interface. The ESP32 microcontroller processed these readings locally, comparing them against the predefined vibration threshold of 0.30 g. Upon exceeding this limit, the system triggered an emergency shut-off sequence, commanding the solenoid valve to close and halt gas flow.

Figure 6 illustrates the complete experimental configuration used during testing, including the inertial sensor unit, the solenoid valve actuator, and the cloud-based monitoring interface. The system was designed to operate autonomously while maintaining real-time feedback capabilities for remote diagnostics and alert verification. (1) denotes the PNI Safe House Dual Gas 250 solenoid valve, which is responsible for automatically interrupting the gas supply when seismic activity is detected. This component is triggered by the control unit once vibration levels recorded by the inertial sensor exceed the calibrated safety threshold. (2) represents the real-time monitoring interface, displayed on a mobile device connected to the IoT system. It visualizes acceleration data as a dynamic graph, enabling remote observation of seismic activity and system response. Figure 7 presents the time-series graph of vibration intensity recorded during a representative seismic simulation. The data show a clear spike in acceleration values, surpassing the actuation threshold and confirming the sensitivity and accuracy of the detection algorithm. These results validate the performance of the safety module under conditions simulating minor to moderate seismic activity.

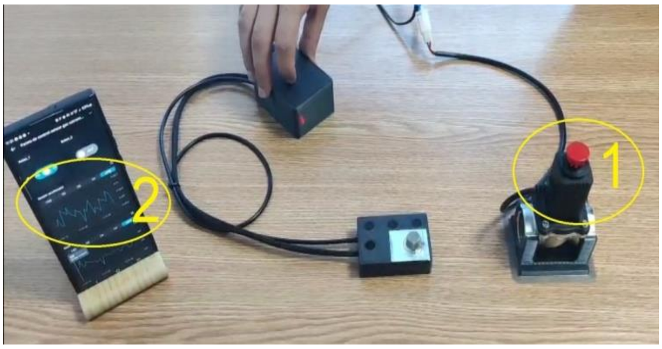

Fig. 6. *System performance evaluation during simulated seismic event*

Fig. 7. *Real-time vibration data acquired during seismic simulation via IoT interface*

4. Conclusions

This study presented the design, implementation, and validation of an IoT-based early warning system for seismic activity in urban gas distribution networks. By integrating a low-cost ESP32 microcontroller with an MPU6500 inertial sensor and an electromagnetic shutoff valve, the system demonstrated reliable detection of vibration events and immediate response through gas flow interruption. Experimental results confirmed a consistent and timely reaction to simulated seismic inputs, achieving an average response time of 2.6 seconds with no false triggers recorded during idle conditions.

The implementation of MQTT-based wireless communication allowed for seamless integration with cloud dashboards, supporting real-time alerts and historical data visualisation via platforms such as Arduino IoT Cloud and Grafana. The system maintained stable performance across repeated test cycles, proving its suitability for autonomous operation without dependency on external supervisory infrastructure.

Given its low cost, ease of deployment, and reliable response time, the proposed system represents a practical solution for improving safety in small to medium urban gas distribution networks, particularly in areas exposed to seismic activity. The system's capabilities can be further enhanced through multi-sensor integration, including gas leak and temperature monitoring, and through validation in real seismic conditions in collaboration with infrastructure operators.

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