American Journal of Data Science and Artificial Intelligence (AJDSAI)

ISSN: 3069-3632 (ONLINE)

VOLUME 2 ISSUE 2 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Data Science and Artificial Intelligence (AJDSAI)

Volume 2 Issue 2, Year 2026
ISSN: 3069-3632 (Online)
DOI: https://doi.org/10.54536/ajdsai.v2i2.7695
https://journals.e-palli.com/home/index.php/ajdsai

BahAI: Smart Home Safety System for Hazard Detection and Notification

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Article Information

Received: March 02, 2026

Accepted: May 05, 2026

Published: September 24, 2026

Keywords

Blynk, Emergency, Household, Internet Of Things (Iot), Real-Time Monitoring

ABSTRACT

Hazards to residential homes, including earthquake disasters, fire and gas leaks, remain safety hazards in the community. Homeowners often face delays in identifying and responding to hazards because there are no widely-available, integrated safety technologies. While there have been previous works demonstrating how Internet of Things (IoT)-based solutions could play a role in home security, research has primarily localized and lack of user-centric evaluations. This study aimed to design and develop a smart home safety warning system capable of detecting hazards (earthquake, fire, gas leak) with a programmed logic for system operation and notification, while evaluating the acceptability and adaptability of prototype. A Design and Development (D&D) research design was utilized in systematically developing, testing, and evaluating the prototype. Results indicate the system's excellent performance. Sensors work well and provide accurate hazard detection, with response times within established safety guidelines. The delivery of notifications and the remote code execution are consistently reliable. The overall evaluation indicates that the system is highly acceptable (M = 4.94) and adaptable (M = 4.72) to evaluators, which suggest the system is easy to use and reliable. The project successfully designed a home safety smart system that can perceive the danger in the local environment, automatically take actions and report to alarm at first time. The prototype is reliable, responsive and user-friendly for residential use, offering an effective means of improving people's safety and preparing them for emergencies in home settings at risk from hazards.

INTRODUCTION

Home safety remained a significant concern worldwide due to the dangers of fire, gas leaks, and electrical hazards that posed threats to human life and property. Millions of injuries and deaths were registered every year due to home hazards that could have been prevented, thus underlining the need for enhanced safety measures (World Health Organization, 2024). In the Philippines, home fires and carbon monoxide poisoning were frequent events because of the lack of access to modern home safety systems and delayed responses (Philippine Statistics Authority, 2023). With the continuous advancement of technology, smart home systems and Internet of Things (IoT) devices made new breakthroughs in the monitoring warning response for home safety in residential areas.

Local studies have proven the effectiveness of IoT applications in mitigating home safety risks. An IoT-based home fire safety system significantly reduced response time by 35% and allowed faster evacuation with reduced property damage (Bajador *et al.*, 2025) while another study recorded a 92% detection rate with their LPG leakage monitoring device, greatly improving household safety in urban areas (Fadlil & Mustofa, 2023). Similarly, IoT smoke detectors improved household preparedness by 87%, as most test households reacted within two minutes after the detection of the hazard (Sy & Agoylo *et al.*, 2024), while wireless alarm systems improved awareness of emergencies by 70% (Bemthuis & Sepanosian, 2025). An IoT-driven warning system also proved that IoT-driven warning systems improved the efficiency of disaster communication by 80% in the barangays of Quezon City (Fabito *et al.*, 2025). Overall, these studies demonstrate the effectiveness of IoT-based safety systems in detecting and responding to hazards within the Philippine context.

Globally, such findings also proved the efficacy of IoT warning systems in home safety and disaster preparedness. In India, an IoT-based fire and gas detection system was designed with 95% accuracy, thus establishing its feasibility for use at an affordable cost (Singh *et al.*, 2025), while in Malaysia there was a 40% reduction in response time using smart home technology (Waqar *et al.*, 2023). IoT-integrated fire alarms with mobile notification also enhanced evacuation efficiency by 60% (Abrar *et al.*, 2023). Similarly, an IoT-based platforms in Bangladesh also identified gas leaks and electrical faults with 93% accuracy (Bala & Kaur, 205). Moreover, a user-friendly IoT monitoring system also increased safety compliance, with a 50% decrease in hazard incidents. These findings establish the global efficacy of IoT in hazard detection and disaster response.

Despite recent developments, home safety systems in the Philippines remained isolated, addressing single hazards without multi-hazard detection and automated systems. Although IoT-based systems solutions existed for particular hazards such as earthquakes, fire, and gas leaks,

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overall systems were limited, making disaster-prone homes vulnerable to hazards. Hence, this study aimed to design an IoT-based home safety system using machine learning and artificial intelligence (AI) to detect and respond to hazards such as fire, gas leaks, and earthquakes, with real-time alert notifications and automated responses.

Specifically, this study 1) designed an IoT-Based Home Safety System for hazards such as a) earthquakes, b) fire, and c) gas leaks; 2) developed a program logic for the prototype; 3) conducted functionality tests on the prototype in terms of its a) functionality of individual components, b) response time, and c) notification remote execution; and 4) evaluated the acceptability and adaptability of the prototype. This research contributed to improving the preparedness of a nation in the face of disaster by making homes safer through real-time hazard detection and automated emergency response. It benefited homeowners, communities, and emergency services in vulnerable areas. Aligned with SDG 9 and SDG 11, it promotes resilient infrastructure and safer, sustainable communities as a model for smart disaster mitigation technologies.

MATERIALS AND METHODS

Materials

The materials used in constructing the development and evaluation of smart home safety systems for hazard detection and notification included the ESP32 microcontroller, KY-026 flame sensor, MQ-2 smoke sensor, MQ-4 gas sensor, SW-420 vibration sensor, PZEM-004T energy monitoring module, DHT-11 temperature and humidity sensor, relay module, LCD display with IC module, buzzer, LED indicators, push buttons, water pump, sprinkler system, electrical wires and connectors, breadboard and jumper wires, regulated power supply, prototype enclosure, smartphone with Blynk application, resistors, transistors, circuit breaker, power adapter, USB cable, and mounting screws and fasteners.

Research Design

The research design employed the Design and Development (D&D) framework, which was grounded on the development and improvement of a smart home safety system for hazard detection and notification. Modern D&D approaches were used on the assessment of innovative projects in accordance to a criteria such as effort, potential, risk and overall product improvement (Kumar & Sharma, 2023). It was made possible to assess the system's design and components, operational process, and overall functionality. During the different phases of development, various groups of participants were involved in testing and evaluating the prototype. These included individuals who took part in functionality testing, acceptability surveys, and adaptability assessments throughout the prototype development process. Their involvement helped ensure that the device met safety and functional requirements while also addressing user needs within the defined target market, allowing for safe and effective use in a real-world environment.

Procedure

Designing of IoT-Based Home Safety System for Hazard Detection and Notification

The prototype was designed through the combination of four primary sensors which each monitored distinct hazard. The KY-026 flame sensor was used to detect fires while the MQ-2 sensor detect smoke. The system used the MQ-4 gas sensor to identify gas leaks and the SW-420 vibration sensor to monitor both earthquake activity and atypical vibrations. The group studied all component functions before beginning the assembly process to achieve optimal operational efficiency. The complete system design showed all hazard detection elements together with their user alert systems which included hazard detection circuits and workflow diagram components. The sensors were installed at their designated location while the wiring was arranged to achieve safety requirements and operational effectiveness and to minimize system disruptions. The enclosure design provided necessary airflow and complete visibility and maintenance access but maintained full hardware and software compatibility until testing began.

Fire Detector

During the fire detection system design phase, both the KY-026 flame-sensing device and DHT-11 temperature and humidity sensors were used to detect fire indicators. The KY-026 device was installed in a location with maximum sensitivity to infrared radiation from flames and DHT-11 device tracked temperature and humidity fluctuations which served as fire detection indicators. The system used both devices to connect with the microcontroller which allowed immediate fire detection to notify users about the detected fire indicators (Darang & Apataya, 2026).

Smoke Detector

In the smoke detection system design stage, it integrated the MQ2 Sensor that could detect both combustible gases and smoke with high precision (IRJET, 2025). The sensor was installed in a location that is prone to both combustible gas and smoke hazards according to the design specifications that included calibration settings for accurate detection. After connecting to the microcontroller, the alert system activates when the smoke concentration reaches the set threshold for that specific area.

Gas Leak Detector

During the gas leak detection system design phase, MQ-4 gas sensor that can identify methane and other flammable gases were used. The sensor was installed in a location close to gas pipelines and stoves. The wiring was arranged to maintain stable and reliable signal transmission. Then, when a sensor is connected to the microcontroller and gas concentration exceeded safe levels the system provided an alert (Fonollosa *et al.*, 2018)

Earthquake Detector

In the earthquake detection system design stage, SW-420 vibration sensor that has ability to detect the motion and ground movement were used (Chandrakumar *et al.*, 2022) The sensor was mounted to a fixed location, and adjusted to be sensitive enough to detect regular vibration as well as higher amplitudes of seismic movement that indicates an earthquake.

Block Diagram of the Prototype

The figure 1 showed the major components of the system and how they were connected. The flame, gas, vibration, and smoke sensors from the input component detected hazards and sent signals to the ESP32 micro-controller

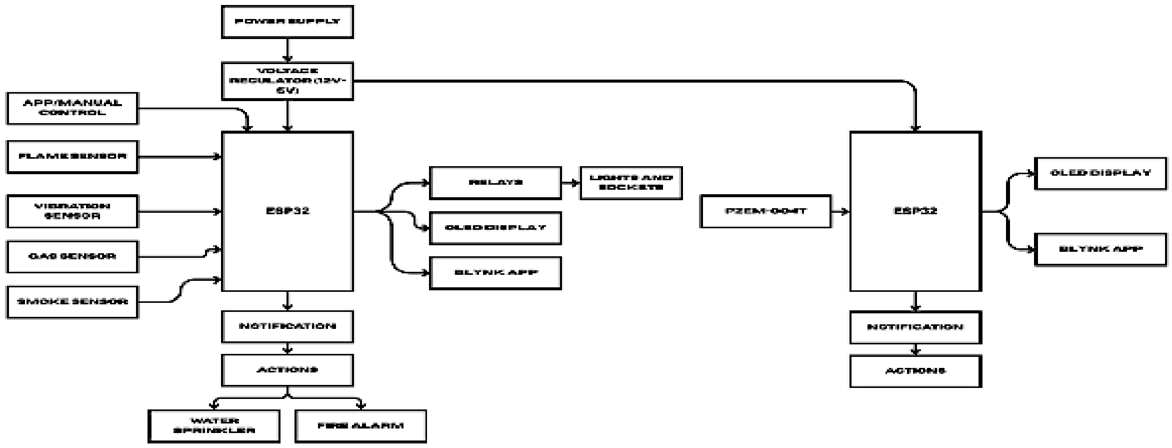

Figure 1: Block Diagram

as a processing unit The microcontroller processed the information from the sensors, which then activated the corresponding output devices. These included a water pump and sprinkler system for fire suppression, a power cut-off relay for electrical hazards, a buzzer or alarm sound for sound notifications, and mobile alters through the Blynk app. To identify the anomalies, an energy management system was employed equipped with a PZEM-004T module to measure voltage, current, power and energy coming from demand loads. All the components were connected in such a way that sensors, microcontroller and output devices communicated always between each other in real time manner for direct risk response.

Schematic Diagram of the Prototype

The figure 2 showed the electrical connections of all components in the system. The sensors were connected to the analog and digital pins of the ESP32 microcontroller for data collection. The relay module is connected to the ESP32 which controls the water pump and power-off. Status of the system was displayed on an LCD interfaced with the system. On the control pin, an alarm or buzzer was connected enabling audible warnings to be triggered under unsafe conditions. All components were powered with a regulated 5V/3.3V power source, and an adequate ground line was provided to ensure robust operation as well as for user safety.

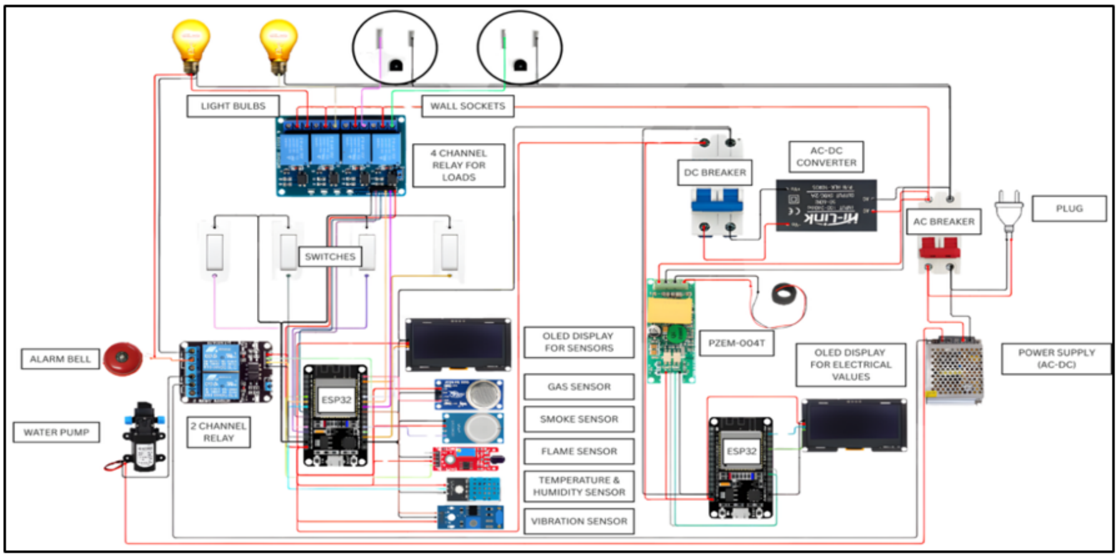

Figure 2: Schematic Diagram

Circuit Diagram of the Prototype

The figure 3 illustrates the connections between all of the system components. The sensors were connected to both the analog and digital pin inputs of the ESP32 microcontroller for data acquisition. The relay module was connected to the ESP32 adding ease of control over the operation of the water pump and shutting down power to the electrical system. The LCD was connected using I2C communication to provide status information about the system. The alarm/buzzer was connected using one of the control pins so the user would have audible notification of a hazardous condition. A 5V/3.3V regulated power supply was provided to all components, while a ground connection was made to each component for safety purposes

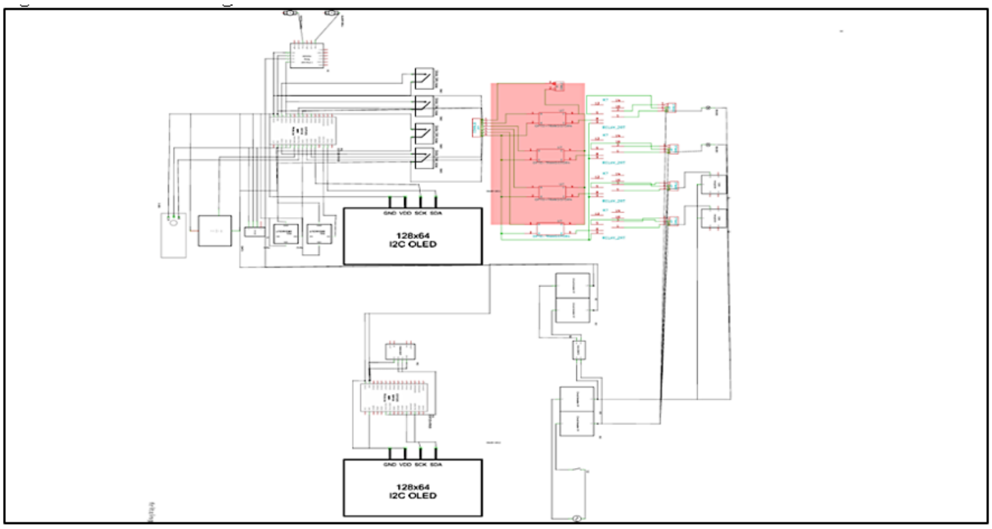

Figure 3: Circuit Diagram

The Prototype

The prototype, as shown in figure 4, combined four types of sensors (fire, gas, smoke and vibration) along with an ESP32 microcontroller, relays and actuators within a single compact package that was developed with considerations of safety, functionality, and ease of use. Predefined control logic, as shown in figure 5, was programmed into the system so that it could operate the sprinkler device via relay activation. Testing this ability was accomplished by using the KY-026 flame sensor and MQ-2 smoke sensor to produce alerts with an alarm/buzzer, an LCD display and a push notification system. The MQ-4 gas sensor was mounted in the lower section of the prototype to capture methane or LPG leaks, and invoke notifications without supplying water from the sprinkler system, which can add further hazards. The SW-420 vibration sensor was triggered by shaking of the prototype box in case of an earthquake. This sensor triggered all electrical components, including the electrical power shutoff, which prevented gas leakage from electrical surges or fire. The home system monitoring will be through the Blynk application, additional enhancements to the prototype included the PZEM-004T energy monitor and the DHT-11 environmental sensor that reported their condition helping determine prototype reliability. The LCD screen provided status feedback to the user, and the manual buttons provided the user with control. Safe routing of connected wires through the prototype enclosure, adequate ventilation for components, and proper placement of interface elements were also considered to be safe practice, ease of upkeep, and household hazard surveys.

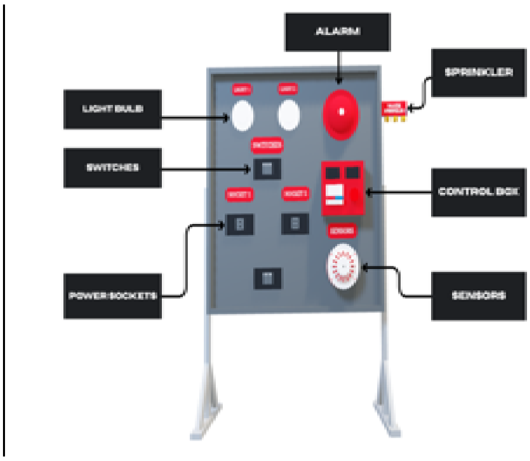

Figure 4: Model of Prototype

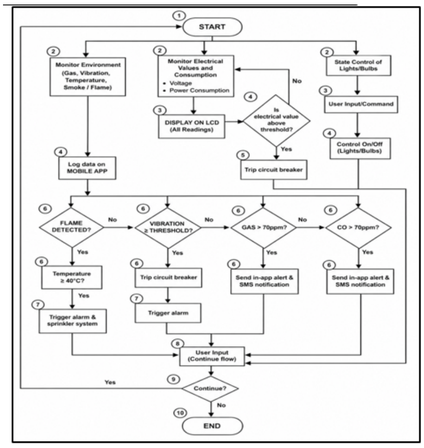

Figure 5: System Flow Diagram

Developing Program Logic

Sensors were constantly checked by the program logic, which compared their value with threshold values and made certain responses if hazards were detected. This included the use of alarms, notifications and output devices such as water pumps or power relays. User interfaces provided status information and manual control, while energy monitoring and data logging assisted with system optimization

Functionality Testing

The Functionality of the system was tested using the System Sensor Activation Points formulas since the checklist evaluation yielded (Yes/No) responses. Every "Yes" corresponded to a successful detection or functioning, while every "No" corresponded to a failure or error. Repeated trials were conducted by exposing the fire, gas, and vibration sensors to hazards. The number of successful detections was then divided by the total number of trials to determine the success rate.

Response Time Testing

The response time was measured by simulating hazards such as fire, smoke, gas leak, and vibration through recording how long the prototype sensor detected the hazard and triggered its buzzer, LCD, and relay using a stopwatch and data logger. For the mobile application, the interval between sensor activation, notification delivery, and the time to execute remote commands was measured with thirty (30) trials per hazard as under Central Limit Theorem, this number of trials can guarantee accurate averages; results were then compared with preset thresholds (≤3 seconds for fire, ≤5 seconds for gas/smoke, ≤1 second for vibration, and ≤5 seconds for application notifications) (Ghasemi & Zahediasl, 2012). The average response time of the fire, gas, and vibration sensors was computed using the formula, For the response time of sensors, by using a stopwatch, the exact time each sensor took to detect the hazard after exposure was recorded in multiple trials. The sum of these times was divided by the number of trials to obtain the average response time.

Notification and Remote Execution Speed Testing

This provided a measure of system latency to alert and execute commands at varying distances. For the notification and remote execution speed, alerts and remote commands through the mobile app were triggered repeatedly. The time interval between sending the command and the system's execution was measured and averaged (Al-Fuqaha *et al.*, 2015).

Evaluation of Prototype and App

The acceptability and adaptability testing evaluated both user perceptions of the usability, functionality, reliability, and general suitability to everyday use of the 3-in-1 safety system and mobile app. The 5-point Likert Scale (1 = Strongly Disagree to 5 = Strongly Agree) survey assessed respondents' evaluations of the prototype with regard to ease of use, reliability, safety, and adaptability to be used in a household. The main criteria were ease of use, reliability, usefulness, adaptability, and acceptability. Respondents for the survey included adults aged 18–60 from Region XII made up engineering graduates or professionals working for safety-related agencies such as the DRRM and BFP. The evaluation of the mobile app followed the same Likert Scale survey used for the prototype to measure ease of use, reliability, usefulness, adaptability, and overall acceptability.

Data Analysis

The data analysis was established using descriptive statistics (mean and standard deviation) to assess the ability of the home safety system to function, respond, notify, and detect hazards such as fire, gas leak, smoke and vibrations. The confidence level of this study will be achieved through 30 trials of each hazard to establish normal distribution of the data according to the Central Limit Theorem, which was also used to assess the usability/consistency of the sensors. An additional trial to evaluate the response time of the Blynk (mobile) application, under a consistent network condition, was also performed using the same method outlined previously. Survey data were analyzed using a weighted mean from the 5-point Likert scale to provide an overall user perception.

Ethical Consideration

Ethical guidelines were observed throughout the research project. Before the research was conducted, written approval was received and confirmed from the principal of Notre Dame of Marbel University- IBED. This research was conducted in accordance with the data privacy law of 2012 (RA 10173), therefore maintaining the confidentiality of the collected data and ensure it was only used for academic purposes. A qualified mentor oversaw the activities and ensured that ethical protocols were adhered to during the research. The researchers contacted the Bureau of Fire Protection (BFP) and the National Disaster Risk Reduction and Management Council (NDRRMC) to obtain clarification with respect to appropriate safety standards related to fire safety, disaster preparedness and responsible use of technology. In order to ensure academic integrity, all sources were appropriately cited, there was no plagiarism, and AI tools were not utilized in the study in order to support the authenticity and credibility of the study.

RESULTS AND DISCUSSION

The prototype is a smart home safety system that monitors fire, gas, vibration, temperature, and humidity hazards. It uses sensors that continuously collect data and send it to the ESP32 microcontroller, which processes the readings in real time. When a hazard exceeds the set threshold, the system automatically activates alarms, triggers the water pump and sprinkler for fire suppression, cuts off

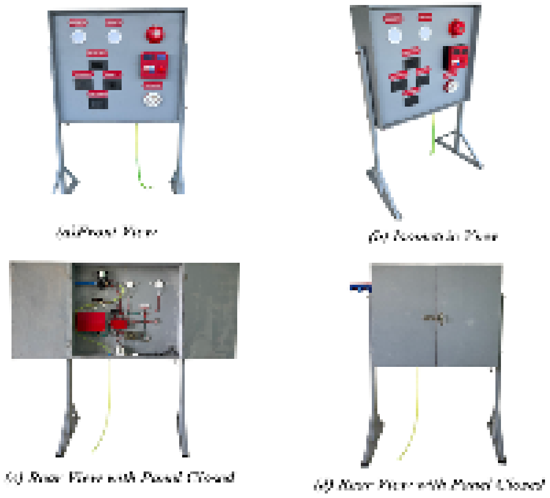

Figure 6: Prototype Design

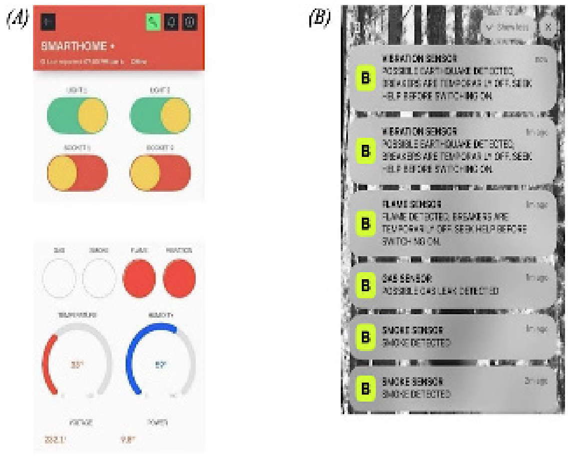

Figure 7: Smart Home Device (a) Control Interface and Real-time Sensor and Safety Status Display, and (b) Real-time Hazard Notifications

electrical power during strong vibrations, and sends instant notifications to the user through the mobile application. The system operates automatically to ensure quick response user safety while allowing manual control when needed.

Smart Home System Dashboard

The Figure 7 (a) shows the smart home dashboard, which serves as the primary control interface of the smart home safety system. The dashboard contains control buttons for turning on/off the alarm, water pump, sprinkler system, and power shutdown relay. These buttons enable the user to manually turn on/off safety responses. Upon clicking the button or detecting a hazard, the signal is processed by the ESP32 microcontroller and immediately implemented in real time, with notifications sent to the user simultaneously via the mobile app. While the lower part shows the monitoring capabilities of the system. Figure 7 (b) presents the real-time hazard notifications that are sent through the application right after the hazard is detected, alerting the user to the type of hazard and thus able to take prompt action. Once earthquake and flame is detected, a notification informs the user and automatically shuts off the breaker. For gas and smoke detection, the system sends a notification indicating the presence of the detected hazard.

Table 1: Performance Data of the Smart Home Safety System's Response Time and Notification Speed

No	Components	Functional	Not Functional
1	ESP32 Microcontroller	/	
2	KY-026 Flame Sensor	/	
3	MQ-4 Gas Sensor	/	
4	MQ-2 Smoke Sensor	/	
5	SW-420 Vibration Sensor	/	
6	Temperature Sensor	/	
7	Humidity Sensor	/	
8	PZEM-004T Energy Monitoring Module	/	
9	Relay Module	/	
10	Water Pump	/	
11	Water Sprinkler	/	
12	Alarm	/	
13	Liquid Crystal Display (LCD)	/	
14	Sockets	/	
15	AC & DC Breaker	/	

Prototype Functionality Test

Table 1 summarizes the performance of the SMART Home Safety System in response time and notification speed tests. Response time was fast across all sensors, although there was some variation depending on the operational conditions, as expected by EN 54-7 standards and recommended gas detection thresholds. The system also had fast notification speed, with consistent and reliable hazard identification and notification even under increasing operational load, as reported in IoT-based safety systems. Overall, these findings confirm that the prototype provides dependable detection, timely response, and notification arrival performance adequate for practical home safety applications. The same results for response time and notification speed were made possible by the stable and high-speed internet connection used during testing. However, it is important to note that a slower internet connection may cause a slight delay between hazard detection and the arrival of the notification (European Committee for Standardization, 2018).

Table 2: Performance Data of the Smart Home Safety System's Response Time and Notification Speed

Hazard	Mean (s) ± SD	
	Response Time	Notification Speed
Fire	2.72 ± 0.75	2.72 ± 0.75
Vibration	2.87 ± 1.34	2.87 ± 1.34
Gas	4.3 ± 0.79	4.3 ± 0.79
Smoke	2.36 ± 0.64	2.36 ± 0.64

The Table 2 gives a summary of the SMART Home Safety System's performance in the response time and notification speed tests. The response time was fast in all sensors, although there was some variation based on operational conditions, as expected in EN 54-7 standards and gas detection thresholds. The system, therefore, also had fast and comparable results in notification speed, with reliable hazard detection and notification even as the operational load increased, complementing trends in IoT-based safety systems (International Organization for Standardization, 2018). Overall, the above findings and results, validate that the prototype provides reliable detection, fast response, and notification arrival performance for practical home safety applications.

Table 3: Evaluation Result for Acceptability

No	Indicators	Evaluation (Mean ± SD)	Interpretation
1	Understanding the functionality of the prototype was easy.	5 ± 0	Very High Level
2	I am satisfied with the performance of the prototype.	5 ± 0	Very High Level
3	I am likely to recommend this prototype to others.	4.75 ± 0.5	Very High Level
4	The prototype was intuitive and easy to use.	5 ± 0	Very High Level
5	The prototype design/layout is intricate and well-thought out.	5 ± 0	Very High Level
6	The wire management of the prototype is satisfactory.	4.75 ± 0.5	Very High Level
7	The features of the prototype are	5 ± 0	Very High Level
8	The different parts of the prototype are easy to navigate.	5 ± 0	Very High Level
9	Overall, I am satisfied with the prototype.	5 ± 0	Very High Level
	Overall Weighted Mean	4.94	Very High Level

Evaluation for Acceptability and Adaptability

Table 3 presents the evaluation of the app's indicator, navigation and links, user interface design, performance and effectiveness based on pre-implementation and post-implementation user ratings on clarity, accessibility, and language quality. The findings in Table 3 indicate that the prototype achieved a very high level of user acceptability, reflecting positive perceptions of usability, clarity, and overall system reliability. The overall positive ratings on all the indicators show that the users had minimal difficulty in comprehending and using the system, a critical factor in safety-related systems. This also shows that the design of the prototype is very much in line with the expectations of the users, which further strengthens the confidence and trust in the system. Researchers have also pointed out that systems that are considered intuitive and trustworthy are more likely to be accepted and used correctly, especially in practical home safety scenarios where rapid understanding and reliability are of utmost importance. The overall acceptability also shows that the prototype is very much suitable for use in a residential setting, where user satisfaction is a key factor in determining continued use and effective response to hazards. However, indicators 3 (recommendation likelihood) and 6 (wire management satisfaction) variation in the ratings is due to the presence of unorganized wiring inside the prototype, which shows that even though the system is highly functional, it can further improve its professional appeal and recommendation levels by improving its aesthetic wire management (Patel & Dalal, 2013 & Zhang & Adipat, 2005).

Table 4: Evaluation Result for Adaptability

No	Indicators	Evaluation (Mean ± SD)	Interpretation
1	The prototype can easily be adjusted to fit different user needs	4.75 ± 0.5	Very High Level
2	It is easy to add new features or functions to the prototype.	4.75 ± 0.5	Very High Level
3	Users can change settings or how the prototype works without trouble	4.5 ± 0.58	Very High Level
4	The prototype can keep up with new trends or technology changes.	4.75 ± 0.5	Very High Level
5	Users can make the prototype fit different places or conditions	4.75 ± 0.5	Very High Level
6	Putting together or taking apart the prototype is simple and doesn't need special tools.	4.75 ± 0.5	Very High Level
7	The prototype's materials are strong and can handle different kinds of weather.	4.75 ± 0.5	Very High Level
8	Storing, moving, and using the prototype in different places is easy.	4.75 ± 0.5	Very High Level
	Overall Weighted Mean	4.94	Very High Level

Table 4 also demonstrates the adaptability of the prototype, as perceived by end-users, and illustrates that the users believe the system is capable of scaling and being flexible. Overall, the data trend suggests that the system is not configured in a fixed manner and can continue to adapt to future expansion based on design intent. This capability is of particular importance to a smart home security system, where ongoing advances in technology and changes in the environment can occur. This flexibility is particularly important for a smart home security system, which need to remain functional and effective ongoing technological advancements and environmental changes. The previous studies have shown that adaptable systems enhance the usability and sustainability of a system in the long term by reducing the need for complete redesign (Sekhon *et al.*, 2017). A high score of adaptability indicates that the system may be long-term used, economical, and compatible in different residential settings. The score of 4.5 in terms of system modification is due to the rigid program logic aimed at ensuring safety and stability.

CONCLUSION

The researchers have successfully designed, developed, tested, and evaluated the BahAI: Smart Home Safety System for Hazard Detection and Notification using an ESP32 microcontroller integrated with fire, gas, and vibration sensors, supported by a programmed system logic and real-time mobile notifications. The prototype is fully functional with all its features, showing excellent consistency and reliability performance to detect home hazards as well as launch the correct corresponding automated safety action responses such as alarms, power shut down of equipment, and fire suppression operation. The system is able to accurately detect hazards and provide timely response with no reported delays of alerts activation and dissemination over operational scenarios. Furthermore, the automated responses and remote execution features of the system operated dependently, which exemplifies that the programmed logic carries out prompt emergency measures. Findings from the evaluation also show high acceptability by the evaluators signifying that the prototype is highly functional, intuitive and residential friendly. Similarly, the adaptability results rated at a very high level, indicating the flexibility, scalability and capability of the system to adapt into future changes in residential environments and technological advances. The synthesized results of the findings, therefore, establish that the smart home safety system is an effective and viable IoT-based solution for improving residential safety and emergency preparedness, especially in residential areas prone to hazards.

Recommendations

The results of this study demonstrate positive outcomes for the Smart Home Safety System which researchers recommend should undergo design work and further testing to develop the system for future studies and further development. Since the system achieves its full operational capacity because the program logic operates without errors and drives its entire system performance, future research and related innovations should adopt and enhance this logic as a foundation for development which should include customizable alert thresholds and response options that protect safety requirements. In relation to system functionality and performance, the system needs additional tests to confirm its operational stability through various internet connection states and power supply variations and different environmental test conditions. Considering the high levels of acceptability and adaptability, the system receive recommendation to be implemented in communities because it proves to be a user-friendly home security solution which works effectively in different home environments. Furthermore, future improvements to physical enclosure design and wire management because these changes will boost durability while enhancing aesthetic appeal, wherein the system will develop secure mechanisms in its future versions which will enable technicians to manually control individual sensors for maintenance and testing purposes which current system limitations prevent because sensors automatically activate at hazard thresholds according to safety-based programming. Lastly, long-term field deployment in actual households is recommended to evaluate durability, maintenance requirements, and sustained performance over extended periods of use.

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