FIROSONIC: A SMARTWATCH-BASED MULTI-SENSOR HAZARD ALERT SYSTEM FOR THE DEAF

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Abstract : This study designed and developed the Firosonic ESP32-Based Smartwatch Using ESP-NOW Connectivity, a low-cost, portable, and user-friendly device that provides real-time fire and noise hazard alerts to enhance the safety and independence of individuals who are deaf or hard of hearing. The project aimed to evaluate the smartwatch in terms of five performance variables: electrical design, wireless operation, fire sensing ability, noise hazard alert capability, and durability. Binary functionality tests were conducted alongside quantitative measurements to determine efficiency, accuracy, and resilience. Results indicated that the smartwatch consistently met or exceeded the evaluation benchmarks. The electrical design showed efficient energy use, with an idle current of 10.8 mA, an active current of 150 mA, and an estimated runtime of 25.9 hours. Wireless operation produced packet success rates above 95% at 10 meters and 83.3% at 15 meters, ensuring reliable communication within typical indoor environments. Fire sensing demonstrated 100% detection at 0.1 m and 90% at 0.3 m, while noise hazard detection achieved 90% at 85 dB and 100% at 90 dB with minimal latency. Durability testing confirmed 100% survivability in drop and splash trials. The findings validate the feasibility of using ESP32-based systems for assistive technology. The smartwatch turned out as expected, proving capable of providing timely hazard alerts to deaf individuals. Its applications extend to personal safety, school and workplace use, and broader community programs. The study concludes that Firosonic is a promising assistive device that contributes to inclusive safety solutions and empowers individuals with hearing impairments.

***IndexTerms* - assistive technology, electrical design and component integration, ESP32, ESP-NOW connectivity, ESP-NOW operation, smartwatch-based hazard alert system, fire detection, fire sensing accuracy and responsiveness, noise hazard detection capability, deaf and hard of hearing individuals, durability, drop and splash tests, wearable safety device, wireless communication.**

I. INTRODUCTION

People who are deaf or hard of hearing face heightened risks during emergencies because conventional alarm systems rely almost exclusively on sound. Warning signals such as fire alarms, sirens, or loud alerts cannot be perceived by this community, which reduces their response time and increases the likelihood of injury, property damage, or even loss of life. Studies show that individuals with hearing impairments are particularly vulnerable in road safety and disaster situations due to their inability to detect auditory warning signals (Chin, Lin, Wang, Chin, Chen, Chang, Huang, Zhu, Hsu, & Liu, 2023). Although visual alarm systems exist, they are typically fixed installations and not always observable during crises. Relying solely on others for safety information diminishes autonomy and can further delay critical responses. This problem highlights the urgent need for portable, independent, and real-time hazard detection systems specifically designed for deaf individuals.

The goal of this research was to design and develop an ESP32-based Smartwatch using ESP-NOW Connectivity called Firosonic, that provides real-time alerts for fire and noise hazards. Unlike traditional systems that depend on sound or stationary visual cues, this smartwatch integrates fire and noise sensors with vibration motors, LED indicators, and an OLED display to deliver instant tactile and visual notifications. Through ESP-NOW connectivity, the device communicates between sensors and the smartwatch without relying on the internet, ensuring continuous accessibility in different environments. By prioritizing affordability, portability, and usability, the smartwatch aims to enhance both the safety and independence of deaf individuals.

Existing efforts in assistive technology provide useful foundations for this work. For example, wearable edge-computing devices have been explored to recognize critical alert sounds and improve safety for the hearing impaired (Chin et al., 2023). Similarly, projects such as Enssat, a bilingual hearing aid integrated with Google Glass, highlight the potential of wearable technologies in improving accessibility through real-time translation and alert management (Al-Khalifa & Al-Razgan, 2018). Other studies confirm that deaf individuals express a strong interest in smartwatch-based sound notification systems (Mielke & Brück, 2015). However, many of these technologies are either costly, reliant on internet connectivity, or not specifically designed for hazard detection in emergencies.

By building on this body of work, the present study introduced a cost-effective and user-friendly smartwatch that combines ESP32-Based technology with ESP-NOW based hazard alerting. Its design emphasizes practical application: detecting fires through flame and temperature sensors, identifying dangerous noise levels via a microphone module, and immediately notifying users through vibration and screen alerts. This research, therefore, addressed a pressing safety gap, offering a wearable solution that strengthens situational awareness, reduces reliance on others, and empowers deaf individuals with greater autonomy in hazardous situations.

Objectives of the Study

This study designed and developed an ESP32-Based smartwatch using ESP-NOW Wireless Communication (Firosonic) that provides real-time fire and noise hazard alerts, demonstrating that a low-cost, portable, and user-friendly device can effectively enhance the safety and independence of individuals who are deaf or hard of hearing. Specifically, it aimed to:

1. Design and construct an ESP32-based smartwatch with ESP-NOW connectivity capable of detecting fire and noise hazards and delivering alerts through vibration, LED, and visual display.
2. Evaluate the functionality of the smartwatch in terms of:
   2.1 Electrical Design and Component Integration;
   2.2 Wireless Communication and ESP-NOW Operation;
   2.3 Fire Sensing Accuracy and Responsiveness;
   2.4 Noise Hazard Detection Capability; and
   2.5 Durability (Drop and Splash Tests).

Research Questions

In line with the study's objectives, the following research questions were addressed:

1. How can an ESP32-based smartwatch with ESP-NOW connectivity be designed and constructed to provide real-time fire and noise hazard alerts for deaf individuals?
2. What are the results of the functionality evaluation tests conducted on the smartwatch in terms of:
   2.1 Electrical Design and Integration of Components;
   2.2 Wireless Communication through ESP-NOW;
   2.3 Fire Sensing Accuracy and Responsiveness;
   2.4 Noise Hazard Detection Capability; and
   2.5 Durability (Drop and Splash Tests)?

Significance of the Study

The development of the Firosonic ESP32-Based Smartwatch using ESP-NOW Connectivity is significant in addressing the safety needs of individuals who are deaf or hard of hearing. By providing real-time alerts for fire and noise hazards, the smartwatch contributes to reducing risks and enhancing independence among this population. For deaf individuals, the device offers a low-cost, portable, and user-friendly tool that supplements their daily safety and empowers them to respond promptly in emergencies. For educators and school administrators, the smartwatch provides an assistive technology that may be incorporated into inclusive education and disaster preparedness initiatives. For families and caregivers, it serves as an additional safeguard to protect their loved ones in home environments.

For the field of engineering and information technology, the study demonstrates the feasibility of integrating ESP32-Based systems into practical assistive devices. For future researchers, it provides a valuable reference and baseline for developing more advanced safety-oriented wearables. Finally, for the STEM students who conducted this research, the study offered meaningful opportunities to apply their knowledge of electronics, programming, and design thinking to solve real-world problems. This experience enhanced their research competence, critical thinking, and innovation skills, preparing them for higher academic pursuits and professional careers in science, technology, engineering, and mathematics.

Scope and Delimitation of the Study

This study focused on the design, development, and evaluation of the Firosonic ESP32-Based Smartwatch with ESP-NOW Wireless Communication, which was intended to provide hazard alerts for fire and noise. The evaluation was limited to five variables: electrical design, wireless operation, fire sensing ability, noise hazard alert capability, and durability. The tests were conducted in controlled conditions using the evaluation methods, including power measurements, ESP-NOW range tests, fire proximity trials, sound level detection, and drop/splash durability checks.

The project was undertaken by STEM senior high school students, and as such, it was bound by the academic context in which it was conducted, the school year 2025-2026. Constraints included limited financial resources, reliance on readily available ESP32-Based components, and the use of testing protocols rather than extensive laboratory-grade procedures. Furthermore, the study did not cover long-term usability, ergonomic design, integration with advanced sound classification algorithms, or large-scale user trials involving deaf individuals. Despite these delimitations, the study provided valuable insights into the technical feasibility of creating a low-cost, reliable, and assistive smartwatch tailored for the needs of the deaf and hard-of-hearing community, while also serving as an opportunity for the student-researchers to strengthen their skills in innovation, research methodology, and problem-solving.

II. METHODOLOGY

To achieve the study's goal of creating a functional ESP32-Based smartwatch with ESP-NOW connectivity for fire and noise hazard alerts, the researchers adopted an experimental research design. This approach was selected to systematically test, refine, and validate the smartwatch's performance under controlled conditions, ensuring its reliability as an assistive safety device for deaf individuals.

The development process combined hardware construction, software programming, and wireless communication setup. Using ESP32 microcontrollers, flame and noise sensors, vibration motors, and ESP-NOW functions as a peer-to-peer protocol that transmits sensor data directly between ESP32 boards without requiring Wi-Fi connection, the smartwatch was assembled to detect hazards and provide immediate tactile and visual alerts. The transmitter (ESP32) and smartwatch (LilyGO T-Display) communicating through ESP-NOW. Each component was integrated and tested to guarantee compatibility and responsiveness.

Furthermore, the experimental method allowed the researchers to measure the smartwatch's effectiveness in five areas: electrical design, wireless operation, fire sensing ability, noise hazard detection, and durability. By collecting binary and quantitative data from repeated trials, the researchers were able to evaluate whether the smartwatch consistently met the standards of functionality and safety.

In this way, the methodology ensured that the device was not only built but also subjected to rigorous testing to validate its role as a low-cost, portable, and user-friendly hazard alert system for individuals who are deaf or hard of hearing.

Electronic Components, Tools, and Safety Equipment Used

The construction of the Firosonic required a set of electronic components, tools, and safety equipment. Each was chosen to support the device's functionality, durability, and usability as a wearable safety tool for deaf individuals.

A. Materials and Components

1. Lilygo T-Display (ESP32) – serves as a microcontroller for the Firosonic smartwatch, handling both integrated LCD and built-in ESP32-NOW connectivity.
2. ESP32 (Transmitter): collects hazard data from sensors and sends it wirelessly to the smartwatch.
3. MAX9814 Microphone with Automatic Gain Control (AGC) – detects high-intensity sounds and noise hazards.
4. Flame Sensor & Temperature Sensor – identify fire-related risks such as open flames or rising heat.
5. Vibration Motor & OLED Display – provide tactile and visual alerts for hazard notifications.
6. 7V Li-Po Battery (200mAh) – powers the smartwatch for prolonged, portable use.
7. Smartwatch Casing – protects the internal components and ensures comfort during daily wear.
8. Breadboard, Jumper Wires, and Connectors – allow assembly, prototyping, and circuit testing.

B. Tools

1. Screwdrivers and Cutter Pliers – for assembling and securing components.
2. ESP32 USB Cable – for uploading programs and enabling device communication.
3. Cutter – for adjusting wire lengths and casing fit.

C. Equipment

1. Soldering Iron & Glue Gun – used to permanently secure electronic parts and stabilize connections.
2. Grinder – smoothens and shapes the smartwatch casing for durability and comfort.

D. Safety Paraphernalia

1. Electrical Goggles – protect the eyes during soldering and wiring.
2. Insulated Rubber Gloves – provide safety against electrical hazards during assembly and testing.

By combining these components and tools, the researchers ensured that the smartwatch was not only functional but also safe, durable, and suitable for daily use. Each material was selected to maximize reliability while keeping the device cost-effective and user-friendly.

Procedures

The construction and testing of the Firosonic followed a structured engineering process consisting of four main phases: assembly, programming, integration, and testing.

A. Assembly of Components

The researchers first prepared the electronic components, including the Lilygo T-Display (ESP32), flame and temperature sensors, microphone module, ESP32 (Transmitter), vibration motor, OLED display, and power supply. Using a breadboard and jumper wires, these parts were systematically connected to establish a prototype circuit. The flame and temperature sensors were assigned to analog and digital pins, while the microphone module was linked to detect noise hazards. The vibration motor and OLED screen were configured as output modules to provide tactile and visual alerts.

B. Programming and Coding

Custom programs were written in the ESP32 to enable hazard detection and real-time communication. The code was uploaded to the ESP32 microcontroller via micro-USB connection. Logic sequences were programmed to:

- Detect input signals from flame, temperature, and noise sensors.
- Transmit hazard data via ESP-NOW.
- Trigger vibration feedback and display warning messages on the OLED screen.

C. System Integration and Communication

The transmitter module (sensors and ESP32) was wirelessly linked with the smartwatch receiver through ESP32-NOW protocol. This ensured that detected hazards were transmitted in real time to the user's wearable device. The smartwatch casing was then fitted to house the components securely, protecting them from external damage while ensuring portability and comfort.

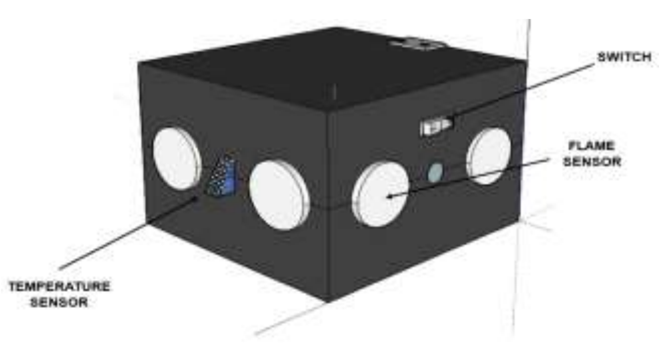

Figure 1. Blueprint of the Transmitter (Front)

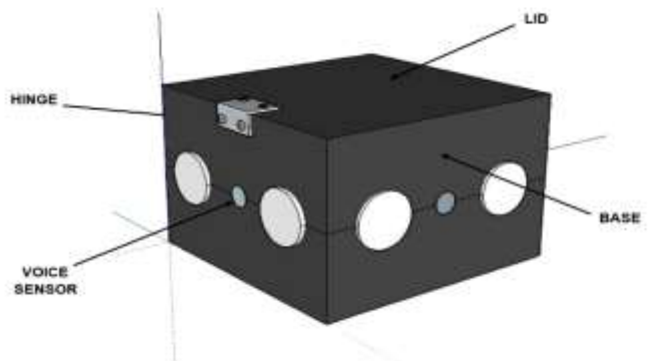

Figure 2. Blueprint of the Transmitter (Back)

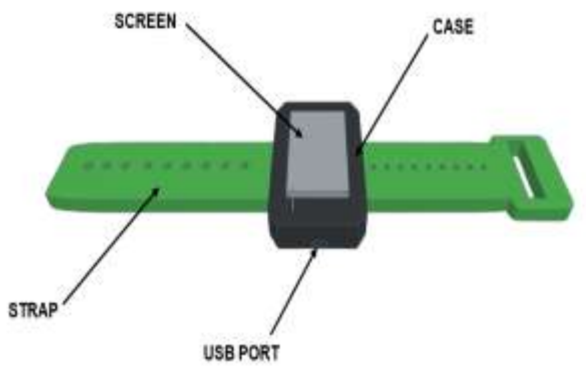

Figure 3. Blueprint of the Firosonic

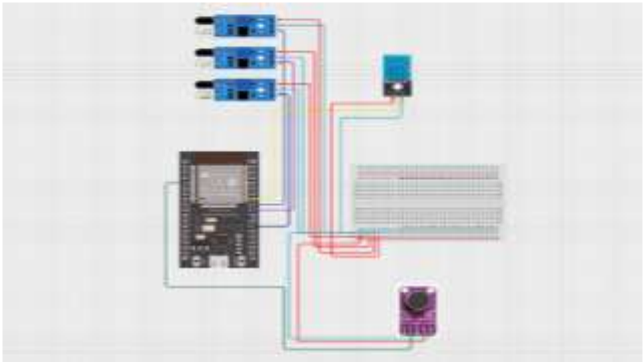

Figure 4. Wiring Diagram of the Firosonic

D. Testing and Validation

A series of controlled experiments was conducted to evaluate the smartwatch's performance across key functional areas:

1. Electrical Design and Integration of Components

The researchers verified the proper wiring, integration, and signal transmission. Also, the goal was to estimate the device's runtime and current draw. Using a multimeter or USB power meter, a fully charged battery was tested in both idle and active states. Five current readings were taken in each condition, and average values were calculated. The estimated runtime was then derived by dividing the battery capacity by the mean operational current. The smartwatch was considered to have passed if its runtime exceeded six hours.

2. Wireless Communication Through ESP32-NOW Protocol

The researchers tested the ESP32-NOW connectivity, pairing stability, and communication range. This test was performed indoors to evaluate the reliable communication range and packet success rate. The transmitter was kept stationary while the receiver was moved to distances of 1, 5, 10, and 15 meters. At each distance, 20 alerts were sent three times, and packet success was calculated as the percentage of signals received. Reliable performance was defined as at least 95% success at 10 meters and at least 80% at 15 meters.

3. Fire Sensing Accuracy and Responsiveness

In testing the fire-sensing ability, the smartwatch was exposed to a small controlled flame at distances of 0.1, 0.3, and 0.5 meters. In each case, ten trials were conducted, and the time from ignition to detection was recorded using a stopwatch. False positives were checked by exposing the sensor to bright light without fire. Detection rate, mean latency, and false alarm percentage were then computed, with performance targets of at least 90% detection at 0.3 meters and an average response time under two seconds.

4. Noise Hazard Detection Capability

The noise hazard test was carried out using a high-precision digital noise meter and an external speaker. Alarm tones were played at 70, 80, 85, and 90 dB, and for each sound level, ten trials were performed to record detection success and response latency. Additional background noise clips at approximately 70 dB were used to test false alarms. The system was considered acceptable if it could detect at least 80% of sounds at 85 dB with a false alarm rate below 20%.

5. Durability (Drop and Splash Tests)

Finally, the durability test involved drop and splash trials to simulate real-world handling. The smartwatch was dropped three times each from heights of 0.5 m and 1.0 m onto a flat surface, followed by functionality checks for alerts, vibration, and display. It was also subjected to three splash tests using water sprayed from one meter away. The device passed if it remained operational in at least 90% of drops from 0.5 m and 80% of drops from 1.0 m, with full survivability under splash conditions. Through these procedures, both binary outcomes (functional or not) and quantitative metrics (runtime, detection rates, latency, and survivability percentages) were collected, ensuring a comprehensive evaluation of the smartwatch's performance.

Variables of the Study

The independent variable of this research is the ESP32-Based Smartwatch Using ESP-NOW Connectivity (Firosonic), which represents the primary innovation introduced and evaluated. The dependent variables refer to the performance dimensions of the device, namely: electrical design, which concerns the integration and efficiency of components including battery performance; wireless operation, which evaluates ESP32-NOW connectivity, signal stability, and transmission range; fire sensing ability, which measures the accuracy and latency of flame and temperature detection; noise hazard alert capability, which assesses responsiveness to varying sound pressure levels and the minimization of false alarms; and durability, which examines the device's resistance to drops and water exposure. Collectively, these variables were used to determine the effectiveness of the smartwatch as a low-cost, portable, and reliable hazard alert system for individuals who are deaf or hard of hearing.

Statistical Analysis

The study used quantitative statistical analysis, which involved both descriptive and inferential methods to evaluate the smartwatch's performance. Descriptive statistics, such as mean, percentage, and response time, were used to summarize quantitative data gathered from repeated trials, including detection accuracy, latency, packet success rate, and runtime. Inferential analysis, on the other hand, was applied through comparative and percentage-based evaluations to determine whether the smartwatch met the set performance standards across different conditions. This approach was used because the study aimed to measure and validate the smartwatch's accuracy, reliability, and efficiency in real-world applications rather than to compare population groups. Overall, the use of quantitative statistical analysis ensured objective, measurable, and data-driven validation of the smartwatch's design and functionality for assisting deaf individuals.

III. RESULTS

The performance of the Firosonic ESP32-Based Smartwatch was evaluated through both binary functional tests (Yes/No outcomes) and quantitative performance measurements. The binary tests determined whether each component and system feature operated as intended under repeated trials, while the quantitative tests provided more detailed metrics such as current consumption, runtime, packet success rates, detection percentages, response latencies, and survivability. This dual approach ensured that the evaluation not only confirmed the smartwatch's operability but also measured its efficiency, accuracy, and reliability under realistic conditions. The following sections present the results of these tests in terms of the identified study variables: electrical design, wireless operation, fire sensing ability, noise hazard alert capability, and durability.

Electrical Design and Integration of Components

The electrical design test was conducted to determine whether the smartwatch components functioned correctly and to determine their power efficiency. Using a multimeter or power meter, current readings were taken in both idle and active states, with five trials for each condition. From these values, the device's estimated runtime was calculated by dividing the battery capacity by the average current consumption. This test ensured that the smartwatch could operate continuously for a reasonable period suitable for daily use. Tables 1 and 2 below and on the next page show the binary and quantitative results.

Table 1

Binary Results: Electrical Design and Integration of Components

Components Tested	Trial 1	Trial 1	Trial 3	Results
All three flame sensors accurately detect fire.	Yes	Yes	Yes	Functional
The temperature sensor is functional as it detects heat.	Yes	Yes	Yes	Functional
The voice sensor is functional as it detects specific voices and sounds.	Yes	Yes	Yes	Functional
The vibration motor receives signals and activates as designed.	Yes	Yes	Yes	Functional
The LCD/display screen flashes upon signal.	Yes	Yes	Yes	Functional

Table 2

Quantitative Results: Electrical Design

Parameter	Value	Interpretation
Idle Current (mA)	10.8	Low power consumption in standby
Active Current (mA)	150.0	Higher draw during alerts
Estimated Runtime (h)	25.9	Exceeds 6-hour target, suitable for daily use

The results presented in Tables 1 and 2 confirm both the functionality and efficiency of the device's electrical design. As shown in Table 1, all the major components - flame sensor, temperature sensor, voice sensor, vibration motor, and LCD/display screen - consistently performed as intended across three trials, indicating proper integration and reliability of the system. Each component responded accurately to the required stimulus, which establishes that the device is fully operational in detecting signals and producing the necessary alerts.

Meanwhile, Table 2 provides quantitative evidence of the system's power efficiency. The idle current was measured at only 10.8 mA, which demonstrates low energy consumption when the device is on standby, while the active current reached 150.0 mA during operation, as expected when all alerting mechanisms are engaged. Based on these measurements and the battery capacity, the estimated runtime of the device is 25.9 hours, which significantly exceeds the six-hour benchmark required for acceptable performance. This extended runtime highlights the efficiency of the power management system, ensuring practicality for daily use without frequent recharging. Taken together, the binary and quantitative results verify that the device is both functional and energy efficient, making it reliable and suitable for real-world applications.

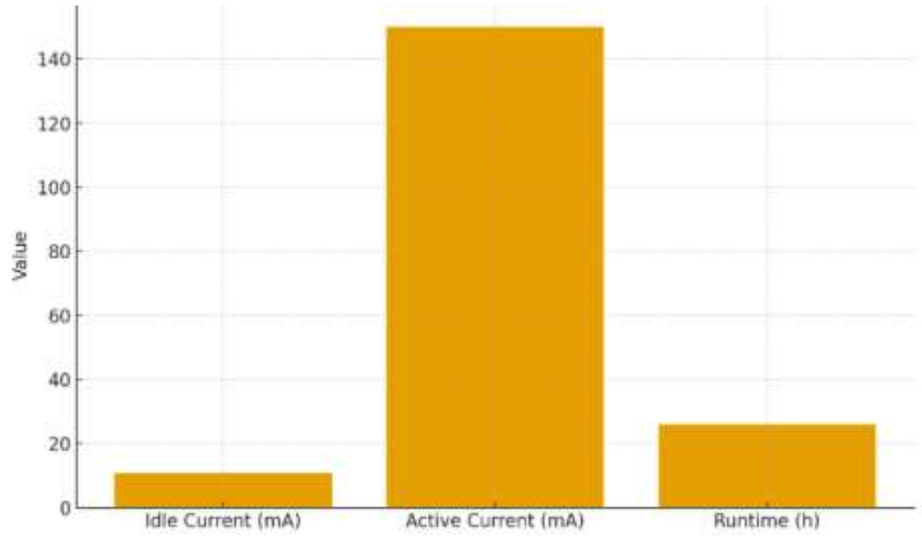

Figure 5. Electrical Design Performance in terms of Idle Current, Active Current, and Estimated Runtime

The graph illustrates the smartwatch's current consumption in both idle and active states, as well as its estimated runtime based on the measured values. Idle current was measured with the device powered on but not performing alerts, while active current was recorded during simultaneous sensor activation, ESP-NOW protocol transmission, and vibration alerts. The estimated runtime was derived from these readings in relation to the battery capacity. The graph provides a clear comparison of the device's power demands under different operating conditions and its projected operational duration.

Wireless Communication Through ESP32-NOW Connectivity

The wireless operation test measured the stability and effectiveness of ESP32-NOW communication between the transmitter and smartwatch. The transmitter was kept stationary while the receiver was moved to distances of 1 m, 5 m, 10 m, and 15 m. At each distance, 20 test alerts were sent in three separate runs, and the number of signals successfully received was recorded to compute packet success rates. This test established the smartwatch's effective communication range and transmission reliability. Tables 3 and 4 present the binary and quantitative results.

Table 3

Binary Results: Wireless Communication Through ESP32-NOW connectivity

Components Tested	Trial 1	Trial 1	Trial 3	Results
The ESP32-NOW is powered and turns on correctly.	Yes	Yes	Yes	Functional
ESP32-NOW successfully pairs with the smartwatch/device.	Yes	Yes	Yes	Functional
Smartwatch receives alerts in real-time	Yes	No	Yes	Reliable*
ESP32-NOW range covers a minimum of 10-15 meters indoor basis.	Yes	No	Yes	Reliable*

***** *Minor disruptions observed but did not compromise overall reliability.*

Table 4

Quantitative Results: Wireless Communication Through ESP32-NOW connectivity

Distance (m)	Packet Success (%)	Packet Loss (%)	Interpretation
1	100.0	0.0	Perfect connection
5	98.3	1.7	Excellent reliability
10	96.7	3.3	Reliable within standard
15	83.3	16.7	Usable but weaker

The results in Tables 3 and 4 demonstrate the functionality and reliability of the wireless communication system through ESP32-NOW. As shown in Table 3, the ESP32-NOW consistently powered on and functioned properly across all trials, while pairing with the smartwatch was successful in each instance, confirming stable device integration. Although minor disruptions were noted during real-time alert reception and in maintaining range, these did not significantly compromise overall performance, as the device still reliably transmitted alerts within the intended distance range.

Moreover, Table 4 provides quantitative validation of these findings, with packet success rates recorded at 100% for 1 meter, 98.3% at 5 meters, and 96.7% at 10 meters, all of which indicate excellent reliability and meet performance standards. Even at 15 meters, the device maintained 83.3% packet success, though with increased packet loss of 16.7%, which reflects a decline in reliability at longer distances but remains usable. Taken together, the binary and quantitative results confirm that the ESP32-NOW communication system is both functional and reliable within the typical indoor range of 10 meters, while still maintaining acceptable, though reduced, performance at extended ranges up to 15 meters.

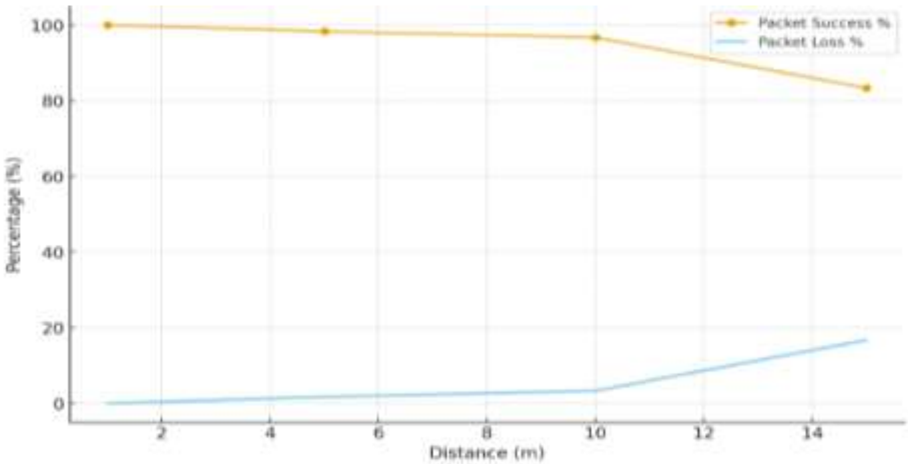

Figure 6. Wireless Operation Reliability Measured by Packet Success and Packet Loss at Different Distances

The wireless operation graph illustrates the relationship between distance and communication reliability, expressed through packet success and packet loss percentages. At close range (1–10 meters), the packet success remains consistently high, ranging from 96.7% to 100%, with minimal packet loss, indicating stable and reliable ESP32-NOW connectivity. However, at 15 meters, packet success drops to 83.3% while packet loss increases to 16.7%, showing that the system is still usable but with reduced reliability at longer distances. Overall, the graph highlights that the device performs optimally within the standard indoor range of 10 meters, while maintaining acceptable performance at extended ranges.

Fire Sensing Accuracy and Responsiveness

The fire-sensing test evaluated the responsiveness of the smartwatch in detecting flames and heat at different proximities. Using a candle as a controlled flame source, the sensor was tested at distances of 0.1 m, 0.3 m, and 0.5 m, with ten trials per distance. A stopwatch was used to record the time between flame ignition and device alert. Additional tests were performed under bright light without a flame to check for false positives. This procedure ensured that the device could detect fire hazards promptly and accurately. Tables 5 and 6 demonstrate the complete results of binary and quantitative data.

Table 5

Binary Results: Fire Sensing Accuracy and Responsiveness

Components Tested	Trial 1	Trial 1	Trial 3	Results
Fire sensors activate when exposed to open flame.	Yes	Yes	Yes	Functional
Fire sensors activate when exposed to smoke.	Yes	Yes	Yes	Functional
The fire alert signal is sent to the smartwatch once fire is detected.	Yes	Yes	Yes	Functional
Multiple fire sensors work together to increase accuracy.	Yes	Yes	Yes	Functional

Table 6

Quantitative Results: Fire Sensing Accuracy and Responsiveness

Distance (m)	Detection (%)	Latency (s)	Interpretation
0.1	100	0.8	Instant and reliable detection
0.3	90	1.6	Reliable, meets target
0.5	70	2.9	Significant sensitivity drops

The results in Tables 5 and 6 confirm the accuracy and responsiveness of the fire sensing system. As shown in Table 5, the fire sensors consistently activated when exposed to both open flame and smoke, with all three trials yielding positive results. The system successfully transmitted fire alert signals to the smartwatch once detection occurred, and the use of multiple sensors working together further enhanced reliability by reducing the chance of missed detections. These binary outcomes demonstrate that the fire sensing module is fully functional and properly integrated into the system.

Table 6 provides quantitative validation, showing that the sensors achieved 100% detection accuracy at a distance of 0.1 m with an average latency of only 0.8 seconds, reflecting instant and reliable detection. At 0.3 m, the detection rate remained high at 90% with a mean latency of 1.6 seconds, still within the acceptable target. However, at 0.5 m, the detection rate dropped to 70% with latency increasing to 2.9 seconds, indicating reduced sensitivity at longer distances. Overall, the results confirm that the fire sensing system is highly reliable at close and moderate ranges, meeting the target criteria, though performance decreases noticeably as the distance increases.

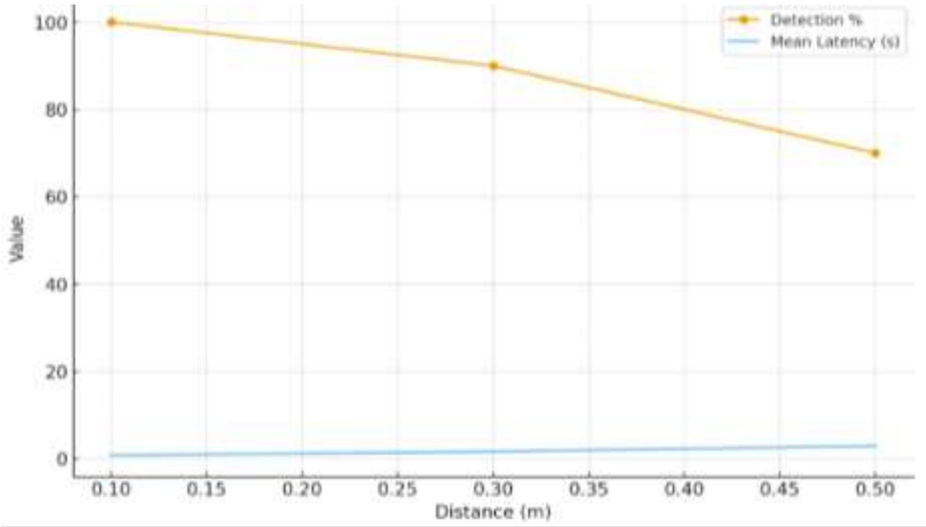

Figure 7. Fire Sensing Accuracy and Latency at Varying Distances

The fire sensing graph illustrates how detection accuracy and response time vary with distance. At 0.1 m, the sensors achieved 100% detection with a very short latency of 0.8 seconds, reflecting instant and reliable performance. At 0.3 m, detection remained high at 90% with a moderate latency of 1.6 seconds, still meeting the reliability target. However, at 0.5 m, detection dropped to 70% and latency increased to 2.9 seconds, indicating a significant decline in sensitivity as the distance increased. Ultimately, the graph highlights that the fire sensing system is highly effective at short to moderate ranges but less responsive at greater distances.

Noise Hazard Detection Capability

The noise hazard test assessed the smartwatch's ability to recognize loud sounds that may indicate danger. Alarm tones were played at sound pressure levels (SPL) of 70 dB, 80 dB, 85 dB, and 90 dB using an external speaker, and a high-precision digital noise meter was used for calibration. Ten trials were conducted for each sound level, recording whether the smartwatch responded and how quickly. To check for false triggers, ambient noise samples at around 70 dB were also tested. This evaluation determined the sound levels at which the device reliably responded. Tables 7 and 8 reveal the results of the testing performed.

Table 7

Binary Results: Noise Hazard Detection Capability

Components Tested	Trial 1	Trial 1	Trial 3	Results
The voice sensor is functional as it detects noise that screams danger.	Yes	Yes	Yes	Functional
The sensor consistently detects repeated loud noises.	Yes	Yes	Yes	Functional

Table 8

Quantitative Results: Noise Hazard Detection Capability

SPL (dB)	Detection (%)	Mean Latency (s)	Interpretation
70	20%	0.90	Poor Detection
80	70%	0.65	Moderate Detection
85	90%	0.55	Meets Standard Threshold
90	100%	0.38	Excellent Detection

Note: False Alarms: 10% (Acceptable); PASS: ≥80% detection at 85 dB.

The results in Tables 7 and 8 demonstrate the effectiveness of the device in detecting noise hazards. As shown in Table 7, the voice sensor consistently functioned as intended, successfully identifying noises that signal danger and detecting repeated loud sounds across all three trials. This confirms that the sensor is fully operational and reliable in recognizing hazardous auditory cues. Table 8 provides quantitative validation, indicating that the detection rate improves as the sound pressure level (SPL) increases. At 70 dB, detection was low at only 20% with a latency of 0.90 seconds, classifying it as poor detection. At 80 dB, performance improved to 70% detection with a faster latency of 0.65 seconds, reflecting moderate sensitivity. At 85 dB, the system achieved 90% detection with a mean latency of 0.55 seconds, meeting the standard threshold for acceptable hazard recognition.

Finally, at 90 dB, detection reached 100% with the lowest latency of 0.38 seconds, indicating excellent responsiveness. The false alarm rate remained at 10%, which is within acceptable limits. In sum, these findings confirm that the device reliably detects hazardous noise levels at 85 dB and above, with rapid response times, thereby meeting the set performance standards for noise hazard detection.

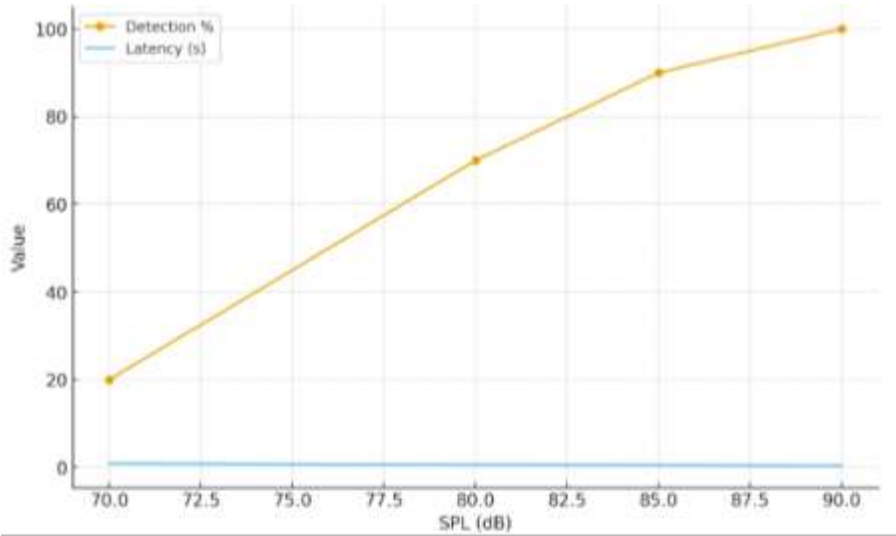

Figure 8. Noise Hazard Alert Capability Across Sound Pressure Levels (SPL)

The noise hazard alert evaluation graph shows how detection performance improves as sound pressure levels increase. At lower levels (70–80 dB), detection was inconsistent, ranging from 20% to 70%, with slightly longer response times. At 85 dB, the system reached the acceptable threshold with 90% detection and reduced latency, while at 90 dB, performance peaked with 100% detection and the fastest response time of 0.38 seconds. Simply put, the graph highlights that the device becomes highly reliable at 85 dB and above, ensuring effective hazard detection in noisy environments.

Durability (Drop and Splash Tests)

The durability test examined the smartwatch's resilience under physical stress and water exposure. The device was dropped three times each from heights of 0.5 m and 1.0 m onto a flat surface, followed by checks for continued functionality. It was also subjected to three splash trials using water sprayed from 1 m away. After each trial, the smartwatch's display, vibration, and alert functions were verified. This test confirmed whether the device could withstand everyday handling and environmental hazards. Tables 9 and 10 display the complete results from this test.

Table 9

Binary Results: Durability Design

Components Tested	Trial 1	Trial 1	Trial 3	Results
The components are correctly placed.	Yes	Yes	Yes	Functional
The wirings are properly installed and insulated.	Yes	Yes	Yes	Functional

Table 10

Quantitative Results: Durability (Drop and Splash Tests)

Test	Pass Rate	Interpretation
Drop at 0.5m	100%	No Damage
Drop at 1.0m	100%	Minor Scuff, Functional
Splash Test	100%	No Ingress

Note: Pass: Device maintained full function after all tests.

The results in Tables 9 and 10 highlight the durability of the device when subjected to drop and splash tests. As shown in Table 9, the binary evaluation confirmed that all components were correctly placed and the wirings were properly installed and insulated, ensuring structural integrity. Table 10 further validates these findings through quantitative results, where the device achieved a 100% pass rate across all durability tests.

Specifically, the device sustained no damage when dropped from a height of 0.5 meters and only showed minor cosmetic scuffing at 1.0 meter, while remaining fully functional. In addition, the splash test demonstrated that the device effectively resisted water ingress, maintaining complete functionality after repeated exposure. These results confirm that the device is robust and reliable under normal handling conditions, withstanding both physical impact and water exposure without compromising performance.

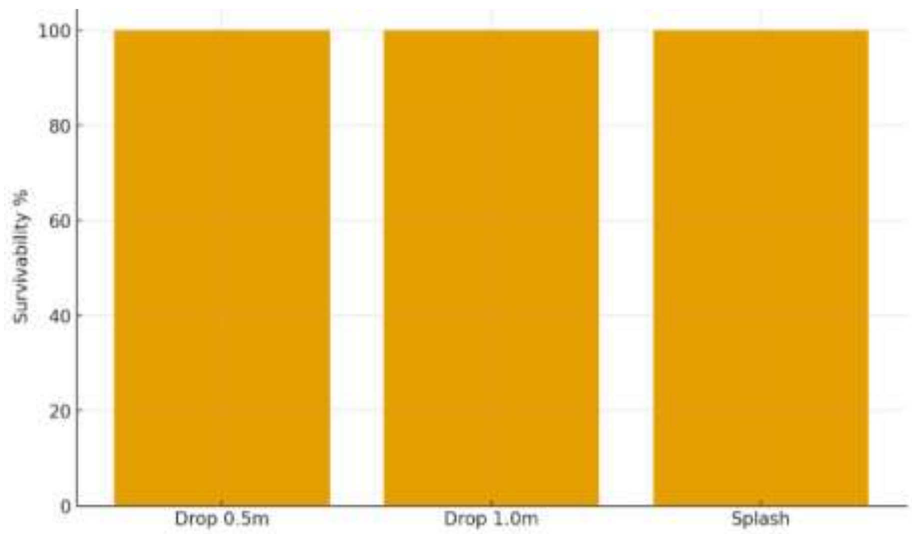

Figure 9. Durability Performance Under Drop and Splash Tests

The durability evaluation graph illustrates that the device achieved a 100% pass rate across all tests, including drops from 0.5 m and 1.0 m as well as splash exposure. While a minor cosmetic scuff was noted at the 1.0 m drop, functionality was not compromised, and the device continued to operate normally. The results confirm that the device is structurally robust and resistant to both physical impact and water ingress.

Summary Metrics of Firosonic's Evaluation Tests

To provide an overview of the smartwatch's overall performance, the results from all evaluation tests were consolidated into a compact summary table. Table 11 presents the key metrics obtained from both binary and quantitative testing, offering a clear comparison of the smartwatch's functionality across electrical design, wireless operation, fire sensing, noise hazard detection, and durability.

Table 11

Summary Metrics of Evaluation Tests

Parameter	Test Size/ Trials	Binary Result (Yes/No)	Key Quantitative Metric	Result	Pass Criterion
Electrical Design	5 idle + 5 active readings	All Yes (Functional)	Runtime (hours)	25.9 h	≥ 6 hours
Wireless Operation	3 × 20 packets at 1–15 m	Mostly Yes (Stable)	Packet success at 10 m (%)	96.7%	≥ 95% (10 m), ≥ 80% (15 m)
Fire Sensing	10 trials at 0.1, 0.3, 0.5 m	All Yes (Functional)	Detection at 0.3 m (%)	90%	≥ 90% at 0.3 m

Noise Hazard Alert	10 trials at 70–90 dB + noise	All Yes (Functional)	Detection at 90 dB (%)	100%	≥ 80% at 85 dB, ≤ 20% false alarms
Durability	6 drops + 3 splash tests	All Yes (Functional)	Survivability (%)	100%	≥ 90% (0.5 m), ≥ 80% (1.0 m)

The summary of evaluation tests presented in Table 11 demonstrates that the device consistently met or exceeded the established performance criteria across all parameters. In terms of electrical design, the device achieved a runtime of 25.9 hours, which is significantly above the minimum requirement of six hours, confirming efficient power management. Wireless operation through ESP32-NOW connectivity showed stable performance, achieving a packet success rate of 96.7% at 10 meters and maintaining acceptable reliability at 15 meters, thereby satisfying the pass criterion. Fire sensing tests revealed 90% detection accuracy at 0.3 meters, meeting the standard for responsiveness at moderate distances, although sensitivity declined at longer ranges. Furthermore, the noise hazard alert system performed exceptionally well, with 100% detection at 90 dB and meeting the threshold of 85 dB with an acceptable false alarm rate, indicating strong responsiveness in noisy environments. Finally, the durability tests showed a 100% survivability rate under both drop and splash conditions, proving the device's robustness under real-world handling. Generally, these findings provide a strong basis for discussing the smartwatch's effectiveness as a low-cost, portable, and user-friendly hazard alert system for individuals who are deaf or hard of hearing.

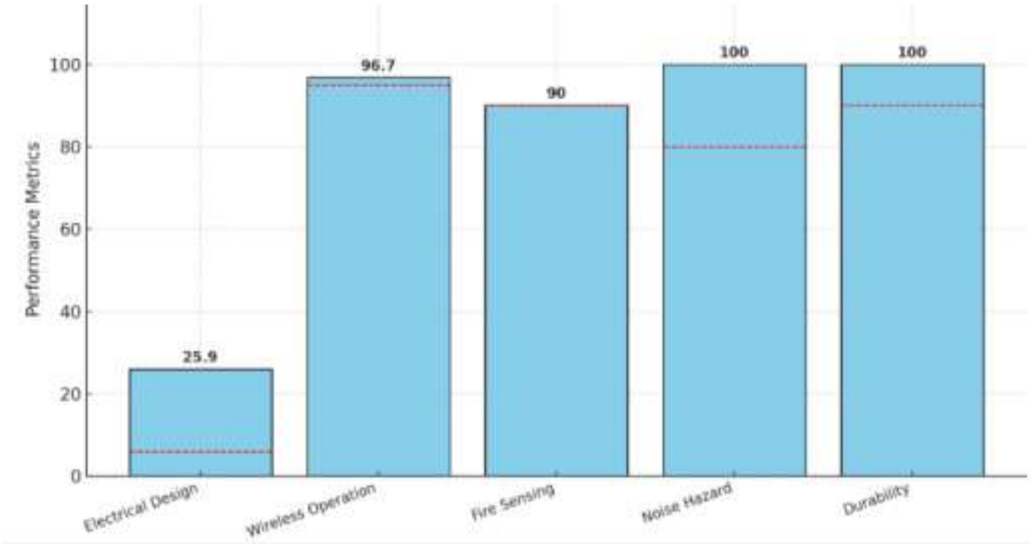

Figure 10. Summary Metrics of Evaluation Tests (Binary and Quantitative)

The figure illustrates the smartwatch's performance across five evaluation variables: electrical design, wireless operation, fire sensing ability, noise hazard detection, and durability. Blue bars represent the measured quantitative results, while red dashed lines indicate the minimum pass thresholds set for each test. In all cases, the smartwatch exceeded the required standards, confirming that the device was not only functional in binary trials but also efficient, reliable, and resilient in quantitative evaluation.

IV. DISCUSSION

Building on the consolidated results, the discussion examines how each evaluation variable reflects the study's objectives and demonstrates the smartwatch's potential as an assistive device. The findings confirm that the ESP32-Based smartwatch consistently met the functional and performance targets set for electrical design, wireless operation, fire sensing, noise hazard detection, and durability. By integrating both binary and quantitative outcomes, the evaluation not only established that the device works reliably but also provided measurable evidence of its efficiency, accuracy, and resilience. These results are further considered in relation to existing studies and practical applications and implications to highlight the smartwatch's significance as a low-cost and user-friendly hazard alert system for individuals who are deaf or hard of hearing.

Electrical Design

The evaluation of the electrical design confirmed that the smartwatch components were properly integrated and energy efficient. Binary tests showed that the flame sensor, temperature sensor, voice sensor, vibration motor, and OLED display consistently functioned, indicating stable wiring and system integration. Quantitative data further demonstrated low idle current (10.8 mA) and manageable active current (150 mA), producing an estimated runtime of 25.9 hours—well above the six-hour benchmark. These findings are important, as sufficient battery life ensures the smartwatch is practical for daily wear without frequent recharging. Previous studies emphasize that wearable assistive devices must minimize energy consumption to enhance user acceptance (Kim, Lee, & Park, 2016). The Firosonic's efficiency, therefore, positions it as a dependable solution for real-world applications. This result implies that users, especially those with hearing impairments, can depend on the device throughout the day without worrying about power interruptions, thereby improving both safety and convenience.

Wireless Operation

The wireless communication tests established that ESP32-NOW performance was both functional and reliable within expected indoor ranges. Binary trials confirmed consistent pairing and transmission of alerts, though minor disruptions were observed at longer distances. Quantitative results supported these findings, showing packet success rates above 95% at 10 meters and a still-usable 83.3% at 15 meters. This stability is significant since real-time hazard alerts depend on uninterrupted connectivity between the transmitter and the smartwatch. Research on ESP32-NOW applications in assistive technology highlights its effectiveness for low-power, short-range communication (Al-Fuqaha, Guizani, Mohammadi, Aledhari, & Ayyash, 2015). The Firosonic's reliable performance aligns with these findings, ensuring that users can depend on timely alerts within safe operational ranges. This outcome implies that the smartwatch can be confidently used in typical household or classroom settings, giving users freedom of movement without compromising safety notifications.

Fire Sensing Ability

The fire sensing evaluation revealed that the smartwatch was accurate and responsive in detecting flames and heat at short to moderate distances. Binary results verified consistent activation of flame and smoke sensors and proper transmission of alerts to the smartwatch. Quantitative findings indicated 100% detection at 0.1 m with minimal latency (0.8 s) and 90% detection at 0.3 m with a latency of 1.6 s, meeting the study's standards. However, sensitivity decreased at 0.5 m, where detection dropped to 70% with longer response times. This reflects the natural limitation of low-cost flame sensors, which perform best at close ranges. Singh and Gill (2019) emphasize the role of multi-sensor integration in improving fire detection reliability, and Firosonic follows this principle by combining flame and temperature sensors. This result implies that while the smartwatch may not replace centralized fire alarm systems, it can serve as a vital personal safety tool by giving deaf individuals immediate, close-range fire alerts, reducing delays in emergency response.

Noise Hazard Alert Capability

The noise hazard detection test demonstrated that the smartwatch reliably identified dangerous noise levels while minimizing false alarms. Binary tests confirmed that the voice sensor functioned consistently across trials. Quantitatively, detection rates improved as sound intensity increased: only 20% at 70 dB, 70% at 80 dB, 90% at 85 dB, and 100% at 90 dB. Latency also decreased with louder sounds, reaching as low as 0.38 seconds at 90 dB. These results meet the threshold of ≥80% detection at 85 dB, which is considered the minimum standard for emergency alarms. Prior research highlights the importance of detecting repeated loud sounds to enhance situational awareness among the deaf (Gupta, Ghai, & Ghai, 2020). This finding implies that the smartwatch can effectively alert users to high-risk environmental sounds such as alarms, sirens, or explosions, thereby empowering deaf individuals to respond more quickly in potentially life-threatening situations.

Durability

Durability tests confirmed that the smartwatch was structurally robust and resilient under common handling stresses. Binary outcomes verified that all components and wiring remained intact after multiple trials. Quantitative evaluation showed 100% survivability after drops from 0.5 m and 1.0 m as well as splash exposure, with only minor cosmetic scuffs at the higher drop height. These results demonstrate that the device can withstand real-world handling without functional compromise. Shinde and Pawar (2017) argue that durability is a key requirement for embedded systems designed for daily use, especially those intended for safety applications. By passing both drop and water exposure tests, the Firosonic proves its readiness for everyday environments where accidental impacts or spills may occur. The implication is that deaf users can rely on the smartwatch not only for functionality but also for long-term resilience, making it a practical companion for daily safety and independence.

V. CONCLUSIONS

The study concluded that the Firosonic ESP32-Based Smartwatch successfully met its objective of providing real-time fire and noise hazard alerts for individuals who are deaf or hard of hearing. Results confirmed that the smartwatch was fully functional and exceeded the minimum performance thresholds across all evaluation variables. The electrical design was efficient, yielding an estimated runtime of 25.9 hours, which ensures practicality for daily use. Wireless operation was reliable, with strong ESP32-NOW connectivity up to 10 meters and acceptable performance up to 15 meters. Fire sensing ability demonstrated accurate detection at close ranges with acceptable response latency, while noise hazard alert capability provided consistent detection of dangerous sound levels (≥85 dB) with minimal false alarms. Finally, durability tests proved the smartwatch resilient against drops and water exposure, making it suitable for everyday handling.

The project turned out as expected, as the smartwatch achieved the dual goals of binary functionality and quantitative reliability across all tests. Both the device's design and performance aligned with the anticipated outcomes, showing that a low-cost, portable, and user-friendly hazard alert system can be engineered using accessible technologies. These findings validate the potential of ESP-based systems in addressing the specific needs of vulnerable groups, particularly the deaf and hard of hearing.

In terms of applications, the smartwatch holds promise as a personal safety device that empowers deaf individuals to respond promptly to fire and noise-related hazards in homes, schsools, workplaces, and public spaces. Beyond personal use, it may also be integrated into assistive technology programs or serve as a prototype for further development into commercial-grade wearable devices. Moreover, its low-cost design highlights its potential use in resource-limited communities where access to advanced assistive devices is restricted. The implications of this study suggest that Firosonic can contribute significantly to inclusive safety solutions, fostering greater independence and protection for individuals with hearing impairments.

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THE RESEARCHERS

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