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AN IOT-BASED EARTHQUAKE EARLY WARNING SYSTEM WITH FUZZY LOGIC FOR UTILITY CONTROL IN TEHRAN

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Abstract
Introduction: In disaster scenarios, while predicting disasters is challenging, preparation is essential. Internet of Things (IoT) technology, which is well-established, can play a significant role in disaster management. For countries, especially those prone to seismic activity, implementing early warning systems is critical to saving lives and minimizing damage. These systems alert individuals and authorities when disasters strike. However, limited attention has been given to post-disaster decision-making for monitoring essential utilities, such as gas and electricity, during critical times. **Methods:** Integrating IoT with a Fuzzy system can improve decision-making after disasters, reducing costs and destruction in urban areas. Tehran, a city with high seismic risk and an extensive gas network, faces significant dangers from damage to gas and electricity systems in the event of a major earthquake. **Results:** The research highlights that the proposed IoT-Fuzzy system performs effectively when compared to the JICA Seismic Hazard Assessment of Tehran. It issues disconnection commands for critical utilities within 10 seconds based on predicted damage levels, helping to reduce secondary damage after an earthquake. This system shows promise in improving post-disaster response and safeguarding urban infrastructure.

Keywords: crisis management; internet of things; fuzzy system; early warning system; smart city; city management.

Introduction

Earthquake often takes place in particular regions across the world. On a worldwide scale, this disaster causes 2.5 million deaths and destroyed many buildings and infrastructure between 1900 to 2018 (Database, 2019). Therefore, it is important to apply novel technologies as an early warning system to reduce injuries and destruction (Mali and Kumbhar, 2016).Traditional earthquake warning systems, such as seismic networks and ground motion sensors, have demonstrated their importance, but they often face challenges such as delayed response times and limited geographic coverage, particularly in densely populated urban areas. These limitations highlight the need for more efficient and responsive systems that can collect real-time data and trigger rapid decisions.

The recent mega earthquakes damaged to the gas pipeline and infra-structures of the urban area. During the Kobe earthquake the shutdown of the related valves to isolate these blocks began six hours after the earthquake and the last block was isolated 15 hours after the earthquake (Katayama, 2004). Such long delays underscore the inadequacy of traditional, manual-response systems, which are not fast enough to prevent extensive damage and loss of life. Other destructive earthquakes such as San Fernando earthquake in 1971, the Loma Prieta seismic event of 1989, Izmit earthquake in 1999 and San Salvador seismic event in 2001, resulted in damaging the pipelines and infra-structures and left sever injuries (Manshoori, 2011).

The risk of a catastrophic earthquake threatens Iran every year (Database, 2019). Tehran, the capital of Iran, is one of the most populated cities in the world. The city is surrounded by several active faults and thus is at a high risk of a sudden destructive earthquake. The gas transmitting network on the other hand, spreads throughout the city. Thus, occurring catastrophic disasters same to Kobe and Izmit events is probable in Tehran.

Many of natural disasters are unpredictable. Therefore, it is necessary to develop a technology to collect appropriate indicators as fast as possible. However, current systems for earthquake monitoring and response often lack the capability to deliver data at the necessary speed, and their reliance on human intervention can result in delays. IoT is known as one of the pioneering technologies, which is susceptible to data changes and can send the sensed critical data in real-time to the cloud server. Nowadays, IoT plays a dynamic role in diverse areas such as national defense, smart grid, intelligent transportation, smart home, and healthcare (Maglogiannis, 2012; Zhou, 2012). However, while IoT is excellent for real-time data collection, it requires robust decision-making systems to interpret and act on that data efficiently in the case of emergencies.

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Lack of real-time precise information about the response of structures and infrastructures leads to the amplification of disasters. The traditional threshold-based warning systems fail to handle the complex and often ambiguous data produced during earthquakes. The IoT technology seems to be an appropriate tool to monitor and manage such issues at the early moments of a post-event, which consequently leads to reduced fatalities and indirect impacts. However, IoT alone may not suffice when rapid and complex decision-making is required. This is where fuzzy logic comes into play. By integrating IoT with fuzzy logic, we propose a more intelligent and adaptive system that can interpret various sensor inputs under uncertain conditions, providing more accurate and faster decisions. Pairing IoT with a fuzzy system can help a crisis manager create a more proactive and efficient network capable of forecasting and managing earthquakes. Such a network may associate with tens of sensing nodes to measure accelerometer data and dispatch them to the cloud server. The measured data is compared to the pre-defined values in the fuzzy system to check if significant changes have occurred.

The proposed system addresses key limitations of current approaches by integrating IoT with fuzzy logic to create an intelligent early warning system that can analyze data more dynamically and respond faster. This paper aims to define the sensor network design for an earthquake early warning system developed based on IoT architecture, incorporating practical experiences and theoretical knowledge. The system is proposed for the possible safe shutdown of gas and electric transmission networks.

This model considers an additional element that may attach to the operational sensors and can process the data using decision-making criteria (DMC). The DMC is defined in the cloud layer and can execute the relevant scenario to reduce indirect loss. By leveraging the fuzzy system's ability to handle ambiguity, the proposed system can enhance decision-making under uncertain conditions, providing quicker and more accurate responses than traditional methods.

Literature review

Since Kevin Ashton introduced the Internet of Things (IoT) in 1999, there has been a significant surge in the number of devices connected to the internet. Currently, these devices are utilized across various application domains (Atzori et al., 2010). Since the introduction of the Internet of Things (IoT) by Kevin Ashton in 1999, there has been a notable increase in the quantity of devices connected to the internet. At present, these devices are employed across a diverse range of application domains.

The IoT system typically consists of sensors or devices that communicate with the cloud via some form of connectivity. Once the data reaches the cloud, software processes it and might trigger an action, such as sending alerts or automatically adjusting the sensors or devices — thus enabling IoT to operate autonomously without user intervention. This capacity for real-time, automated responses makes IoT particularly suitable for disaster management, where timely action is critical.

Today, a broad spectrum of industries, from transportation and logistics to healthcare, smart environments, and knowledge management, can benefit from IoT technologies. The continued development of new smart devices and internet-connected products suggests that futuristic applications such as robot taxis, city information models, and enhanced game rooms will soon become mainstream (Nord et al., 2019; Jahanbakhshian et al., 2020; Thoma et al., 2012). Moreover, IoT technologies play a critical role in disaster relief operations, aiding in the planning, management, and analysis of both immediate and long-term impacts (Azizzadeh, 2022; Jianshe et al., 1994).

In the context of earthquake disaster mitigation, recent studies have demonstrated the effectiveness of IoT. For instance, a pilot study validated the integration of IoT technology with ShakeMap data for earthquake early warning systems. The platform was shown to optimize emergency responses by categorizing actions into automatic responses, guidance, and system automation. This demonstrates IoT's potential to enhance public safety during seismic events, making real-time data processing and rapid decision-making possible (Ahn J.-K. et al., 2024).

One of the primary activities enabled by such technologies is the timely delivery of relief supplies from distribution centers to hospitals in coordination with the schedules of medical teams (Lee et al., 2006). However, effective crisis management planning also depends on several other factors, including climatic conditions, topology, habitat, and the availability of resources (Duhamel et al., 2016). The ability of IoT to provide real-time data on these variables can significantly improve the precision and effectiveness of disaster response.

Recent advancements have led to the development of IoT-based earthquake early warning systems. For example, one system, which utilizes smartphone sensors, Sensor Web Enablement (SWE), and MQTT, was designed for Ecuador's seismic activity and offers up to 12 seconds of warning before the peak seismic impact. This system emphasizes real-time monitoring, customization, and addresses concerns related to energy consumption and user safety (Zambrano et al., 2017). Such systems highlight the practical benefits of IoT in early disaster warning and management, providing communities with crucial seconds to mitigate potential damage.

The term fuzzy logic, introduced by Zadeh in 1965, refers to a form of multivalued logic in which truth values can range between 0 and 1 (Zadeh, 1965). It is used to handle the concept of partial truth, where values can extend between completely true and completely false. Fuzzy logic is particularly valuable in situations where data is uncertain or imprecise, which is often the case during natural disasters like earthquakes. When paired with IoT, fuzzy logic can enhance decision-making by processing complex data and providing a more nuanced understanding of risk.

Fuzzy logic has been widely adopted in civil engineering, especially in earthquake engineering for tasks such as crisis management (Nokhbatolfoghahaayee et al., 2010), crisis management in gas transmission networks (Foghahaayeea et al., 2014), hazard evaluation (Şen, 2011), motion earthquake records (Ahumada, 2015) and Earthquake Prediction (Valizadeh et al., 2024). However, a significant research gap exists regarding the integration of IoT and fuzzy logic for earthquake mitigation. While IoT provides a real-time data stream, fuzzy logic can analyze this uncertain and imprecise data, enabling more effective disaster response systems.

Moreover, the role of IoT in disaster management extends beyond earthquakes, with various solutions being developed to address disasters like fires and earthquakes. IoT architecture and its implementations, such as early-warning systems, offer valuable insights for stakeholders in securing smart city infrastructure and effectively managing disaster risks (Abdalzaher, 2023; Sharma et al., 2021; Pierleoni, 2023). This study aims to address this gap by proposing an IoT-based earthquake early warning system that integrates fuzzy logic to improve crisis management and the operational reliability of critical infrastructures such as gas and electricity networks.

Methods

Theoretical Background

An image of the current literature associated with the studied topic is presented herein. The key role of technology in disaster management is helping to relief forces to More purposeful helping to injury. There is no doubt that efficient emergency response management following an earthquake is a critical element in reducing seismic risk. Research has shown that inadequate emergency responses or secondary disasters can increase the death toll from an earthquake by up to tenfold.

Japan, holding a leading position internationally, places great importance on observational experiments both indoors and outdoors, landslide debris flow studies, research on forecast models, early warning system research, and the advancement of monitoring systems for landslides and debris flow (Takaoka, 2006). Individuals will have between a few seconds to several dozen seconds to respond, depending on their location. According to the performance report by the Japan Meteorological Agency (JMA) on the earthquake early warning (EEW) system for the Mw 9.0 Tohoku earthquake in 2011 (Hoshiba et al., 2011; Hoshiba and Ozaki, 2014). An earthquake early warning (EEW) was issued more than 15 seconds before the onset of intense ground motion in Tohoku, which was relatively close to the epicenter. This is an excellent example of the effectiveness of an EEW system. The Istanbul Earthquake Rapid Response and Early Warning System (IERREWS) is identified as an EWS solution for earthquake threats. The system collects seismological data through 100 robust motion accelerometers, enabling a better understanding of seismic wave propagation (Erdik et al., 2003).

The fast loss estimate systems is applied in Japan and Taiwan at present defined respectively (Fumio, 2001; Yeh et al., 2006).

A fast loss estimate instrument known as Earthquake Loss Estimation Routine (Bogazici University) was made by the European Commission (EC) funded Network of Research Infrastructures for European Seismology (NERIES) (Özbey et al., 2004) to be applied by European agencies, among them the European Mediterranean Seismological Center (EMSC) to compute and broadcast earthquake loss estimations of near-real-time to the related emergency reaction organizations (Strasser, 2008).

The effectiveness of earthquake early warning (EEW) systems in mitigating earthquake hazards and reducing casualties, particularly in major earthquakes, has been thoroughly demonstrated in both Japan and Mexico (Doi, 2011). In Mexico, earthquake alerts from the seismic warning system were transmitted to Mexico City more than 60 seconds before the destructive waves arrived, facilitated by 12 digitally strong motion field stations along the Coast of Guerrero. In Japan, the earthquake early warning (EEW) system is supported by over 1,000 uniformly distributed stations across the country, providing real-time monitoring data. Both inland and offshore earthquakes are detected, and warnings are issued when the maximum seismic intensity on land exceeds five lower (approximately VII on the Modified Mercalli Intensity scale). The proposed on-site earthquake early warning system (EEWS) has demonstrated an 80 % success rate in accurately predicting earthquake intensity levels and can automatically send an alarm message at least eight seconds before the peak S-wave trains reach the earthquake epicenter (Seng).

The United States Geological Survey (USGS) has been working on a method to detect earthquakes shortly after they begin. This method involves first calculating the energy of the P-wave, which subsequently provides data on the earthquake's location and intensity.

According to Buzduga et al. (2015), in the event of a survivor in a collapsed building, the electrostatic sensor transmits information via a radio transmitter, which is received by a radio receiver. The survivor's exact location is then identified by the connected microcontroller. Dan Wang et al. designed an earthquake alarm system using wireless sensors, which operates more quickly than other systems. The key to improving the system's overall efficiency lies in the strategic placement of the sensors.

The effectiveness of earthquake early warning (EEW) systems is greatly influenced by the accuracy of P-wave arrival detection. EEW's automated P-wave selecting algorithms have had issues with incorrectly picking up noise and missing P-waves. A convolution neural network (DPick)-based automatic algorithm has been developed (Yanwei, 2021).

Sultanov et al. (2020) have conducted extensive studies on the Strength of underground pipelines under seismic effects.

Alphonsa A et al. introduced a method wherein P-waves detected by sensors are transmitted through a Zigbee transmitter to a Zigbee receiver that is integrated into the Internet of Things (IoT). The IoT subsequently forwards warning messages to smartphones.

System structure

The architecture of an early warning system was developed based on IoT technology and fuzzy system with respect to expert knowledge and international researchers. These systems with P-wave recognition could shut-down gas, electric network before the destructive earthquake wave occurs. The system is an advanced version of early warning system discussed in the literature. The system consisted of five sensors measure multi parameters described in sensor section. the data is uploaded to the cloud through multi-hop wireless communication from the data aggregator. After local and server validation, this data will be processed in cloud server and after that system executes the relevant scenarios and Operational sensors are given operational commands (Fig. 1).

Utilizing early warning systems prior to the occurrence of earthquakes can significantly reduce human errors. Hein Hilary posits that over 85 % of safety accidents in enterprises are attributed to unsafe human behavior. Numerous accident investigations corroborate these findings. Therefore, monitoring unsafe behaviors of employees is crucial within an enterprise accident early warning system.

The acquisition of real-time accelerograms based on data from three axes facilitates the early detection of the primary seismic wave (P-wave), which is the first seismic wave that occurs following an earthquake and features a significant compression component.

The P-wave travels faster than other seismic waves but is less hazardous because it is a compression wave, typically resulting in minimal damage. In contrast, the S wave moves at approximately half the speed of the P wave. As a transverse wave, it induces dangerous shaking. R/L waves, which are surface waves generated at the epicenter through the combination of P and S waves, propagate through the Earth's crust until they dissipate their energy. R/L waves create horizontal and vertical oscillations in structures and are considered damaging waves. They travel more slowly than other seismic waves, at about one-third the speed of P waves. Earthquake guard systems utilize this characteristic of R/L waves to „predict" earthquakes before they are felt by individuals (Aki, 2004).

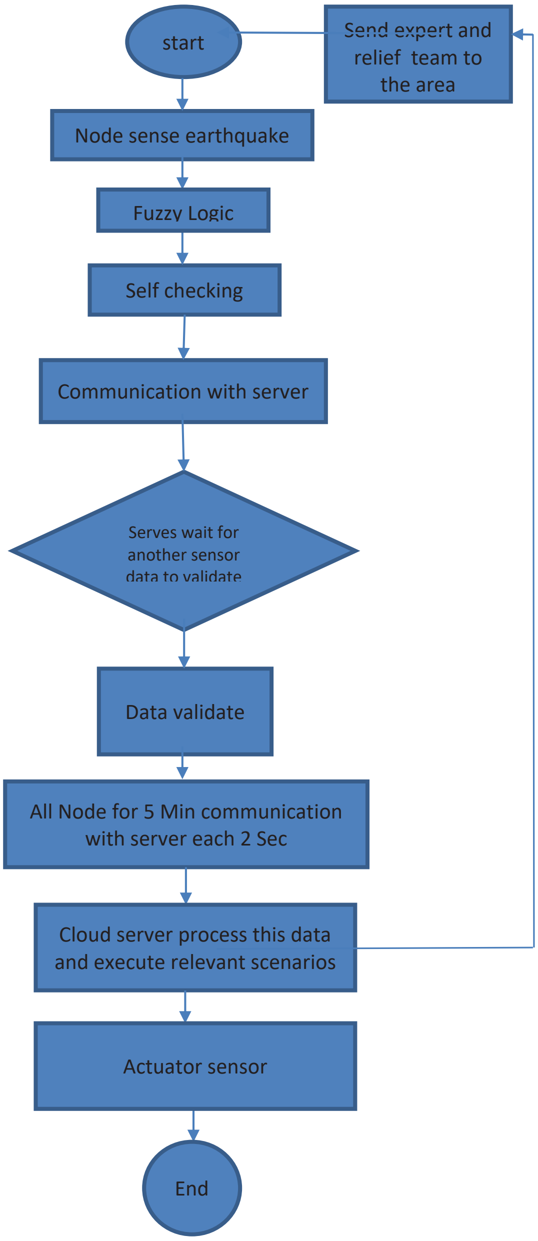


Fig. 1. Flow chart system

The suggested IoT-based solution to manage disaster effectively contains three steps, which is presented in Fig. 2:

1. Information Gathering sensors and Actuator sensors;
2. Information Transmission;
3. Information Processing and Decision making;

Information gathering sensors and actuator sensors

This section divided in 2 parts, section one is about the kind of sensor which is getting information, and section two is about actuator sensor to execute cloud server commands.

Receivers

This sector is also one of the most significant parts, because the procedure of data processing is the same as the eye system. It is necessary to measure the exact data used in the decision-making stage.

Each node is made up various hardware devices and consists five sensors; PGA (peak ground accelerator) sensor, fire detection sensor, temperature sensor, humidity sensor GPS sensors to monitor real data (Fig. 3).

Actuator sensors

Actuator sensors should be settled upon the gas distribution and electrical substations. Then the server sends the signal to the actuator sensor to disconnect or connect the area controlling by each sensor (Fig. 4).

The expert monitor the site after the earthquake and restore the area, where has not been serious damage.

Receiver Sensor position

To establish an effective earthquake monitoring network, it is essential to install a sufficient number of sensors and strategically distribute them across the area to be monitored. According to Mojarab et al. (2017) the sensors should be spaced no more than 10 kilometers apart to accurately detect seismic activity (Fig. 5). Our network covers an area of 1,350 km² (30 km × 45 km) and consists of 54 sensor nodes.

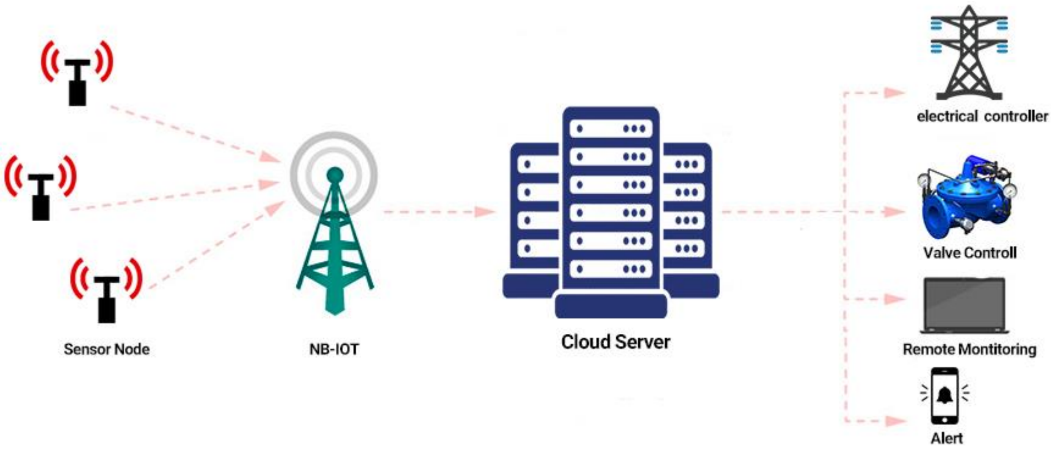


Fig. 2. IoT early warning system architecture

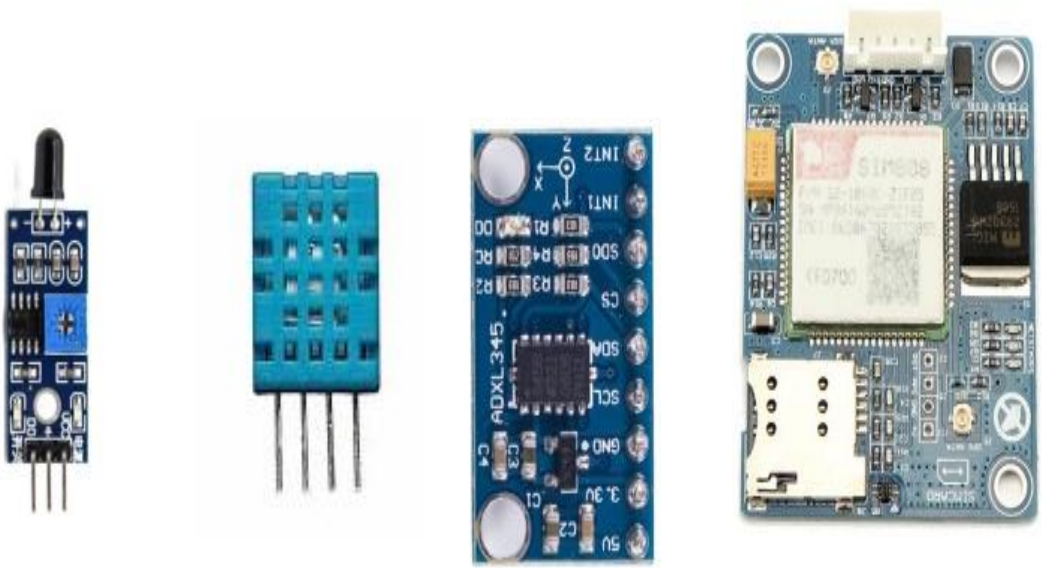


Fig. 3. Receiver Sensors

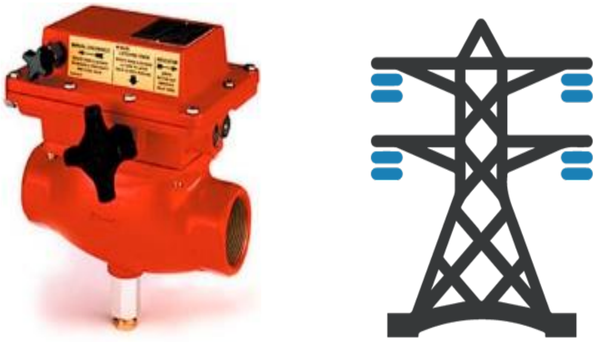


Fig. 4. Gas and Electrical Actuator

These 54 sensor nodes have been carefully positioned throughout Tehran based on a combination of seismic risk assessments and population density. Locations near the active fault lines, such as the North Tehran Fault and Rey Fault, were prioritized, given their heightened risk of significant seismic events. Critical urban infrastructures, including gas pipelines, electricity grids, and densely populated areas, were also key factors in the selection of sensor sites. This ensures both comprehensive monitoring and early warning capabilities for high-risk zones.

In alignment with the Tehran Fault Scenario, the sensors in these specified locations (as illustrated in Fig. 5, which includes a detailed map of the sensor network layout) transmit seismic data to the central server. Additionally, sensors placed outside the predefined fault zones are designated to detect unknown fault activities, ensuring that potential new seismic threats are also monitored.

Validating input date

The system is equipped with a self-validation device to check sensor value to decrease the number of errors in the system and prevent from a huge and inefficient data. When the PGA value is more than the defined value (0.1 G) in the system, the data is transmitted to server and sensor will be connected to cloud server directly for 5 minutes every 2 seconds. The next is to check the data received at the same time from at least 2 nearest nodes. This double check reduces the fake alarm and improve accuracy in the system.

Information Transmission

Transmission layers are a fusion of various networks. It securely transfers the information obtained from the perceptual layer to the application layer or vice versa.

IoT transmission has developed fast and created different ways to communicate between things to things or things to a human. We compare the best framework in transmission in Table 1, then choose a better transitions framework for the research concept.

The objective of this research is to identify a secure, low-power, stable, and cost-effective communication technology suitable for an IoT-based earthquake early warning system. After careful evaluation of the available technologies, Narrowband IoT (NB-IoT) is selected as the most appropriate choice for this project. Its advantages include extended transmission range, low power consumption, and high operational efficiency.

Given the broader context of the Internet of Things, early warning systems can be considered critical components of smart city infrastructures. Moreover, utilizing NB-IoT eliminates the need for

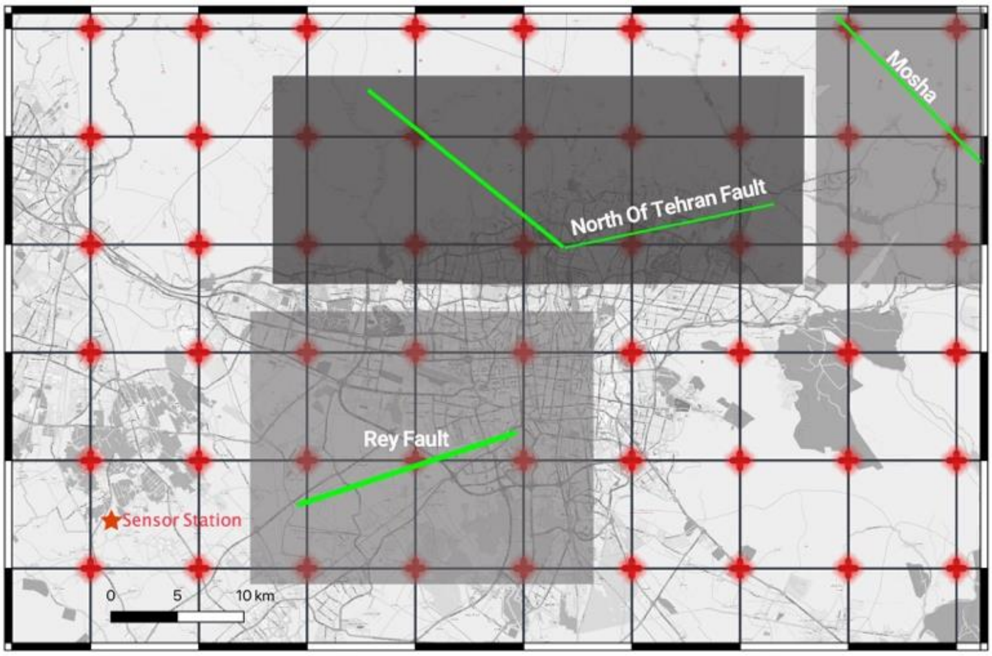


Fig. 5. Sensor position

Table 1. **Transport layer (Chen et al., 2017; Raza, 2017)**

Technology	Frequency	Data Range	Transmission Range	Date rate (up and down link)	Power Usage (energy Consumption)	Operating life (battery)	Cost
2G/3G	Cellular Bands	10 Mbps	35 Km	No limitation	High	4–8 hours 36 days (idle)	High
Bluetooth 4 LE	2.4 Ghz	24 Mbps	50 m	No limitation	Low	Hours	Low
802.15.4	subGhz, 2.4 GHz	250 kbps	200 m	No limitation	Low	Up to 4 years	Low
LORA	SubGhz, 2.4 GHz (868/915 MHz)	More than 50 kbps	2–10 km	EU: 30 bps – 50 kbps US:100–900 kbps	Low	10–20 years (idle) / 120 hours (communication)	Medium
LTE Cat 0/1	Cellular Bands	1–10 Mbps	Several kilometers	Up to 1 MBPs	Medium	2–3 hours (communication) / 12 days (idle)	High
NB-IoT	Cellular Bands (180 KHZ)	0.1–1 Mbps	10–15 km	150 kbps (NB) up to 1 mbps	Medium		High
SIGFOX	subGhz	< 1 kbps	Several kilometers	4x8 b/day (down) 100 bps (up)	Low	10–20 years (idle) / 120 hours (communication)	Medium
WiMax	subGhz	34 Mbps – 1 Gbps	40 km	No limitation	Low	hours	Low
WIFI	subGhz, 2.4 Ghz, 5 Ghz	0.1–54 Mbps	up to 10 m	No limitation	Medium	4–8 hours 50 days (idle)	Low
ZigBee	2.4 Ghz	250 kbps	10–500 m	No limitation	Low	Up to 2 years	Medium

a separate communication system, thus significantly reducing maintenance costs. This integration will facilitate timely alerts and improve the overall effectiveness of the early warning system in Tehran.

Information processing and execute command by using Fuzzy Logic

Due to the severe damages caused by previous earthquakes, collision of gas and electricity network, or gas leakage leaded to the secondary explosions and damages. This study aims to reduce this type of damage by using the defined fuzzy system.

To detect damages of the gas and electrics network, fuzzy logic methods were used with inclusion of four criteria, of gas pipeline, gas compressor, distribution circuits, electric boost station as shown in Fig. 6.

Input criteria

The values received from the sensors are transformed into fuzzy sets like 'Low probability risk failures', 'Medium probability risk failures', 'High probability risk failures', based on HAZUS methodology (FEMA, 1999) (Table 2).

Gas network

HAZUS methodology is divided in two vulnerable sections of the gas network. Section one is about the compressor station and section two is about gas pipeline. Both of these components are seismically vulnerable. It is worth mentioning that their probable failure can cause fire disasters. So that, this part discusses stages based on these boundaries (FEMA, 1999).

The fuzzy scenarios defined are appropriate to the conditions of the gas and electricity facilities in Tehran. Compressor stations are regarded to be an Anchored of Compressor Stations.

The damage States Definition in Fig. 7 is based on the HAZUS methodology for Compressor Stations; and since HAZUS has not determined an accurate level of failure for gas pipeline, the damage States Definitions for gas pipelines according to (Lanzano et al., 2014) is displayed in Fig. 8. The membership function for Gas Compressor Stations and gas pipelines shown in Figs. 9–10.

Electrical network

Electrical network vulnerability in HAZUS methodology is also divided in two:

1. Distribution Circuits;
2. Electric boost station.

Damage state of Distribution Circuits (contain poles, wires, in-line equipment and utility-owned equipment at customer sites) and Low voltage Substations power (34 kV to 150 kV) shown in Figs. 11–12. The membership function for Distribution circuits and Substations electric shown in Figs. 13–14. Low voltage (34 kV to 150 kV) are regarded for substation power for Tehran city.

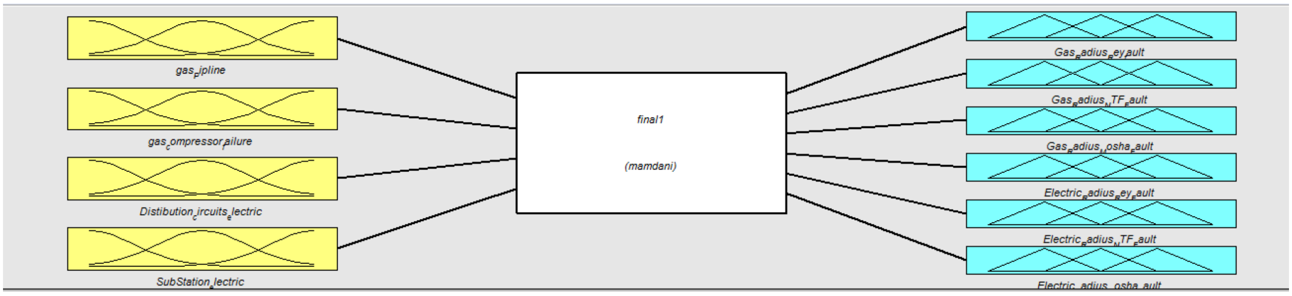


Fig. 6. Fuzzy system of Early warning system

Table 2. **Value of linguistic variable**

Criteria Variable	Low probability risk failures	Medium probability risk failures	High probability risk failures
Gas Compressor Stations	Acceleration 0-0.238	Acceleration 0.238-0.34	Acceleration 0.34-1.0
Gas Pipeline	Acceleration 0-0.406	Acceleration 0.406-0.58	Acceleration 0.58-1.0
Distribution circuits electric	Acceleration 0-0.28	Acceleration 0.28-0.4	Acceleration 0.4-1.0
Low voltage Substations	Acceleration 0-0.203	Acceleration 0.203-0.29	Acceleration 0.29-1.0

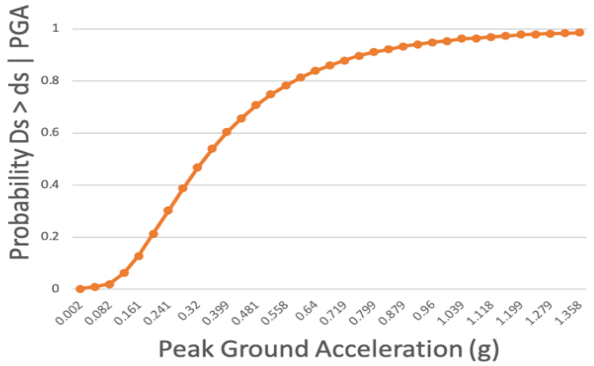


Fig. 7. Fragility Curves for Compressor Stations with Anchored Components (FEMA, 1999)

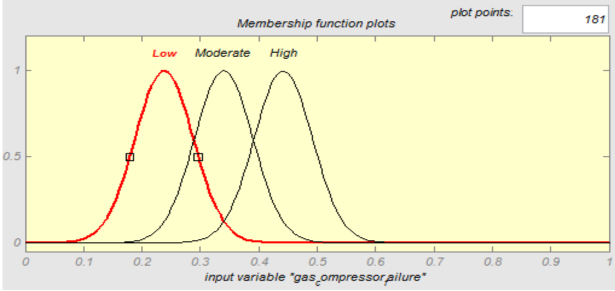


Fig. 9. Membership function Gas Compressor Stations

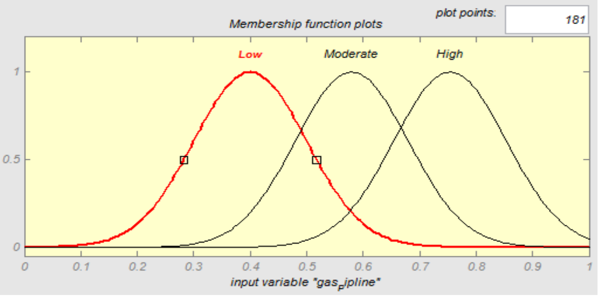


Fig. 10. Membership function gas Pipeline

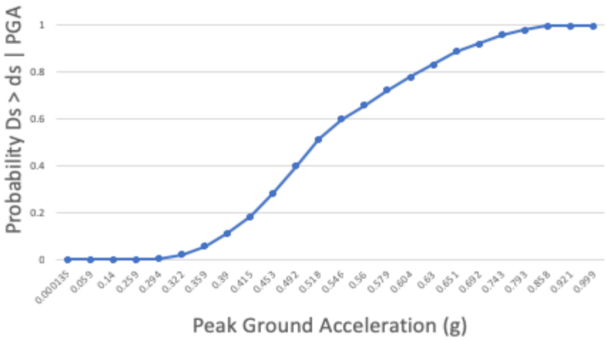


Fig. 8. Fragility curves for gas pipelines (Lanzano et al., 2014)

Output criteria

Shut-down and alarm command are the output of this system and transformed into fuzzy sets like "Minor damage", "Moderate Damage", Extensive Damage", "Complete Damage" (Table 3–4). The Rules of this system.

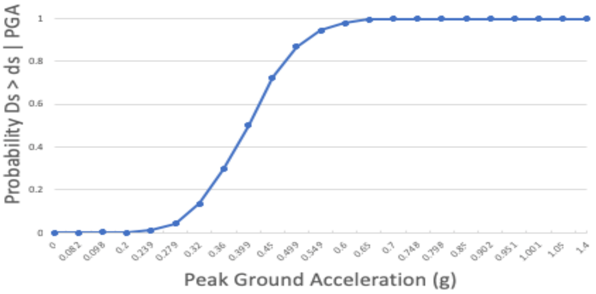


Fig. 11. Fragility curves Distribution Circuits (FEMA, 1999)

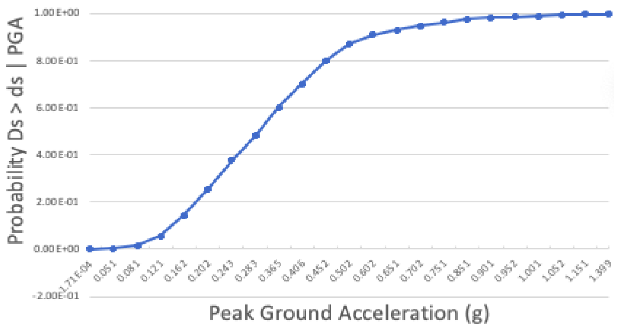


Fig. 12. Fragility curves for Low voltage Substations (FEMA, 1999)

Design base on expert opinion. Membership function shut-down commands shown in Figs. 15–22.

Case Study: Tehran City

In the Middle East, Tehran as Iran capital, is the second-largest metropolitan region with a population about 8.5 million. This city is a high seismic hazard area, which can cause significant damages to economic, social and political sectors in the event of an earthquake (Fig. 23). Hence, it is important to use early warning system to prevent secondary destructive damage. Furthermore,

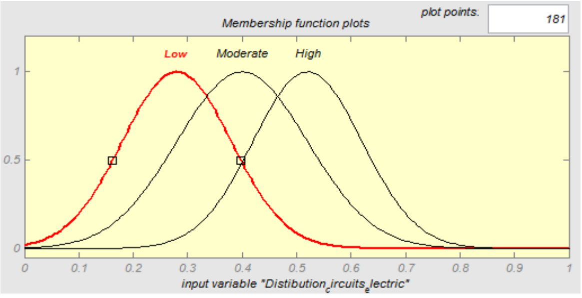


Fig. 13. Membership function Distribution circuits

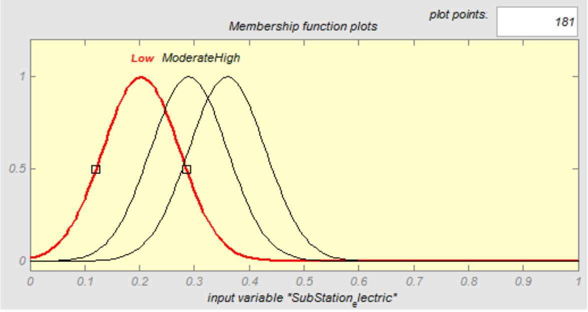


Fig. 14. Membership function Substations electric

Table 3. **Shut-Down Command Gas**

Linguistic Variables	Define	Range
R1	Minor area	0–6
R2	Moderate area	8–14
R3	Major area	16–22
R4	Complete area	24–30

Table 4. **Shut-Down Command Electric**

Linguistic Variables	Define	Range
R1	Minor area	0–8
R2	Moderate area	10–16
R3	Major area	18–24
R4	Complete area	26–30

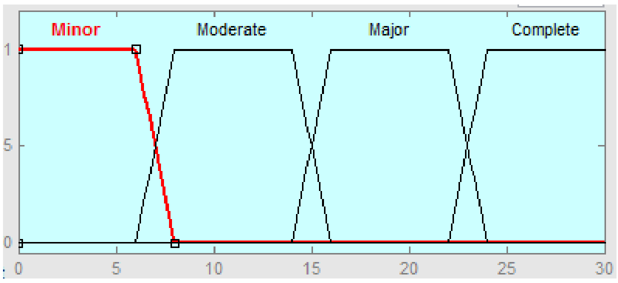


Fig. 15. Membership function shut-down command–gas–Rey fault

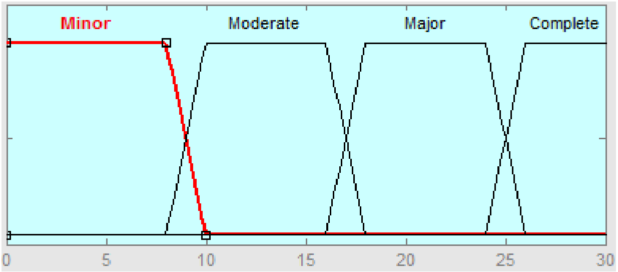


Fig. 16. Membership function shut-down command–electric–Rey fault

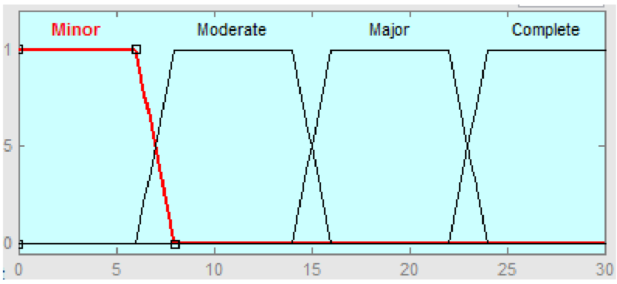


Fig. 17. Membership function shut-down command–gas–North of Tehran fault (NTF)

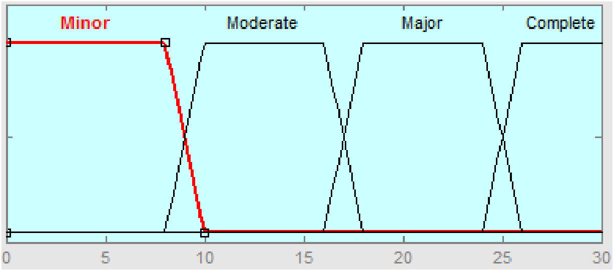


Fig. 18. Membership function shut-down command–electric–North of Tehran fault (NTF)

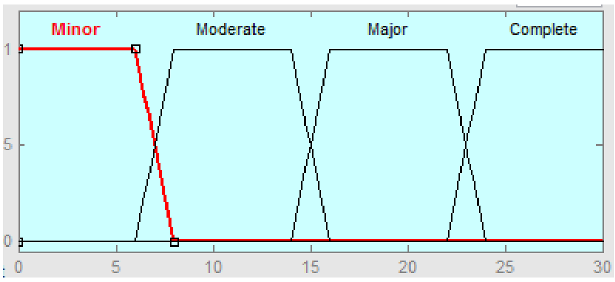


Fig. 19. Membership function shut-down command–gas–Mosha fault

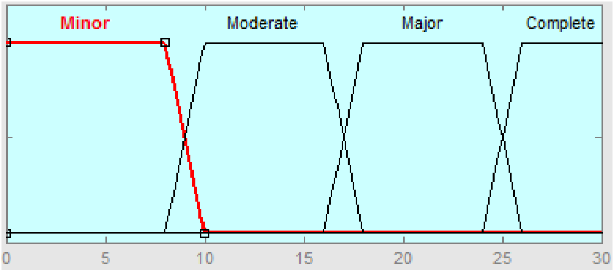


Fig. 20 Membership function shut-down command–electric–Mosha fault

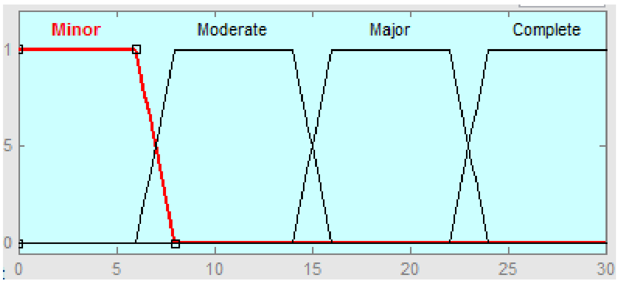


Fig. 21. Membership function shut-down command–gas–undefined fault

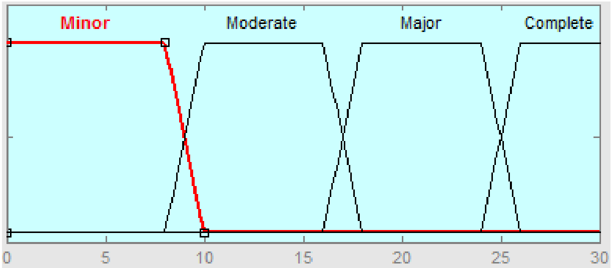


Fig. 22 Membership function shut-down command–electric–undefined fault

there exists more than 65,000 gas riser and approximately 100 km long gas pipeline and make it impossible to manage the city in a traditional way in critical time.

Cooperating with the Tehran Municipality in 2000, the International Co-operation Agency of Japan (JICA) developed the Tehran earthquake damage reduction program. The agency evaluated the different kinds of earthquake events in Tehran and their damage and casualties.

In Table 5, more thorough data on the characteristics of the faults is presented (JICA)

Rules

Tehran, it is located on three major faults, "NTF", “Ray” and “Mosha”. If they are activated, it can Bring irreparable damage to the city (JICA).

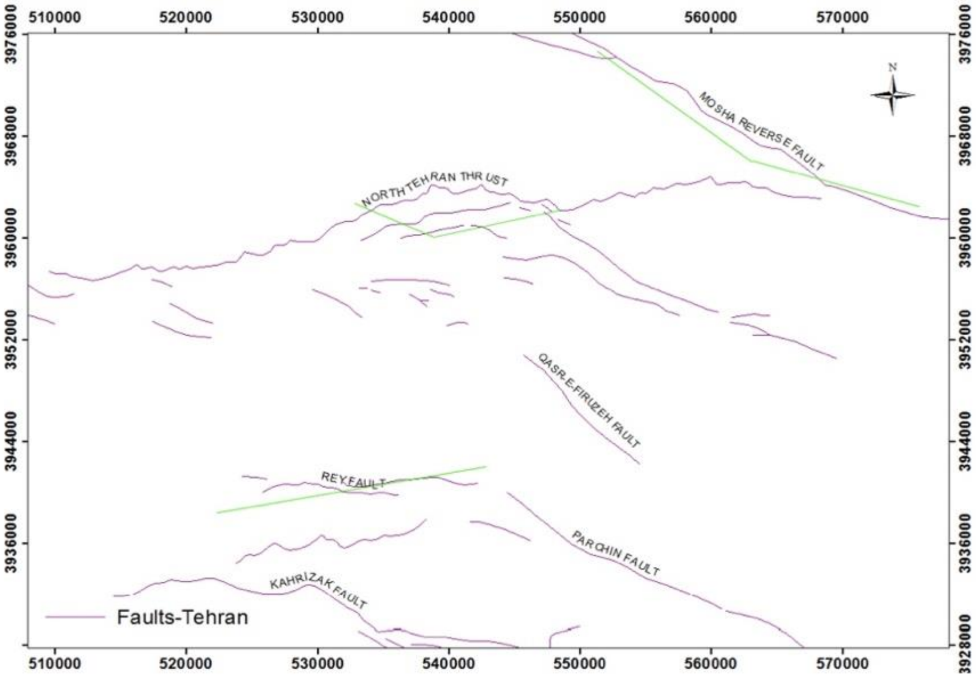


Fig. 23. Fault around the region of Tehran (JICA, 2000)

The final commands issued by the system are defined based on the scenario faults mentioned and for the areas outside the scenario faults, the unknown fault scenario will be implemented. The number of scenarios and rules defined for post-earthquake loss control in Tehran are 72, the scenarios being defined based on the opinion of experts.

These values set like "Minor or R1", "Moderate or R2", "Major or R3", "Complete or R4" (Table 6–7). These functions indicate how radically the gas or electricity should be shut-down command base on the failure level caused and the Maximum amount of PGA produced from each fault. According to these outputs, actions alert and disconnect the valve of gas and electricity executed to prevent secondary destructive damage

Table 5. **Name of Tehran Fault with Detail (JICA)**

Name	Magnitude (Mw)	Fault length (km)
Mosha fault	7.3	68
North of Tehran fault (NTF)	7.3	90
Rey fault	6.6	20

Laboratory study

In the laboratory model, an ADXL345 sensor was utilized to detect seismic activity, while a DHT11 sensor was employed to monitor environmental temperature and humidity. Data from these sensors were transmitted to the server via an Arduino Uno module. The server, developed using Node.js, processes this data and executes the appropriate scenario based on predefined fuzzy logic criteria (Fig. 24–25).

The result of this report was that after creating artificial waves with a vibrating device, the seismograph sensor detects the waves in less than 4 seconds, and then cuts off the gas and electricity taps in less than 6 second, and also lights up the warning light. This model was made only to test and implement the accuracy of the sensors.

One of the main differences between this model and the previous models is that most models issue warnings a few seconds earlier than the destructive wave, which often have a monitoring aspect. But in this model, due to the dispersion of seismograph sensors in the city, it detects the initial wave in less than 4 seconds, and based on the risk of JICA models (JICA) and the distance from the epicenter to the lifeline, first the level of damage to the gas and electricity network It is predicted and then the relevant scenario is implemented based on that.

Results

Using IoT technology and a fuzzy algorithm, this system detects seismic waves and makes decisions based on predefined fuzzy scenarios in less than 10 seconds, issuing executive commands to disconnect the city's critical lifelines to prevent secondary damage. According to the models mentioned in the Literature Review section of this research, the proposed model demonstrates acceptable results.

Also, in the first chapter of the JICA studies, which is the only documented source of Seismic hazard assessment and enforcement measures to prevent secondary hazards in Tehran's metropolitan area, it identified the radius that gas and electricity lines would have to be shut-down as scenario faults became active. Using the results of these studies, the performance of the fuzzy system defined in Table 8 is investigated which shows acceptable results (JICA). In addition to gas and electricity transmission lines, the proposed model consider the gas pressure boost compressor stations as

Table 6. **Shut-Down - Gas Network**

Fault Name	Damage to gas pipeline Damage to compressor station	Low	Medium	High
Rey	Low	R1	R3	R3
	Medium	R3	R3	R3
	High	R3	R3	R4
NTF	Low	R1	R3	R3
	Medium	R3	R3	R3
	High	R3	R3	R4
Mosha	Low	R1	R2	R3
	Medium	R2	R2	R3
	High	R3	R3	R4
Undefined	Low	R1	R2	R3
	Medium	R2	R3	R3
	High	R3	R3	R4

Table 7. **Shut-Down - Electric Network**

Fault Name	Damage to electric network Damage to electric station	Low	Medium	High
Rey	Low	R1	R3	R3
	Medium	R3	R3	R3
	High	R3	R3	R4
NTF	Low	R1	R3	R3
	Medium	R3	R3	R3
	High	R3	R3	R4
Mosha	Low	R1	R2	R3
	Medium	R2	R2	R3
	High	R3	R3	R4
Undefined	Low	R1	R2	R3
	Medium	R2	R3	R3
	High	R3	R3	R4

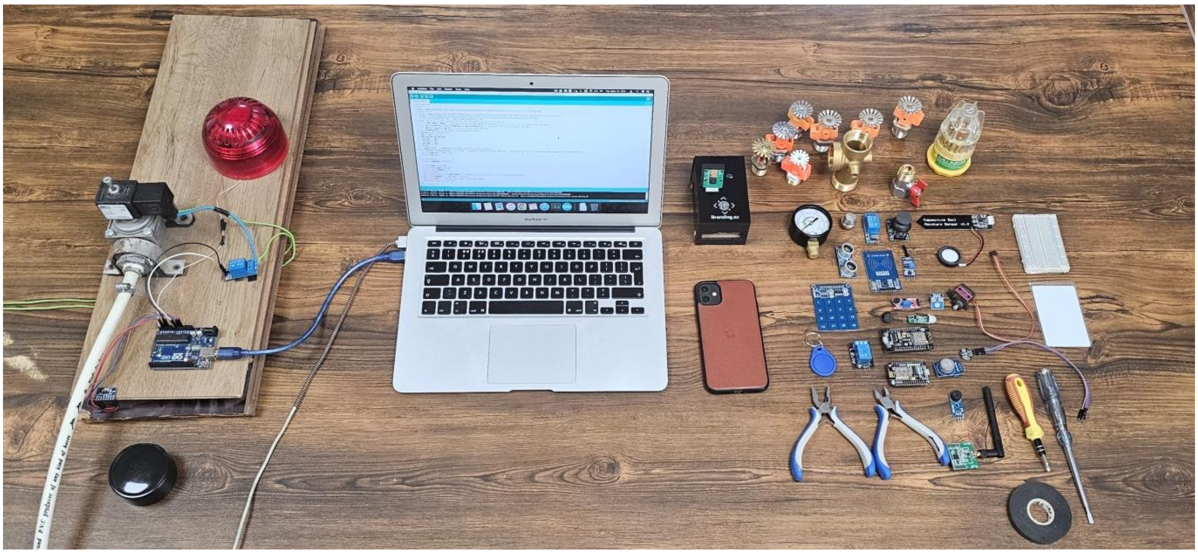


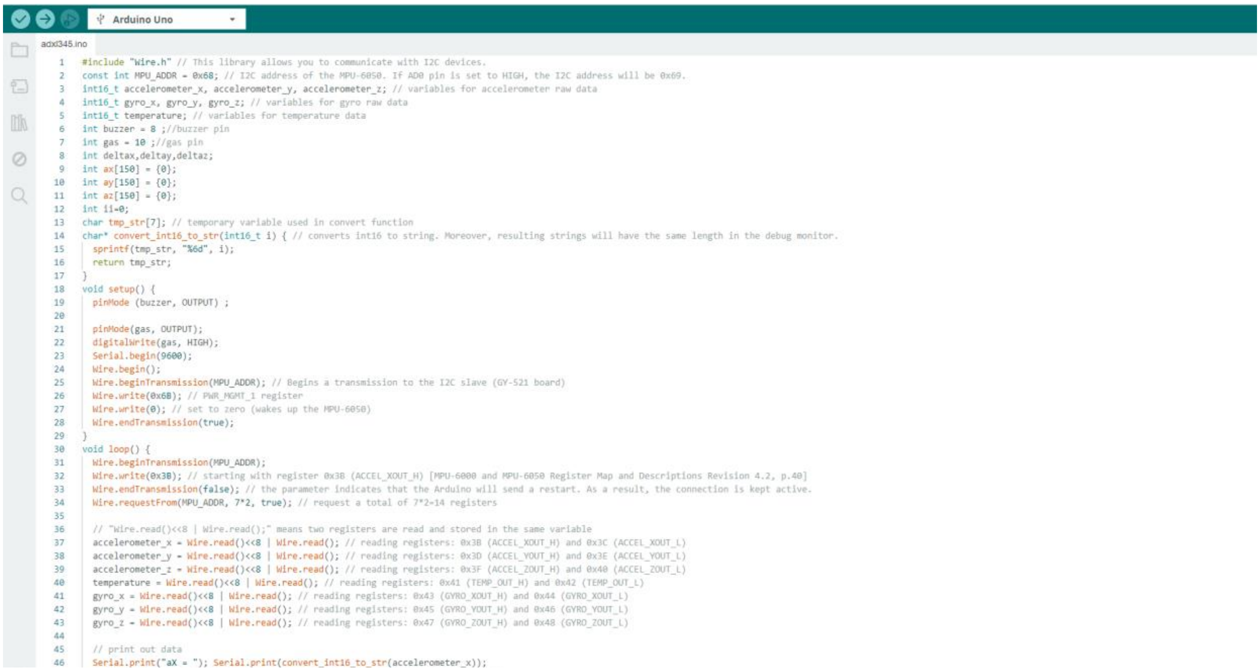
Fig. 24. Laboratory Setup for Testing the Accuracy of the IoT-Based Earthquake Early Warning System with Fuzzy Logic Integration

well as power pressure boost station in the defined fuzzy system.

Conclusion

In the face of inevitable seismic events, the unpredictability of earthquakes presents significant challenges for disaster preparedness and response. An effective early warning system is essential for mitigating damage to infrastructure, safeguarding assets, and preserving human lives. This study focused on Tehran, a city with high seismic potential and dense gas and electric utility networks, highlighting its unique vulnerabilities. The proposed IoT-based early warning system, integrated with fuzzy logic, represents a significant advancement in disaster management strategies. By offering real-time data processing and operational command capabilities, this system addresses critical delays often associated with traditional methods, particularly during the crucial early hours following an earthquake.

The results of this research demonstrate that the proposed system yields acceptable outcomes when compared to the comprehensive Seismic Hazard Assessment of Tehran (JICA). Within less than 10 seconds, based on the predicted level of damage to the city's lifeline infrastructure, the system issues



```
#include "Wire.h" // This library allows you to communicate with I2C devices.
const int MPU_ADDR = 0x68; // I2C address of the MPU-6050. If AD0 pin is set to HIGH, the I2C address will be 0x69.
int16_t accelerometer_x, accelerometer_y, accelerometer_z; // variables for accelerometer raw data
int16_t gyro_x, gyro_y, gyro_z; // variables for gyro raw data
int16_t temperature; // variables for temperature data
int buzzer = 8 ;//buzzer pin
int gas = 10 ;//gas pin
int deltax,deltay,deltaz;
int ax[150] = {0};
int ay[150] = {0};
int az[150] = {0};
int ii=0;
char tmp_str[7]; // temporary variable used in convert function
char* convert_int16_to_str(int16_t i) { // converts int16 to string. Moreover, resulting strings will have the same length in the debug monitor.
  sprintf(tmp_str, "%6d", i);
  return tmp_str;
}
void setup() {
  pinMode (buzzer, OUTPUT) ;

  pinMode(gas, OUTPUT);
  digitalWrite(gas, HIGH);
  Serial.begin(9600);
  Wire.begin();
  Wire.beginTransmission(MPU_ADDR); // Begins a transmission to the I2C slave (GY-521 board)
  Wire.write(0x6B); // PWR_MGMT_1 register
  Wire.write(0); // set to zero (wakes up the MPU-6050)
  Wire.endTransmission(true);
}
void loop() {
  Wire.beginTransmission(MPU_ADDR);
  Wire.write(0x3B); // starting with register 0x3B (ACCEL_XOUT_H) [MPU-6000 and MPU-6050 Register Map and Descriptions Revision 4.2, p.40]
  Wire.endTransmission(false); // the parameter indicates that the Arduino will send a restart. As a result, the connection is kept active.
  Wire.requestFrom(MPU_ADDR, 7*2, true); // request a total of 7*2=14 registers

  // "Wire.read()<<8 | Wire.read();" means two registers are read and stored in the same variable
  accelerometer_x = Wire.read()<<8 | Wire.read(); // reading registers: 0x3B (ACCEL_XOUT_H) and 0x3C (ACCEL_XOUT_L)
  accelerometer_y = Wire.read()<<8 | Wire.read(); // reading registers: 0x3D (ACCEL_YOUT_H) and 0x3E (ACCEL_YOUT_L)
  accelerometer_z = Wire.read()<<8 | Wire.read(); // reading registers: 0x3F (ACCEL_ZOUT_H) and 0x40 (ACCEL_ZOUT_L)
  temperature = Wire.read()<<8 | Wire.read(); // reading registers: 0x41 (TEMP_OUT_H) and 0x42 (TEMP_OUT_L)
  gyro_x = Wire.read()<<8 | Wire.read(); // reading registers: 0x43 (GYRO_XOUT_H) and 0x44 (GYRO_XOUT_L)
  gyro_y = Wire.read()<<8 | Wire.read(); // reading registers: 0x45 (GYRO_YOUT_H) and 0x46 (GYRO_YOUT_L)
  gyro_z = Wire.read()<<8 | Wire.read(); // reading registers: 0x47 (GYRO_ZOUT_H) and 0x48 (GYRO_ZOUT_L)

  // print out data
  Serial.print("aX = "); Serial.print(convert_int16_to_str(accelerometer_x));
```

Fig. 25. Arduino Coding for Wave Detection and Data Transmission to Cloud Server

Table 8. **Compare Results of JICA and IoT-Fuzzy Early Warning Model**

Fault	Maximum PGA (G) (JICA)	Network	IoT-Fuzzy early warning model shut down command	Shut-down command by JICA (JICA)
Rey	0.5 G	Gas	19 km	18 km
Rey	0.5 G	Electric	23 km	20 km
NTF	0.3 G	Gas	13 km	10 km
NTF	0.3 G	Electric	16 km	12 km
Mosha	0.1 G	Gas	4 km	2 km
Mosha	0.1 G	Electric	6 km	0 km

disconnection commands, effectively preventing secondary destructive incidents. This rapid response capability marks a key improvement in reducing the overall impact of seismic events in highly vulnerable urban environments.

Several limitations to this study should be acknowledged. First, the system's effectiveness is largely contingent on the reliability and accuracy of the sensors. Over time, environmental factors, wear, or earthquake-related damage may degrade sensor performance, potentially leading to false alarms or failure to detect seismic events. The use of industrial-grade sensors is recommended for more accurate detection of earthquake waves. Moreover, maintaining and managing a large network of sensors poses significant logistical challenges, necessitating regular maintenance to ensure optimal performance.

Second, the and electric networks, is essential to prevent unauthorized access or potential cyber-attacks. To enhance security, block-chain technology could be integrated to safeguard the integrity of the network and the data it processes.

Future research directions should focus on several key areas to enhance the proposed system. First, integrating additional machine learning techniques could improve predictive accuracy and real-time responsiveness, offering more refined decision-making models. Second, applying this model to other cities with diverse seismic risks would enable comparative analyses, revealing strengths and weaknesses across different urban environments and contributing to the refinement of disaster response strategies. Third, incorporating advanced sensors — such as environmental sensors, satellite imagery, or structural health monitoring — could further improve the system's ability to assess and respond to seismic risks. Lastly, exploring the socio-economic impacts of implementing such systems would provide insight into the long-term value and benefits, particularly in terms of cost savings and the reduction of human and material losses during seismic events.

In conclusion, the proposed IoT and fuzzy logic integration represents a promising approach to enhance earthquake preparedness and response in urban environments. By addressing current limitations and exploring new research avenues, future studies can build upon this work to develop more comprehensive solutions that ensure the safety and resilience of communities facing the ever-present threat of earthquakes.

Issue of data privacy and security must be addressed due to the extensive data collection by IoT devices. Protecting sensitive information, particularly in the context of critical infrastructure like gas.

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СИСТЕМА РАННЕГО ПРЕДУПРЕЖДЕНИЯ ЗЕМЛЕТРЯСЕНИЙ НА ОСНОВЕ IOT С НЕЧЕТКОЙ ЛОГИКОЙ ДЛЯ УПРАВЛЕНИЯ КОММУНАЛЬНЫМИ СЛУЖБАМИ В ТЕГЕРАНЕ

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Аннотация
Введение. Сценарии стихийных бедствий предсказать сложно, но подготовиться к ним необходимо. Технология Интернета вещей (IoT), получившая широкое распространение, может сыграть значительную роль в борьбе со стихийными бедствиями. Для стран, особенно подверженных сейсмической активности, внедрение систем раннего предупреждения имеет решающее значение для спасения жизней и минимизации ущерба. Эти системы оповещают людей и власти о наступлении стихийных бедствий. Однако принятию решений после стихийных бедствий по мониторингу основных коммунальных услуг, таких как газ и электричество, в критические периоды уделяется ограниченное внимание. **Методы**. Интеграция IoT с экспертной системой на основе нечеткой логики (Fuzzy system) может улучшить процесс принятия решений после стихийных бедствий, сократить расходы и разрушения в городских районах. Тегеран, город с высоким сейсмическим риском и разветвленной сетью газоснабжения, сталкивается со значительной опасностью повреждения газовых и электрических систем в случае сильных землетрясений. **Результаты**. Исследование показало, что предложенная система IoT-Fuzzy эффективно работает по сравнению с оценкой сейсмической опасности Тегерана, проведенной Японским управлением международного сотрудничества (ЯУМС/ JICA).Система выдает команды на отключение критически важных коммуникаций в течение 10 секунд, основываясь на прогнозе уровня повреждений, помогая снизить вторичный ущерб после землетрясения. Эта система показывает перспективы в улучшении реагирования после стихийных бедствий и защиты городской инфраструктуры.

Ключевые слова: управление кризисными ситуациями; интернет вещей; экспертная система на основе нечеткой логики (Fuzzy system); система раннего оповещения; электронные административные услуги (умный город); городское управление.