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Abstract-- Falls in older adults pose a serious risk to the population, being the leading cause of loss of independence and serious injuries. To mitigate the consequences of these accidents through timely intervention, this study presents the development and validation of a portable early warning and monitoring device for fall detection. The device consists of a microcontroller and an inertial sensor, using an algorithm based on experimentally calibrated acceleration thresholds. The methodology integrates laboratory testing and functional validation in a real-world setting. The results demonstrate that the system has reached TRL 5 maturity, achieving a false positive rate of 0 during validation of daily activities and an average alert transmission time of 4.02 seconds. It is concluded that the architecture provides a robust and effective solution for remote assistance, ensuring the notification of critical events. Keywords-- Older adults, Fall detection, ESP32, IoT, Wearable.

Abstract-- Falls among the elderly represent a serious risk to the population, being the leading cause of loss of autonomy and severe injuries. To mitigate the consequences of these accidents through timely intervention, this paper presents the development and validation of a portable early warning and monitoring system for fall detection. The device integrates a microcontroller and an inertial sensor, using an acceleration threshold-based algorithm calibrated experimentally. The methodology combines laboratory tests with functional validation in a real-world scenario. Results demonstrate that the system has achieved a TRL 5 maturity level, with a false positive rate of 0 during daily activity validation and an average alert transmission time of 4.02 seconds. It is concluded that the architecture provides a robust and effective solution for remote assistance, ensuring notification of critical events.

Keywords-- IoT, Fall detection, Elderly, Wearable, ESP32.

INTRODUCTION

The safety of older adults has become a priority given the sustained growth of this population segment. In Mexico, more than 14% of the population is 60 years of age or older, and it is estimated that by 2030 this figure will double, according to INEGI. This change poses multiple challenges, one of the most serious being fall prevention. According to the World Health Organization (WHO), accidental falls are the leading cause of serious injuries, hospitalizations, and loss of independence among older adults. Between 28% and 35% of older adults experience at least one fall per year.

However, traditional solutions, such as panic buttons, are very limited, as they rely on manual activation by the user, which is not feasible if the user is unconscious or immobilized following a fall.

This paper describes the development of an early warning system based on an IoT architecture. A technological solution aimed at significantly improving the quality of life and independence of older adults through continuous monitoring and automatic emergency notification.

General Objective

To develop a portable early warning and monitoring system for detecting falls in older adults and/or people with motor disabilities.

Specific Objectives

- Design the hardware and software architecture of the wearable device, selecting the electronic components (inertial sensors, microcontroller) and communication protocols suitable for real-time monitoring.
- Implement and calibrate a detection algorithm based on acceleration thresholds (S-factor) that effectively distinguishes between daily activities and fall events.
- Link the device to a user-centered mobile application that enables the receipt of immediate alerts and the management of the patient's medical history.
- Validate the system's performance through experimental testing of latency, detection accuracy, and usability in controlled environments and real-world scenarios.

Justification

In light of the global phenomenon of population aging, the development of an automatic fall detection system is a technological solution that significantly improves the safety and autonomy for older adults and people with motor disabilities. The developed device, based on inertial sensors and automatic notifications, provides a rapid response to a fall event, facilitating timely communication with family members or emergency services. Thus, it contributes to reducing the physical and psychological consequences resulting from these events, thereby improving quality of life. This project has a positive focus, as it seeks to provide greater safety for people and will enable greater autonomy for older adults.

DEVELOPMENT

The project was structured using a mixed-methods approach, integrating applied, literature-based, and experimental research, focused on creating a tangible technological ecosystem. The literature review provided the theoretical foundation for the technical selection of components, the analysis of the system's operational requirements, and the study of regulations; experimental research was conducted for the calibration phase and subsequent user validation; and through applied research, the system's engineering was realized, using theoretical and experimental findings to achieve a functional technological ecosystem. As a result, a technology readiness level (TRL 5) project was achieved for the validation of the integrated system in a relevant environment.

Various techniques were used for data collection. To validate the algorithm's performance, a controlled experiment was conducted to gather quantitative data, involving a series of tests designed to determine the appropriate settings for fall and impact thresholds to ensure detection at different heights, thereby calibrating the device to minimize false positives. Additionally, a checklist was created by using the device on two test subjects, recording the occurrence of false positives while they performed daily activities.

Similarly, various qualitative data collection techniques were applied, including a series of interviews with healthcare personnel to gather recommendations regarding the device's functionality—highlighting the need to generate an event log—as well as surveys of caregivers and family members to identify the requirements necessary for a system of this nature. In this way, a solution aligned with medical and care requirements was successfully created.

The system architecture is structured as a complete ecosystem comprising three main modules:

- **Wearable Device:** The wearable monitoring device was designed and built as a watch that integrates inertial sensors to measure the person's movements. The choice of components was essential for the device to detect kinematic patterns and sudden changes in position, as established by Martínez Méndez and Romero Huertas (2013) in their analysis of motion assessment in health applications. Similarly, local data analysis using fall detection algorithms allows for differentiation between daily activities and actual falls, based on the sensitivity and specificity criteria analyzed by Estrada Marmolejo and Moran Garabito (2017).

Figure 1. *Portable device for monitoring and detecting falls*.

Source: Author's *own work* (2025).

- **Cloud server:** This infrastructure was designed using the three-layer IoT computing architecture model validated by Rebeiro et al. (2022) as a reference, who note that cloud integration is essential for effective real-time alert management and reducing health consequences. In this way, the system ensures that the notification is delivered without distance restrictions, ensuring that the caregiver receives the alert immediately regardless of physical proximity to the patient.

- **Mobile App:** The app's primary objective is to alert family members or caregivers to an incident in real time, create medical reports, and review incident history. The app was designed with a user-centered approach, following the guidelines of Álvarez Rodríguez et al. (2015) to establish a simple interface and linear task flows; this was complemented by the criteria of Archundia et al. (2016) to ensure the clarity of alerts.

For the physical implementation of the device, an architecture based on the use of compact microcontrollers with dual-core processing capabilities and integrated connectivity was chosen, thereby achieving efficient management of sensor readings and wireless transmission.

- **Processing unit (ESP32):** An ESP32 SoC was used as the device's core; this choice was driven by its 32-bit dual-core architecture and integrated connectivity. This allows for the parallel execution of the filtering algorithm and communication protocol, thereby meeting the requirements for minimal latency and the transmission of critical alerts (Rebeiro et al., 2022). Similarly, the use of a portable device for real-time processing ensures a rapid response to critical events.
- **Inertial sensor systems (**MPU-6050): For the acquisition of kinematic data, an MPU-6050 module was selected, based on the analysis by Martínez Méndez and Romero Huertas (2013), in which they determined that the fusion of accelerometry and angular velocity data is the standard for the precise biomechanical evaluation of human movement. The accelerometer is used to measure linear acceleration along the X, Y, and Z axes to determine the impact force; in contrast, the gyroscope monitors changes in orientation.
- **Feedback interface:** For user interaction, a monochrome OLED display and a beeper were integrated into a compact design for wrist wear. This implementation follows the digital accessibility criteria validated by Archundia et al. (2016), applying the principle of sensory redundancy, which dictates that combining visual stimuli with auditory signals is essential to ensure the perception of an alert.

To ensure an immediate response, a local processing architecture was established, allowing the detection logic to run directly on the microcontroller. In this way, the device identifies the accident and automatically activates the local alarm, using Wi-Fi connectivity to transmit the notification remotely to the server.

The implemented algorithm is threshold-based, a technique validated by Estrada Marmolejo and Moran Garabito (2017, p. 31), using the calculation of the S-factor, also known as the sphere filter. As the authors state, "the use of the S-factor is a way to consider the total acceleration with respect to all axes." This magnitude is calculated using the following equation:

$$Factor\_S = \sqrt{x_{out}^2 + y_{out}^2 + z_{out}^2}$$

Where:

- Factor_S: Represents the magnitude of the total acceleration vector.
- $x_{out}, y_{out}, z_{out}$: Represent the instantaneous acceleration values of the X, Y, and Z axes.

The monitoring protocol continuously checks whether Factor S is equal to or greater than the critical impact threshold (U_{imp}). This parameter sets the system's sensitivity variable and its final numerical value, which was determined experimentally to distinguish between a sudden movement and a fall. If the device detects that the established condition is met ($Factor\_S \geq U_{imp}$), it immediately activates the local response and transmits the data to the server to report the situation in the mobile alert

.

ANALYSIS AND DISCUSSION.

Definition of technical specifications based on clinical validation

The device's architecture was not established arbitrarily but resulted from a requirements engineering process validated through a field study. This phase collected data from 50 family members and caregivers, in consultation with healthcare professionals, including specialists in geriatric medicine, nursing, and physical rehabilitation. This enabled the establishment of critical variables that guided the design of the firmware and hardware.

Analysis of the results obtained demonstrates that response speed is a primary factor, accounting for 41% of use cases, even surpassing concerns about physical injury

. The results determined that immediate assistance is a critical factor in mitigating secondary complications resulting from a fall, which is why the firmware was designed with real-time processing.

Similarly, the technical necessity of an incident report was identified as a critical requirement for clinical evidence. During the interviews, Dr. Jesús Guzmán emphasized the troubling situation: "Family members do not usually report these types of incidents," which can result in a lack of the information needed to make a diagnosis. To address this issue, an automatic incident logging module was implemented in the application. This allows healthcare staff to access objective, chronological tracking of each event for precise adjustments to the patient's treatment.

As shown in Figure 1, this report is structured into two strategic sections: the medical profile, which displays personal, medical, and additional information about the patient; and a section with the history presented in tabular form, organizing events chronologically by date, exact time, alert confirmation status, description of the event, and the time it took to assist the patient.

Figure 2. *Example of a patient report.*

Source: Author's *own work* (2025).

Additionally, other requirements for system functionality were presented. Ease of use was ranked as one of the most valued features at 28%, and immediate assistance at 25%.

This guided both software development—where complex configurations were eliminated in favor of automated and intuitive processes—and hardware architecture, where a watch-style device was chosen after confirming that this format offers the highest user adherence and comfort.

Calibration of detection threshold parameters.

To ensure the system's reliability, an experiment was conducted to determine the optimal threshold values for free fall and impact. The main objective was to strike a balance between sensitivity for detecting real falls and the ability to ignore sudden movements. As Estrada Marmolejo and Moran Garabito (2017) point out, significant progress has been made in algorithms; the challenge lies in adjusting the parameters to minimize false alarms without compromising user safety.

The experiment's configuration was based on the user's biometrics and the classification of physical events, defining two scenarios: a false positive ranging from 10, 20, and 50 cm to simulate the accelerations typical of daily activities; and a real fall of 70 and 100 cm. The results obtained are shown in Table 1.

Table 1. *Tests for selecting algorithm thresholds*.

Fall Threshold	Impact impact	Drop 10 cm	Height of 20 cm	Height of 50 cm	Height of 70 cm	Height of 100 cm
2000	8,000	5	5	5	5	5
2000	12,000	3	4	5	5	5
2,000	15,000	0	1	4	5	5
2,000	18,000	0	0	2	5	5
3,000	8,000	5	5	5	5	5
3,000	12,000	1	2	3	5	5
3,000	15,000	0	0	0	5	5
3,000	18,000	0	0	1	5	5
4,000	8,000	5	5	5	5	5
4,000	12,000	3	4	4	5	5
4,000	15,000	0	0	2	4	4
4,000	18,000	0	0	0	3	4

5,000	8,000	4	5	5	5	5
5,000	12,000	4	3	3	5	5
5,000	15,000	0	0	0	3	4
5,000	18,000	0	0	0	2	4

Source: Author's *own work* (2025).

Analysis: The results reveal a correlation between the magnitude of the thresholds and system performance. With a fall threshold set to <2000, critical sensitivity was observed, resulting in 100% of daily movements being classified as falls. On the other hand, when the parameters were set to their maximum values, restrictive behavior occurred, omitting 40% of the simulated real falls, which represents a safety risk. The optimal point in the configuration was found at 3000 for the fall threshold and 15000 for the impact threshold. This calibration resulted in 0 alerts during daily activities and 5 during simulated falls, thereby validating its use.

Latency and connection reliability testing.

Once the algorithm thresholds were established, the efficiency of the IoT was evaluated; the main objective of this stage was to verify compliance with response speed by timing the exact duration between the event and the alert notification.

A total of 100 tests were conducted under standard network conditions, measuring the time from when the device confirmed the fall until the mobile app received the alert. The tests demonstrated complete consistency in connectivity. Table 2 below details the times recorded during the 100 iterations.

Table 2. *Record of latency times in alert transmission*.

Response Response	2	3	4	5	6	7	8	9
Number of attempts	7	36	25	19	9	2	1	1

Source: Author's *own work* (2025).

Analysis: Based on the results obtained, it is demonstrated that the system maintained a 100% connection. Regarding speed, there is an average response time of 4.02 seconds. This demonstrates that the implemented architecture processes and transmits data efficiently. By maintaining the average and ensuring that no response time is excessively long, the system ensures that the alert arrives at the precise time.

Functional validation in a real-world scenario.

To verify the system's operation outside of laboratory conditions, a pilot study was conducted to detect false positives during daily activities. The test subjects were a 76-year-old man and a 71-year-old woman, both with reduced mobility. The test lasted 60 minutes per participant, during which the subjects performed their usual daily activities without simulating traumatic events. The results observed during these sessions are shown in Table 3.

Table 3. *Test Results for Daily Living Activities*.

Subject	Age	Monitoring Time	False positives recorded
A	76	60 min	0
B	71	60 min	0

Source: Author's *own work* (2025).

Analysis: During the test in both cases, no errors were recorded in the emergency protocol, demonstrating that the algorithm functions properly in real-world situations involving older adults, thereby validating the established thresholds.

CONCLUSIONS

Following the development of the system, a functional IoT architecture focused on older adults was successfully implemented, achieving a technology readiness level (TRL) of 5 through validation in uncontrolled real-world scenarios. Calibration tests of the s factor played a significant role in the device's operation; This configuration allowed us to effectively distinguish between daily activities and falls, resulting in a total of zero false positives in the validation with test subjects.

The system's performance is entirely satisfactory, meeting response time requirements with an average alert time of 4.02 seconds. This demonstrates that the dual-processing architecture is robust for an emergency application. Finally, the integration of complementary functions into the system—such as the automatic generation of incident logs in the mobile app, adds value to the ecosystem. This validates the device as a viable technological tool for detecting falls.

FUTURE WORK

Future plans for the system include the integration of artificial intelligence, with the goal of evolving the threshold algorithm into machine learning models capable of identifying complex biomechanical patterns and detecting gait instability patterns, in order to anticipate falls. **REFERENCES**

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