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Development of Earthquake Detection and Warning System Based on Sensors

Fu-Hsien Chen, Horng-Lin Shieh,* and Jih-Fu Tu

Lunghwa University of Science and Technology,
No. 300, Sec. 1, Wanshou Rd., Guishan District, Taoyuan City 333326, Taiwan

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Earthquakes often cause severe disasters. Taiwan is located in an earthquake zone, where earthquakes occur frequently. For example, the Meinong earthquake in Kaohsiung in 2016 and the Hualien earthquake in 2018 caused the collapse of buildings in Tainan and Hualien, resulting in a total of 232 deaths and more than 100 injuries. Due to the strong vibration, earthquakes are often accompanied by fire and the leakage of toxic gases, causing loss of life and property. In this study, we integrate Arduino, sensors, and transmission technology to design an earthquake detection and warning system. When an earthquake is detected, the system immediately notifies everyone to evacuate. When the harmful gas concentration exceeds a critical value, the warning light is switched on, and the exhaust fan is turned on to extract the indoor toxic gas. When the flame sensor detects a flame, the system activates an alarm to warn people to escape quickly. In the designed system, capacitive three-axis accelerators are used as vibration measurement sensors to issue warnings in the early stage of an earthquake. In addition, the system includes an IR flame sensor to detect fires and an MQ series air quality sensor to detect harmful gases. The newly designed sensing system not only has the advantage of notifying people immediately during an earthquake but is also cheap and easy to use.

1. Introduction

Taiwan experiences frequent seismic activity due to the ongoing subduction of the Philippine and Eurasian plates.(1) Old buildings are often cracked and tilted due to earthquakes. As shown in Fig. 1(a),(2) the 2016 Meinong earthquake in Kaohsiung caused a building to collapse in Yongkang District, Tainan City, killing 115 people. Figure 1(b) shows a building that collapsed during the Hualien earthquake in 2018.(3) This earthquake was the most severe in Taiwan since the Kaohsiung Meinong earthquake in 2016. The quake caused four buildings to collapse and 17 people to die. Earthquakes are often accompanied by fires and toxic gas leakage. Therefore, their detection is also necessary when an earthquake occurs.

In this study, we integrate embedded systems, wireless transmission technology, network access, and sensors to design an earthquake-sensing system. When an earthquake is detected,

*Corresponding author: e-mail: shieh@gm.lhu.edu.tw
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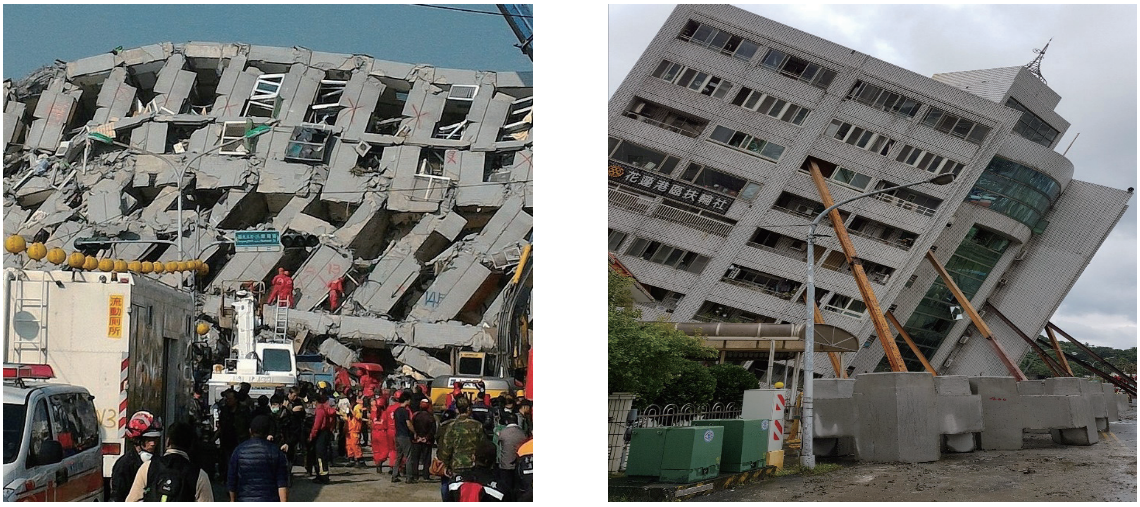


(a) (b)

Fig. 1. (Color online) (a) Building collapse caused by the Kaohsiung Meinong earthquake. (b) Building collapse caused by the Hualien earthquake in Taiwan.

the system warns users with a buzzer and notifies people immediately of a tilted building, harmful gas leakage, or a fire.

The designed system includes Wi-Fi wireless transmission combined with a three-axis accelerator, an MQ series sensor, and a flame sensor to detect earthquakes, harmful gases, and fires, respectively. The system can not only warn users to escape early but also detect possible threats to life when earthquakes occur.

2. Literature Review

Hsu(4) proposed a wireless earthquake early warning and detection system that used a three-axis accelerometer to detect earthquakes. In the system, temperature-sensitive changes were avoided by using capacitors with direct current (DC) to reduce noise. The sensing signal of the three-axis accelerometer was transmitted through the serial peripheral interface (SPI). It then sent the signal to the server using a wireless network, and a data analysis method was used to notify the user of the risk. The advantage of the system is the use of DC capacitors to reduce the noise density of the three-axis accelerometer. However, it only detects earthquakes and does not warn users of building tilt, harmful gases, and fires caused by earthquakes.

Hsu and Sheu(5) proposed an ultralow-complexity algorithm for an earthquake early warning system. The algorithm used the moving average method to eliminate short-term noise and collected the turning points where the earthquake starts to be detected as important feature points for earthquake identification. Then, the quadratic differentiation method was used to differentiate the turning points and calculate the earthquake's magnitude. The primary purpose of their study was to quickly and accurately calculate the magnitude of earthquakes.

Yoon *et al.*(6) developed a fingerprint and similarity thresholding algorithm (FAST) to analyze seismic waves. FAST built a compressed fingerprint waveform based on the main identified features, stored similar fingerprints in a database to enable a quick search, and monitored a series of earthquake detections.

Jayron *et al.*(7) developed an earthquake detector unit system using Arduino Mega and an ADXL335 accelerometer. In this system, when the Arduino Mega earthquake detector detected ground motion of a specified intensity level, the system triggered an alarm that made a sound. A solar panel system was integrated to power the designed system. Such a solar-power-operated earthquake detector with an automatic alarm system helped raise awareness when earthquakes occurred, reducing physical harm to humans and accidents. In the system, an LCD was used to display messages on the current status and readings of the ADXL335 accelerometer. Although its solar power supply reduced its environmental impact, it could not detect the harmful gases produced when an earthquake occurs.

Grover and Sharma(8) defined information about an earthquake and designed a system to predict earthquakes. Their paper briefly introduced various types of seismic waves with their respective frequencies. Their developed system integrated an Arduino Uno microcontroller (ATMega 328) and an accelerometer (ADLX335) used to measure seismic data in earthquake-prone areas, which were connected to a data center by a wireless network. The ADLX335 is a small, thin, low-power, complete three-axis accelerometer with signal-conditioned voltage outputs(9) and can measure static and dynamic accelerations in the X, Y, and Z directions. The microcontroller converted this data into a digital form, then sent it wirelessly to the data center. If there is no earthquake, the system is in a measurement loop. If the system predicts an earthquake, the system produces a warning sound to users.

Faiazuddin *et al.*(10) combined the IoT, a Raspberry Pi 4 device, Arduino Uno, sensors, and ThingSpeak cloud technology to build an indoor air quality monitoring system. The system mainly detects indoor CO_2, CO, NO_2, H_2, NH_3, and other gases. The relevant measurement data is sent to the cloud for MySQL storage and analyzed in real-time with ThingSpeak. The monitoring system builds a module for calculating the air quality index (AQI), which collects information from various sensor network nodes to increase the number of network nodes deployed and more accurately measure the air quality.

Liu *et al.*(11) implemented a low-cost and practical mobile indoor air quality monitoring system using Arduino and sensors. They used tracking and obstacle avoidance sensors to achieve autonomous movement and gas sensors for indoor air quality monitoring. The system collected data for CO, PM2.5, temperature, and humidity with the framework and professional measurement instruments. The experimental results showed that the errors for the CO and PM2.5 concentrations, temperature, and humidity were only 0.086, 0.81, 0.15, and 1.2%, respectively. It was found that the accuracy with Arduino and the sensors was similar to that of professional instruments.

Schieweck *et al.*(12) integrated the concept of smart homes with the efficient use of energy and ventilation technology in low-energy buildings. They analyzed in detail the impact of environmental parameters measured in Germany and Sweden on indoor air quality, personal thermal comfort, and occupancy behavior in smart homes. They also introduced sensor technology to assess the level of pollution. As different types of sensing technologies are suitable for different situations, they evaluated available sensor technologies, discussing the application of sensors and their limits and possibilities for monitoring the concentration of particles and gaseous pollutants indoors.

3. System Architecture

Figure 2 shows the architecture of the proposed system. The server, which is the data center, is used to set up the database system required for the design and store sensor data and serves as a monitoring interface to display data and respond to queries. The embedded system uses Arduino as its core. The sensing modules in the system are seismic and building tilt sensor modules, which use an ADXL345 three-axis accelerometer. Smoke, gases, and air quality are respectively sensed by MQ-2, MQ-5, and MQ-135 sensors, and a flame is detected by an IR flame sensor.

3.1 User interface

The user interface includes functions such as user login, wireless communication operation, database query, data statistics, and a hazard alarm, as follows:

A. **User login:** Responsible for creating user accounts, entering user passwords, and verifying database access rights.
B. **Wireless communication operation:** Responsible for establishing a wireless connection between the server and the Wi-Fi router, including the IP address and port setting.
C. **Database query:** Various data queries, including air quality, building inclination, and flame information.
D. **Data statistics:** The data for a week, a month, or the whole year is presented in a graphical interface to facilitate inquiries from users about environmental changes.
E. **Hazard alarm:** When an earthquake, gas leakage, or fire occurs, or the building is tilted beyond a certain angle, the system issues a warning sound to alert users of the problem.

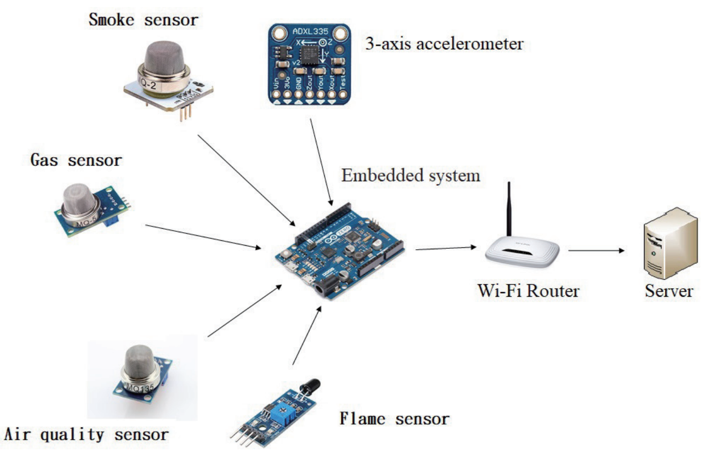


Fig. 2. (Color online) Architecture of proposed system.

3.2 ADXL345 three-axis accelerometer

The accelerometer calculates the acceleration in three dimensions.(13) The proposed system uses an ADXL345 three-axis accelerometer for earthquake sensing and building tilt detection, which is a thin, short gravity sensor with low power consumption. It consists of fixed and moving plates that deflect in any direction subject to acceleration in the x, y, and z directions.(14) Its digital output data is in the format of a 16-bit binary code, which is transmitted with an SPI or I^2C digital serial transfer. It is ideal for static acceleration or center-of-gravity tilt sensing applications, and its high resolution (4 mg/LSB) enables the measurement of changes in the tilt of less than 1.0°.

Figure 3 shows the diagram of the tilt angles for ADXL345. The following angles are calculated as(13)

$$\alpha_1 = \tan^{-1}\left(\frac{A_x}{\sqrt{A_y^2 + A_z^2}}\right), \tag{1}$$

$$\beta_1 = \tan^{-1}\left(\frac{A_y}{\sqrt{A_x^2 + A_z^2}}\right), \tag{2}$$

$$\gamma_1 = \tan^{-1}\left(\frac{A_z}{\sqrt{A_x^2 + A_y^2}}\right), \tag{3}$$

where A_x, A_y, and A_z represent the acceleration values in the respective directions of the coordinate axes, while α_1, β_1, and γ_1 represent the angles between each acceleration vector and the horizontal line.

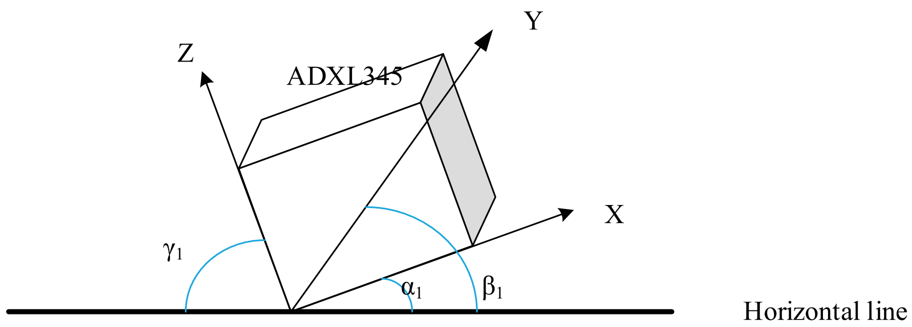


Fig. 3. (Color online) Tilt angle diagram for ADXL345.

3.3 IR flame module

The IR flame sensing module uses IR rays that are sensitive to flames and IR receiver tubes to detect the presence of fire, and then converts the brightness of the flames into a voltage signal output. The critical characteristics of the flame model are as follows.

A. The module detects light sources whose flame wavelength ranges from 760 to 1100 nm.[15] The larger the flame, the longer the test distance.
B. The detection angle is about 60° and is not sensitive to flame light.
C. The sensitivity is adjusted with an adjustable precision potentiometer.
D. The working voltage is 3.3–5 V.
E. The voltage increases with the distance from the flame source.

The output voltage in the case of no fire source is 4.8 V. When a fire occurs, the voltage value read by Arduino is lower than 4.0 V, and the system reports a suspected fire. The statistics of the relationship between distance from fire source and output voltage are presented in Table 1.

3.4 Air quality sensor module

In this study, the air quality is monitored using MQ series sensors. These sensors detect six different gases, namely, methane, propane, butane, smoke, carbon monoxide, and ammonia. They have a fine porous stainless steel mesh for rapid heat transfer to prevent a gas explosion, and they use tin dioxide (SnO_2) as a gas-sensing material as it has low conductivity in clean air. When the concentration of harmful gases in the air increases, the conductivity of the sensor increases, and then a simple ADC conversion circuit converts the change in conductivity into an output signal corresponding to the gas concentration. MQ sensors are classified as follows.

MQ-2: Smoke gas sensor.
MQ-3: Alcohol sensor.
MQ-4: Methane gas sensor.
MQ-5: Liquefied gas/methane sensor.
MQ-6: Propane/liquefied gas sensor.
MQ-7: Carbon monoxide/combustible gas sensor.
MQ-8: Hydrogen gas sensor.

Table 1
Relationship between distance from fire source and output voltage.

Distance (mm)	Output (V)	Distance (mm)	Output (V)
10	0.06	20	0.07
40	0.09	60	0.1
80	0.11	100	0.13
200	0.18	300	0.19
400	0.22	500	0.25
600	0.30	700	0.32
800	0.43	900	0.50
1000	0.70	2000	1.44
8000	3.52	—	—

MQ-9: Carbon monoxide/methane/liquefied gas sensor.

MQ-135: Air pollution/harmful gas sensor.

Because of the impact of air quality at home, we use four types of sensors: MQ-2, MQ-5, MQ-7, and MQ-135.

4. Experimental Results

Figure 4(a) shows the front view of the house model built for this study. Sensors are installed in the upper left corner of the house. The Arduino and three-axis accelerometer are located at the bottom of the model, and the wireless Wi-Fi router is placed behind the model house as shown in Fig. 4(b). Figure 4(c) shows the user interface, where "IP" displays the IP address of the house model and "3-axis accelerometer" displays the angles α_1, β_1, and γ_1 measured by the three-axis accelerometer. The menus "Smoke", "Air quality", "Gas", and "Flame" display the indoor smoke quantity, air quality, gas concentration, and fire monitoring value, respectively. The graphs on the right of each monitoring item display the monitoring status, where the blue line indicates the monitoring value and the red line indicates the critical value. When the system detects a monitoring value exceeding the threshold, it generates a warning sound and displays the sign "Warning message". The "Start" button in Fig. 4(c) is used to start the system, the "End" button is used to stop the system, and the "View" button is used to view the log of abnormal events.

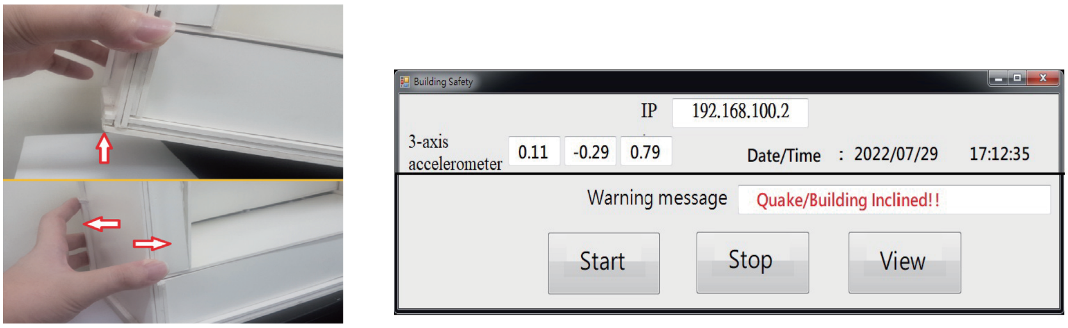
Figure 5(a) shows how the up, down, left, and right displacements in an earthquake were simulated. Figure 5(b) shows the values measured by the three-axis accelerometer. The values of 0.11, −0.29, and 0.79 indicate an earthquake, and the system sounds an alarm and displays a warning message.

To simulate gas leakage, we use a gas lighter to generate gas at a distance of about 5 cm from the sensor as shown in Fig. 6(a). As shown by the blue line in Fig. 6(b), when the system detects gas with a concentration exceeding a threshold value, a warning message is displayed to inform the user of a gas leakage.

Figure 7(a) shows the fire used for testing. We use a gas lighter to generate a flame about 5 cm from the sensor. Figure 7(b) shows that when a fire is generated, the sensor immediately detects it and displays a fire alarm message. It also generates a warning sound. In the figure, the blue line shows the value for the flame and the red line shows the threshold value.

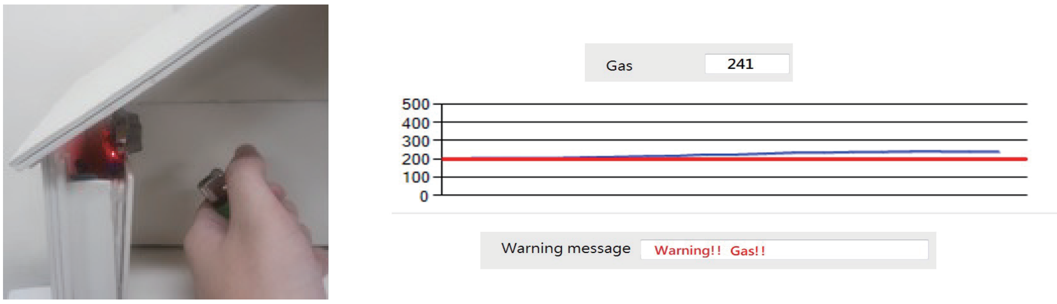
(a) (b) (c)

Fig. 4. (Color online) (a) House model built for this study. (b) Wi-Fi router. (c) Human–machine interface.



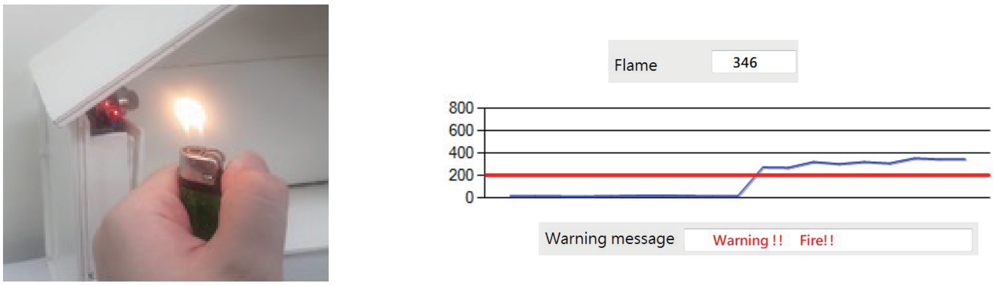
(a) (b)

Fig. 5. (Color online) (a) Simulation of an earthquake. (b) Warning message generated when the sensor detects an earthquake.



(a) (b)

Fig. 6. (Color online) (a) Gas-sensing experiment. (b) Warning message generated by the system when the sensor detects gas.

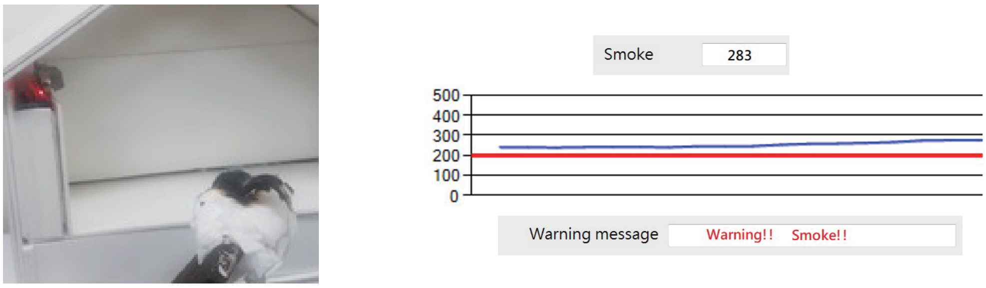


(a) (b)

Fig. 7. (Color online) (a) Fire experiment. (b) Warning message generated when the sensor detects a fire. A warning sound is also generated.

Next, we generate smoke by burning tissue paper as shown in Fig. 8(a). When smoke is generated indoors, the smoke detection line in blue exceeds the red line indicating the threshold value, and the system generates a warning sound and message.

When there is an earthquake, gas, or fire in the room, the system records the event along with the time of occurrence in the back-end server system through the wireless network. As shown in Fig. 9, when the user presses “View”, the system displays all abnormal events, which can be queried.



(a) (b)

Fig. 8. (Color online) (a) Smoke experiment. (b) Warning message generated for smoke.

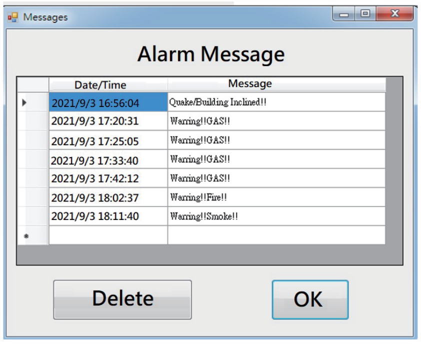


Fig. 9. (Color online) Query of abnormal events in the database.

Table 2
Comparison of system in this study with other systems.

	Jayron *et al.*[7]	Grover and Sharma[8]	Proposed method
Earthquake detection	√	√	√
Warning sound	√	√	√
Harmful gas detection	×	×	√
Flame detection	×	×	√
Data center	×	√	√

Table 2 shows a comparison of the system designed in this study with other systems. A large earthquake causing damage to buildings is often accompanied by fires and toxic gas leakage. Therefore, it is necessary to detect earthquakes, fire, and toxic gas concentrations at the same time. Our newly designed system detects all three, whereas the systems designed by Jayron *et al.*[7] and Grover and Sharma[8] detect earthquakes but not fire and toxic gases. To detect possible fires and abnormal toxic gas concentrations when an earthquake occurs, our system stores the data in a cloud database through wireless transmission for subsequent inquiries. The system designed by Grover and Sharma included a data center to store seismic data but lacked information on fire and toxic gases. The system developed by Jayron *et al.* did not include a data center. Therefore, our system has greater functionality than the other systems.

5. Conclusions

When an earthquake occurs, the time available to find a sheltered space is only a few to a dozen seconds. Therefore, in the early stages of an earthquake, it is important to provide early warnings to people to seek shelter as soon as possible. To warn people of an earthquake, harmful gas, or fire so that they can evacuate effectively, we established an earthquake disaster prevention system combining Arduino, sensors, and 4G transmission technology. The results of testing the system showed that it functions appropriately. In the future, the system will require modularization and packaging so that it can be applied as a disaster prevention system in houses, businesses, factories, public offices, and schools. The designed system provides the basis for a large-scale application to warn people of earthquakes and accompanying fires and gas leakage.

Acknowledgments

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