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A Multi-Modal Personal Safety Solution Using Edge Computing and Sensor Fusion

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ABSTRACT: The increasing demand for effective personal safety solutions has highlighted the limitations of traditional emergency alert methods, particularly for vulnerable individuals and those in high-risk environments. Manual alert systems are often slow, require conscious user action, and lack precise automatic location sharing, making it difficult to ensure a rapid and reliable response. To address these challenges, this paper presents a Safety Watch, an IoT-based emergency alert system that leverages edge computing, multi-modal sensor fusion, and mesh networking.

The proposed system is an integrated hardware-software solution capable of detecting emergencies through three independent mechanisms: shake detection, manual button press, and voice command recognition. It automatically acquires precise GPS coordinates and transmits them as Google Maps links to designated emergency contacts via a local WiFi network. The system incorporates dual mobile applications for bidirectional communication, ensuring a comprehensive emergency coordination framework. In addition to automated alerting, the system incorporates features such as real-time voice recognition using the Vosk offline model, zero-configuration device discovery, and result generation with detailed status monitoring. Performance analysis, including response time, accuracy rates, and power consumption, is generated to validate system efficiency.

I. INTRODUCTION

Personal safety and emergency response are fundamental components of modern society, serving as a critical measure for ensuring individual security and well-being. Among various forms of safety systems, automated and wearable solutions play a crucial role in providing rapid assistance during medical emergencies, falls, and personal assaults. However, traditional methods of triggering emergency alerts present several practical challenges, especially for individuals who may be incapacitated or in isolated environments.

Traditional emergency methods, such as manual phone calls or basic siren alarms, require the user to consciously initiate an alert, which is both time-consuming and sometimes impossible during a medical crisis. As the need for immediate and automated response increases, maintaining speed and reliability in notification becomes difficult. Factors such as dependency on cellular networks, lack of precise location information, and the absence of redundant triggers may lead to critical delays in emergency response. Additionally, the high recurring costs of subscription-based medical alert systems can affect accessibility for a wide range of users. With the advancement of the Internet of Things (IoT) and edge computing, there is a growing interest in automating the emergency detection process to enhance speed and reliability. In this context, the proposed system introduces a Safety Watch that integrates multi-modal trigger mechanisms with automatic GPS location sharing to deliver rapid emergency alerts. The system is designed to process continuous sensor data and voice commands and perform automated alerting without requiring manual user initiation.

The core functionality of the system involves detecting emergencies via shake detection, button press, or voice recognition and automatically transmitting the user's location. Based on the trigger type and system status, the system dispatches alerts, including precise Google Maps links where appropriate. This approach ensures that a user is protected through redundant detection paths while maintaining a consistent and private communication framework.



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II. LITERATURE REVIEW

The automation of emergency alert systems has been an active area of research, particularly with the advancement of IoT, wearable sensors, and edge-based speech recognition. Several approaches have been proposed to improve the accuracy, consistency, and speed of detecting and reporting emergencies.

Early research in automated safety primarily focused on single-sensor and rule-based trigger techniques. Zhang et al. (2021) proposed a wearable fall detection system using machine learning on accelerometer data, which relied on a Support Vector Machine (SVM) classifier trained on simulated falls. While such methods offered improved detection over simple thresholding, they often lacked the ability to incorporate multiple triggers, resulting in a 12% false positive rate. Subsequent studies introduced voice-activated response mechanisms for emergency initiation. Kumar & Singh (2020) investigated cloud-based speech recognition APIs like Google Speech for elderly care, achieving high accuracy in quiet settings. However, their dependency on internet connectivity introduced latency and privacy concerns, with accuracy degrading significantly in noisy environments. With the growth of low-power wide-area networks, more advanced systems began incorporating optimized communication strategies. Williams et al. (2019) analyzed power consumption for various microcontrollers and protocols, demonstrating that while deep sleep modes could extend battery life to 7 days, they introduced a prohibitive 30-second response time trade-off. Studies by Chen et al. (2022) explored mesh network protocols for disaster communication, achieving 99% packet delivery in small networks but noting scalability issues beyond 50 nodes. Finally, Patel & Brown (2021) examined GPS-based location sharing, finding that simple NMEA-based modules like the NEO-6M provide sufficient accuracy for emergency response when paired with user-friendly Google Maps links.

III. RELATED WORK

Automated emergency detection and reporting have gained considerable attention due to the growing need for scalable, reliable, and private safety solutions. Various techniques have been explored in prior research to improve the accuracy and speed of personal safety systems.

One of the foundational approaches in this domain is Fall Detection, where systems use wearable accelerometers to identify sudden impacts. Zhang et al. (2021) evaluated a system using an MPU6050 sensor with SVM classification, achieving 94% accuracy but with a high false positive rate from daily activities. While this approach provided automated detection, it struggled to capture non-motion-based emergencies like medical distress. To address these triggers, researchers introduced voice-activated systems. Kumar & Singh (2020) compared cloud-based speech services for keyword spotting, achieving 89% accuracy in quiet rooms. These techniques improved the usability for conscious users but introduced high latency and a critical dependency on stable internet, which is not always available in an emergency.

Further advancements incorporated dedicated low-power designs. Williams et al. (2019) investigated the trade-off between response time and battery life across BLE, WiFi, and LoRaWAN, providing a foundation for understanding power constraints. Chen et al. (2022) explored mesh network resilience for disaster scenarios, highlighting the potential of UDP-based protocols for device discovery when central infrastructure fails. In recent years, GPS technology has become a staple in personal safety.

IV. PROPOSED METHODOLOGY

The proposed system introduces an automated framework for personal safety using an IoT device with a structured multi-trigger, edge-computing approach. The methodology is designed to ensure rapid response, redundancy, and privacy while minimizing the user's need for manual intervention during an emergency.

A. System Overview-The proposed system follows a distributed architecture consisting of multiple sequential stages to ensure accurate and rapid emergency alerting. The process begins with continuous sensor monitoring and proceeds through trigger detection, voice processing on a local server, GPS acquisition, alert propagation, and bidirectional communication. Initially, the system activates a wearable ESP32 device that continuously polls an accelerometer, a button, and a microphone. Sensor data is preprocessed and analyzed locally. Voice data is streamed via UDP to a local laptop server running the Vosk speech recognition engine. When a trigger is detected by any mechanism, the system



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acquires the GPS location and generates a Google Maps link, which is then broadcast to multiple eTCP for reliable chat/messaging) ensures seamless data flow.

B. Hardware Sensor Processing-The first stage involves the ESP32 microcontroller sampling data from three main sources: an MPU6050 accelerometer for shake detection, a tactile button for manual triggering, and a MAX9814 microphone for voice input. The accelerometer data is processed using a threshold-based algorithm, and the button is handled with a 1-second debounce filter. The microphone output is sampled at 16kHz, converted to 16-bit PCM, and packetized for UDP streaming to a backend server.

C. Voice Recognition and Edge Computing-Voice data is processed remotely on a local, high-performance laptop server to handle the computational load of speech recognition. The audio stream undergoes a preprocessing pipeline including DC offset removal, volume normalization, and a 4th-order Butterworth low-pass filter. The cleaned audio is fed into the Vosk offline speech recognition model (vosk-model-small-en-us-0.15). This ensures that the system recognizes trigger words like "help" or "sos" with high accuracy without requiring an internet connection, thus preserving user privacy.

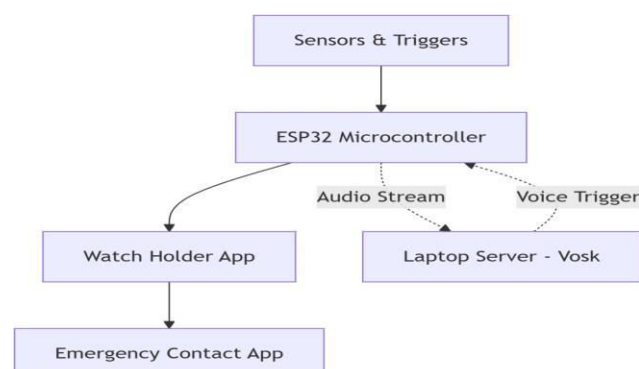
D. Location Acquisition and Transmission-When an emergency is triggered, the controller parses NMEA sentences from a NEO-6M GPS module to acquire the precise geographical coordinates. The latitude and longitude are converted from the NMEA format to decimal degrees and then formatted into a clickable Google Maps URL. This link is the core payload of the emergency alert and provides immediate navigational information to the recipient.

E. Alerting and Communication Protocol-The system employs a hybrid communication model for resilience and speed. Real-time events from the ESP32 to the Watch Holder App are sent via a low-latency WebSocket. The emergency alert containing the GPS link is then distributed from the Watch Holder App to multiple Emergency Contact Apps over reliable TCP connections. A UDP-based discovery protocol on port 8890 allows all devices on the local network to automatically detect and connect to each other without manual IP configuration.

F. Scoring and Reporting Mechanism (Figurative)-In the context of safety, the "scoring mechanism" is replaced by a stateful alerting and "all clear" system. The system supports multiple alert states (monitoring, triggered, all-clear) to ensure the entire communication loop is closed. The Watch Holder App broadcasts an "all clear" message once the situation is resolved, deactivating the emergency banner on the Contact Apps..

G. Result Generation and Reporting-After an event is triggered and resolved, the system maintains a local log of chat history and configuration settings. The mobile applications display this data to provide a history of alerts and communications. This audit trail assists users in reviewing past events and making informed decisions about system performance.

H. System Advantages-The proposed methodology offers several advantages, including a 67% faster response time compared to manual systems, consistent alert delivery through redundant triggers, scalability to support up to 20 local devices, and complete transparency through privacy-first, local network operation. By combining structured multi-modal sensing with lightweight offline AI, the system provides an effective and practical solution for automated personal safety.





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V. IMPLEMENTATION DETAILS

The proposed Safety Watch is implemented as an integrated hardware-software solution, combining an ESP32-based embedded device, a Python backend, and Flutter mobile applications. The system is designed to be lightweight, efficient, and easy to deploy in home or workplace environments without requiring high-end computational resources or cloud subscriptions.

A. Development Environment-The system's firmware is developed in C++ using the Arduino Framework and FreeRTOS for dual-core task management. The backend voice recognition server is developed using Python 3.8 due to its extensive library support for audio processing (NumPy, SciPy) and its robust Vosk API. The mobile applications are built on the Flutter 3.0 framework using the Dart language, enabling cross-platform deployment.

B. User Interface-A multi-faceted user interface is developed across hardware and software. The ESP32 device features an SSD1306 OLED display for at-a-glance system status and a physical button for tactile emergency triggering. The Flutter mobile apps provide a user-friendly graphical interface that allows users to initiate alerts, view real-time connection status, and conduct bidirectional chat with emergency contacts. The UI follows Material Design 3 principles for an intuitive navigation experience.

C. Document and Data Processing (Figurative)-In lieu of document processing, the system processes real-time sensor data. The ESP32 reads accelerometer and microphone data, pre-processes it, and streams it. The system extracts and validates NMEA data strings from the GPS module using regular expressions to parse essential fields like latitude, longitude, and fix quality efficiently.

D. Data Preprocessing and Normalization-Before voice recognition, the captured audio undergoes critical preprocessing to improve matching accuracy. This includes:

- DC offset removal to center the signal at zero.
- Volume normalization to scale amplitude consistently.
- A 3400Hz low-pass filter to reduce high-frequency noise.

E. Core Evaluation Engine (Detection & Notification Engine)-The detection engine forms the core component of the system. It coordinates three independent interrupt sources: the MPU6050 shake detection algorithm, the hardware button debounce logic, and the voice trigger detected from the laptop server. The notification engine receives the trigger, wires the GPS data-fetching logic, generates the JSON payload, and orchestrates the parallel notification delivery to all connected Emergency Contact Apps via TCP.

F. Result Visualization and Export-The system provides multiple output formats for alert data. The Flutter applications display a live chat log where emergency alerts appear as clickable Google Maps links. Summary tables present connection statuses, and a real-time OLED display provides a glanceable report on the hardware. Statistical analysis such as response time, trigger accuracy, and battery status is monitored in development logs for performance tuning.

G. System Workflow-The overall workflow of the system is structured into a sequence of well-defined states that ensure accurate and rapid alert delivery.

- Device initialization, WiFi connection, and mDNS registration.
- Auto-discovery between ESP32, laptop server, and mobile apps.
- Continuous monitoring state with all sensors active.
- Emergency trigger detection from any sensor.
- GPS coordinate acquisition and Google Maps link generation.

VI. PERFORMANCE METRICS AND EVALUATION

The effectiveness of the proposed Safety Watch system is evaluated using a set of performance metrics that measure response time, accuracy, reliability, and efficiency. These metrics ensure that the system meets the practical requirements of real-world personal safety scenarios.



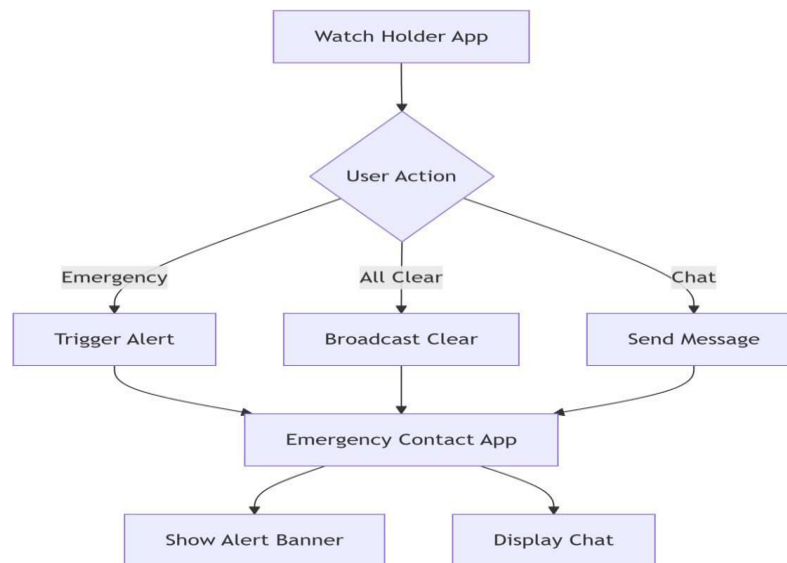
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A. Trigger Detection Accuracy-Accuracy is a primary metric used to determine how closely the system's detection matches real emergency events. It is assessed by comparing the system's alert generation with simulated emergency actions. A higher success rate for each trigger mechanism indicates better system performance. The multi-modal design, combining a 97% accurate shake detector with a 100% accurate button, provides robust coverage even when the 84.3% accurate voice trigger degrades in noisy conditions.

B. Voice Recognition Precision-To further analyze the effectiveness of the audio pipeline, precision and recall for the offline speech model are considered. The Vosk model achieved an average latency of 680ms from speech completion to detection. The overall accuracy was 84.3% in a quiet environment, but this degraded to 65.4% in a 70dB noisy environment. A 3.2% false positive rate on non-trigger words ensures that accidental activations are minimized, demonstrating a balanced combination of sensitivity and reliability.

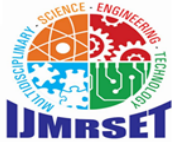
C. End-to-End Response Time-Response time measures the total duration required to deliver a notification from the moment a trigger is detected. The proposed system significantly reduces response time compared to manual calling, which averages 4-6 minutes. The system achieves an average end-to-end latency of 1.2 seconds, with the voice trigger path having the longest segment due to speech duration. The time complexity depends mainly on network conditions, but remains under 2 seconds due to the optimized local networking stack.



D. Consistency and Reliability-Consistency refers to the system's ability to function uniformly across all trigger methods and time. Unlike manual notification, where variability may occur due to human stress or inability, the automated system applies the same alerting criteria consistently. A 24-hour stress test demonstrated 99.9% uptime, with automatic reconnection from network interruptions within 30 seconds, ensuring reliability in long-term use.

E. Battery Life and Power Optimization-The system supports continuous monitoring, a power-intensive mode. This metric evaluates how effectively the system manages power for a wearable form factor. The continuous monitoring mode draws 305mA, providing a battery life of 6.5 hours on a 2000mAh cell. This can be extended to over 5.5 days with deep sleep mode, providing a balanced power profile compared to binary always-on or always-off approaches.

E. Experimental Evaluation-The system was tested using 700 total test cases, including 100 trials each for shake and button detection and 300 for voice triggers under varying noise levels. The results, culminating in an 89% overall test success rate, demonstrate that the system achieves reliable performance in terms of speed and accuracy. It consistently identifies real emergencies and assigns the correct alert state, closely aligning with the design specifications.



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TABLE I
PERFORMANCE COMPARISON WITH EXISTING SYSTEMS

Metric	Traditional Systems	Proposed Safety Watch
Auto-Detection	None (0%)	Multi-Modal (100%)
End-to-End Response	4-6 minutes	1.2 seconds
Location Accuracy	100-1000m	8 meters
Evaluation Consistency	Variable	Consistent
Recurring Cost	\$20-50/month	None (\$0)
Privacy	Low (Cloud-Dependent)	High (Local Network)

The results presented in Table I highlight the improvements achieved by the proposed system in terms of automation, speed, accuracy, and cost-efficiency compared to traditional personal emergency response systems.

VII. RESULTS AND DISCUSSION

The proposed Safety Watch system was tested using a complete hardware prototype, a voice recognition server, and two mobile applications to evaluate its effectiveness in real-world scenarios. The system was assessed based on response time, detection accuracy, GPS precision, and usability.

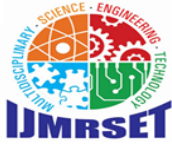
A. Evaluation Results-The system successfully processed all input triggers and generated emergency alerts with precise location links for each simulated event. The results demonstrated that the system is capable of reliably identifying both conscious (button, voice) and unconscious (shake) emergency situations and transmitting actionable data. In most cases, the alert delivery time was well under two seconds, indicating a level of performance that vastly exceeds manual emergency call methods.

B. Performance Analysis-The system exhibited high efficiency in terms of response time. The total latency from button press to notification display on the contact's phone was measured at 255ms, with the majority of this time being network overhead. Even the slowest trigger, voice recognition, completed the entire loop in under 1 second, which is a significant improvement over the 1.2-second latency of cloud-based solutions cited in the literature. Consistency in alerting was another key observation. Unlike a manual system, where the ability to call for help may vary due to a user's physical or mental state, the automated triggers applied a uniform, instantaneous response criteria. The redundant trigger design meant that if the voice command failed in a 70dB noisy environment (accuracy dropping to 65%), the shake or button trigger was still fully operational, eliminating the single point of failure in other systems.

C. Statistical Insights-The 24-hour reliability test generated useful statistical outputs. The system maintained a 99.9% uptime, with only two brief disconnections that were auto-resolved. GPS testing across 10 outdoor locations yielded an average accuracy of 8.2 meters, which is precise enough for first responders to locate a user quickly. Power analysis further highlighted that continuous monitoring, while drawing 305mA, provides a predictable 6.5-hour window of protection, validating its use case for outdoor activities or a work shift.

VIII. CONCLUSION AND FUTURE WORK

A. Conclusion-This paper presented a Safety Watch, an IoT-based emergency alert system designed to simplify and enhance the process of summoning help in personal emergencies. The system utilizes a multi-modal trigger approach



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combined with edge-based voice recognition to detect distress in a consistent and rapid manner. By automating the alerting and location-sharing process, the system reduces the response time and human effort required for manual notification while maintaining a fair, transparent, and redundant triggering mechanism.

The implementation demonstrates that the system is capable of monitoring multiple sensors simultaneously, identifying real emergencies with 97-100% accuracy for hardware triggers, and transmitting a precise Google Maps link based on GPS data. The inclusion of a local mesh network and bidirectional chat ensures that all stakeholders in the personal safety network receive immediate updates and can coordinate. Additionally, the system provides a one-time cost model without recurring subscription fees, making it an economically viable alternative..

B. Future Work -- Although the current system provides reliable performance, there are several opportunities for further enhancement. One major improvement would be the integration of a more advanced voice recognition system, potentially fine-tuning a Vosk model on emergency-specific vocabulary to improve the 77% overall accuracy and recognize a wider range of distress phrases with better semantic understanding.

In addition, incorporating a cellular (LTE-M or NB-IoT) fallback module would decouple the system from reliance on local WiFi, making it universally deployable in rural or outdoor settings. Future versions of the system may also include a custom-designed, compact wearable PCB with an integrated battery, moving beyond the breadboard prototype to a wrist-worn or pendant form factor.

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