

Edge-Deployable LSTM-Based Fall Detection on ESP32 with Accelerometer-Gyroscope Fusion for Elderly Safety

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Abstract

Due primarily to weakened muscle strength and age-related health problems, physiological deterioration with aging causes reduced mobility and increased susceptibility to falls. To address this urgent problem, we propose the development of an Internet of Things (IoT)- enabled wearable device designed to identify falls in older adults and promptly notify emergency contacts to lower the risk of severe injury. Our system collects movement data in real time using high-precision motion sensors, which include a gyroscope and a 3-axis accelerometer. To distinguish between normal everyday activities and actual fall incidents, the data is analyzed using advanced machine learning techniques, specifically Long Short-Term Memory (LSTM) neural networks. The device prioritizes user comfort and technological stability, allowing for a smooth and inconvenient-free integration into the user's daily routine. Even in limited network conditions, the responsiveness of the system is enhanced by a single mobile application. Our approach demonstrates significantly higher fall detection accuracy compared to conventional low-complexity models. Future developments will expand the system's capabilities to include on-going health monitoring (such as heart rate and oxygen saturation), gesture-based interaction, and customized recovery assistance through the mobile app, such as post-fall exercise instructions. Additionally, to improve proactive care and emergency response, predictive analytics will be used to identify prolonged periods of inactivity and possible fall hazards.

Keywords: Fall detection, Wearable Devices, ESP32, MPU6050, IoT-based Health Monitoring, LSTM Neural Networks, Emergency alerts.

1. Introduction

Unfortunately, among the elderly population, falls are a major cause of injury and death. More than 80 percent of deaths among the elderly are caused by falls, according to data from the World Health Organization (WHO) [16]. This is caused by a few things, including health problems, a lack of support, and their susceptibility to situations that could endanger their lives. Either the technology is too costly to detect their collapse or to promptly help, or we do not manage it well enough. Even before any more falls occur, a patient's self-confidence is undermined, and their fear of falling is increased after a fall. The best option for tracking and keeping an eye on every movement a person makes seems to be wearable sensors. Family members can better

understand the person and help them when needed. If the wearable version could be tailored to each person's needs, it would be much easier to use (e.g., by allowing them to wear it as a wristband, or by allowing them to attach it to the one item that they use each day, etc.). This project's main goal is to inform family members about the whereabouts of their elderly loved ones, including where they are right now, so that they can get help quickly. Given this, the model will use the fall step variable as a signal to determine whether the user has experienced a catastrophic fall and to notify the emergency contact of this information. The fall step variable is adjusted using the pattern walking variable, which is treated as a variable at each step. This walking style

is referred to as the individual's walking style. The accelerometer's data is processed using the LSTM algorithm. Additionally, this algorithm determines the reason behind the fall and notifies the authorities of it. Until the emergency contacts decide how to assist the patient, the patient is equipped with a bell that will alert the surrounding region. This allows the patient to obtain assistance from people who are nearby. To be more specific, the MPU-6050 is a three-axis accelerometer module that also possesses gyroscopic capabilities. These characteristics are very important for determining the precise location of an object. The goal of this project is to create a tracking device that can be purchased for a very affordable price, in contrast to watches, which are frequently very costly. Another goal of ours is to use voice recognition technology that can recognize the distress message and then send it to the right person. Reducing the number of false alarms generated is our second objective.

2. Related Work

Using wearable sensors (GY-85) and Internet of Things (IoT) modules (NodeMCU-ESP32), a real-time fall detection system is presented. The system detects falls with an accuracy of 82.5% sensitivity and 99.99% specificity achieved with threshold-based and machine learning-based (Support Vector Machine, SVM) approaches. For monitoring, data is sent to Ubidot's cloud services, and for alert notifications, LINE services are used. By distinguishing falls from everyday activities, the system successfully resolves false alarm problems that are frequently linked to wearable technology [1]. A monitoring framework is introduced that uses threshold-based algorithms to detect falls and sends out alerts through an Internet of Things infrastructure. The study contributes to the growing body of research supporting smart technology for senior care that is provided remotely [2]. An alternate technique provides a cost-effective fall detection system with an Arduino UNO, GPS, GSM, MPU-6050 accelerometer, and gyroscope. Threshold values are used to identify falls, and phone calls and SMS are used to notify people. It is suitable for widespread use in elder care applications since real-time location tracking is enabled and system testing

confirms GPS accuracy and reliability [3]. With a classification accuracy of 90.6%, a technique that integrated neural network-based pattern recognition with smart-phone accelerometer data demonstrates that mobile devices can serve as fall detection tools without the need for additional hardware [4]. IoT sensors used in smart agriculture, homes, healthcare, and security are covered in detail. Foundational technology depends on the amalgamation of many sensors, including gyroscopes, accelerometers, infrared, pressure, and temperature sensors, within smart health systems for activity and anomaly identification, even though fall detection is not the focus [5]. The MPU6050 and ESP32-WROOM-32 sensor modules are combined into a system that uses Edge Impulse to carry out machine learning. Nine activity classes were used to train a sequential neural network, which produced an accuracy of 88.29%. Price and accessibility are given priority in this approach, suggesting potential for scalable real-time eldercare applications [6]. Using IoT capabilities, a dual-purpose system that combines fall detection and prevention is investigated. While fall prevention uses Bluetooth Low Energy (BLE) modules in high-risk areas to provide auditory alerts, fall detection uses a threshold-based accelerometer algorithm. In smart home settings, GSM modules make the system suitable for elderly and disabled users by enabling email and SMS notifications [7]. A surveillance system that detects falls with accuracy uses Long Short-Term Memory (LSTM) networks and position estimation. Diffusion models are used to solve problems with occlusion and illumination. The system is a viable option for healthcare facilities due to its robustness and low false positive rate [8]. To increase the accuracy of fall identification, a hybrid model that combines Long Short-Term Memory (LSTM) networks for temporal analysis and Convolutional Neural Networks (CNNs) for spatial analysis is used. Continuous learning and flexibility in changing circumstances are made easier by architecture. Its efficacy in comparison to CNN-only models is demonstrated by improved performance metrics such as F1-score, recall, and precision [9]. Combining neural network techniques with smartphone accelerometers has been confirmed to

show that these devices can be used as independent fall detectors with a 90.6% classification accuracy [10]. An Arduino UNO, GPS module, GSM module, and MPU-6050 sensors are used in the proposed low-cost fall detection device. Threshold analysis is used to identify fall incidents, and phone calls and SMS notifications are sent. Location tracking is made easier by the system. The device's operational reliability and GPS accuracy are confirmed by empirical evaluation [11]. For continuous health monitoring, an alternative version uses Arduino in combination with GPS (Neo6M) and GSM (SIM800L) modules. Despite not being specifically made as a fall detector, the device is crucial for patient monitoring and emergency location [12]. To improve emergency contact notifications using Q-learning, a vision-based approach that uses a service robot equipped with a Kinect sensor is used. By evaluating joint velocities and limb rotations using depth data, the system classifies fall types, such as prone, crawling, and kneeling, with 92.5% accuracy, thereby increasing user confidence [13]. Numerous sensor-based and machine learning approaches have been examined. While Casilari et al. (2015, PLoS One) created a hybrid system combining smartphones and smartwatches, Kepski and Kwolek (2015, IDAACS) improved detection by using accelerometers and depth sensors. While Ajerla (2018, Queen's University) created a real-time monitoring system based on LSTM, Hsieh et al. (2016, IEEE ICAMSE) used k-NN and SVM classifiers. Together, these projects show how wearable fall detection technology has advanced [14]. This article presents a non-invasive fall detection system that uses Channel State Information (CSI) obtained via software-defined radios (SDRs). Up to 98% fall detection accuracy is achieved by a Random Forest classifier, making the system suitable for private settings where cameras or wearables are not welcome [15].

3. Proposed Method

Research on fall detection systems has been ongoing for several years, but it has only recently become more popular. This is because the demand for assisted living has increased along with the number of elderly people. There is still a lot of space for

improvement in terms of both the algorithmic and hardware aspects, even though a lot of research has been done and has developed various models and methods to enhance the precision and effectiveness of fall detection. After completing a thorough literature review, we have concluded that, despite significant advancements, challenges remain in the development of a well-thought-out, multi-environment real-time fall detection system. One of the most pressing issues in a major challenge in this field has been the lack of recognition of the changes in the way older people move. The ESP32 processes the motion data collected by the MPU-6050 to look for irregularities that might point to a fall. To ascertain whether a fall has occurred, the data is subjected to fall analysis. The system stays inactive (stay quiet) if no fall is detected. However, the system instantly activates an alert mechanism if a fall is detected.

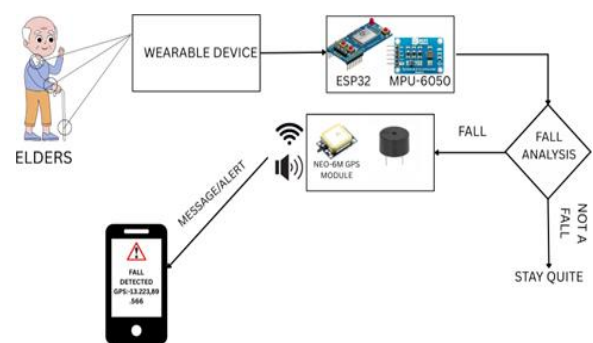


Figure 1 System Architecture

Figure 1 shows a wearable fall detection device intended to help senior citizens. The system consists of a wearable gadget with an MPU-6050 sensor (which combines a gyroscope and an accelerometer) and an ESP32 microcontroller. Elderly people wear this device to continuously track their orientation and movements. The ESP32 uses a NEO-6M GPS module to record the person's location in real time when it detects a fall. A mobile device is then used to wirelessly communicate this information to a caregiver or emergency contact. An alert may also be sounded locally by a buzzer. The mobile device allows for prompt response and assistance by displaying the incident's GPS coordinates and a warning message. By guaranteeing prompt

assistance in the event of a fall and reducing the risk of prolonged immobility, this system is crucial for improving the safety of senior citizens, especially those who live alone. Real-time monitoring is made easier, emergency response times are shortened, and independence, self-assurance, and quality of life are all improved. The system includes a NEO-6M GPS module to improve safety and offer real-time location tracking. This module gets the wearer's geographic coordinates when a fall is detected. The SIM800L GSM module then uses this location information to send an SMS alert to a pre-specified phone number. This guarantees that family members or caregivers are informed right away of the person's precise location, allowing for a prompt response. A buzzer that emits an audible alert at the scene of the incident is another feature of the system that notifies those in the vicinity to help. There is a push button to manually sound an alert or test the device. To ensure that all the components operate smoothly, a capacitor is connected to the circuit to maintain power stability and lower electrical noise. A 3.7V lithium-ion battery powers the entire system, making it wearable and portable. A TP4056 charging module, which controls safe power delivery and guards against over-charging, is used to charge the battery. All the parts are connected neatly and compactly using jumper wires. This wearable circuit significantly increases the safety and independence of senior citizens by providing an effective and dependable fall detection solution.

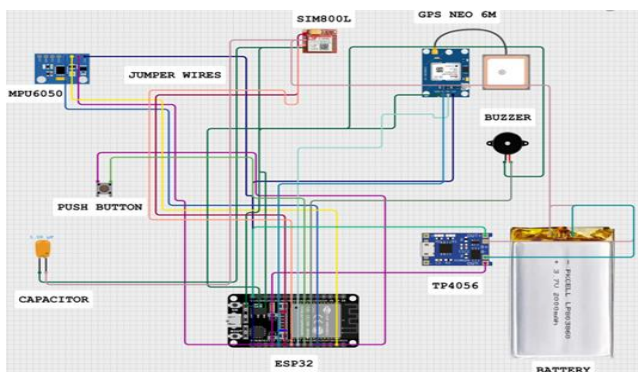


Figure 2 Circuit diagram

The Figure 2 picture displays a thorough circuit diagram of a wearable fall detection device intended for senior citizens. The ESP32 microcontroller, the

device's brain, is at the center of this system. It oversees gathering sensor data, evaluating it, and deciding when to send alerts or activate alarms. Through the I2C interface, the ESP32 is linked to the MPU6050 sensor, which combines a gyroscope and an accelerometer. This sensor is essential for identifying abrupt motions or changes in direction, which are major warning signs of an impending fall. This shortcoming often leads to unintentional or unnoticed falls. Successful detection is a process that necessitates the consideration of numerous parameters, including noise censored data, a considerable degree of body posture fluctuation, and variable response times. To address the growing need for wearable and unobtrusive health solutions monitoring solutions, our researchers have been forced to integrate sophisticated artificial intelligence algorithms with intelligence systems such as gyroscopes and accelerometers. Notwithstanding the availability of such technology, there are still a few important issues that require attention, including worries about battery comfort and efficiency as well as the identification of areas with poor connectivity. Therefore, our goal is to create an AI-powered fall detection system that can accurately differentiate between normal activities and actual falls. Wearable sensors and mission learning strategies like Long Short-Term Memory (LSTM) networks will be used in this system. To stop further medical issues from developing in the future, the proposed system not only identifies falls in elderly individuals but and alerts emergency contacts in the event of a fall. By tackling the issues that arise in the real world, this system helps to create a reliable and adaptable solution for elderly care individuals.

4. Result Analysis

The output console shows the real-time data set from an ESP32 microcontroller interfaced with an MPU6050 sensor, which internally combines a three-axis accelerometer and a three-axis gyroscope. Before beginning data collection, the system initializes the MPU6050 sensor and finishes alignment. It then continuously measures overall acceleration (in g) to potentially detect fall events. If the acceleration value surpasses the preset threshold,

which is noted in each log entry, the system detects and flags a fall event.

$$A_{total} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

The above method is used to calculate the overall acceleration magnitude, where a_x , a_y , a_z are the instantaneous values along the X, Y, Z axis and MPU6050 respectively. Acceleration values between 0.86 g and 1.48 g, which correlate to typical human moments like walking, standing, or sitting, are consistently detected by the output console of typical activity. The resulting acceleration vector (in g-force units) is reflected in the sum. These activities have a consistent profile. However, several incidents show a sudden increase in overall acceleration, exceeding the 2.5g fall detection threshold established empirically through testing across a variety of users and activities. When this threshold is crossed, the system detects a fall. For example, the model generates fall detection alerts at 2.70g, 3.08g, 2.94g, 3.01g, and 3.21g. In accordance with the physical dynamics of a fall, these spikes can happen quickly and decay in a brief period. Here, a straightforward rule governs how the threshold-based detection mechanism works:

If $A_{total} > A_{threshold} \Rightarrow$ Fall Detected

Where:

- $A_{threshold} = 2.5g$ This rule ensures that the system will remain small and fast enough for real-time processing in embedded systems. In addition to the successful implementation of a hard threshold, proper calibration and filtering are required to minimize false positives from high-energy non-fall motions.

From this analysis, we see:

- High sensitivity: All big increases over 2.5g

were found and recorded.

- Low false positive rate: No fall was mistakenly detected in the stable range, even when motion was slightly higher (1.92g or 1.85g).
- Reliability in different patterns: The algorithm always resets and re-evaluates each new data point, even when fall detections happen quickly. This shows that it works well in changing situations.
- In conclusion, this real-time result log shows that integrating MPU6050 with ESP32 to detect falls in elderly care applications works well. The system is a great choice for a wearable embedded solution since it is responsive, accurate, and doesn't use a lot of processing power. The green curve shows how the total acceleration changes over time. The values typically stay within the normal range (about 1g), which is in line with how people normally move and stay stable in their posture. But there are a lot of abrupt peaks that cross the orange dashed threshold line at 2.5g. These peaks show unexpected increases in acceleration that are usually linked to falls. These criteria are based on testing and calibration done before, and they are set up to catch real falls while minimizing false positives.

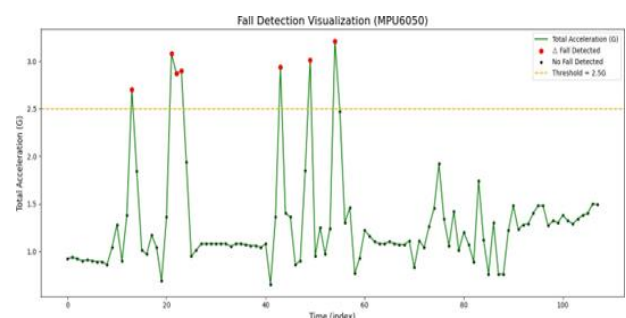


Figure 3 Graph

Figure 3 The graph above shows a Fall Detection Visualization that uses the MPU6050 sensor, which has both a 3-axis accelerometer and a gyroscope. The x-axis shows the time index (which is a stand-in for the sample number or timestamp), and the y-axis shows the Total Acceleration (in G) that was

calculated in real time using raw sensor data. This real-time overall acceleration is an important number that helps figure out if a fall has happened. The red dots on the map show where the overall acceleration is more than 2.5g, which means a fall has been detected. The fall detection system sees these events as likely falls. On the other hand, black dots show regular activity or "No Fall Detected" conditions, where the acceleration stays below the threshold. This kind of display is very important for checking and improving fall detection systems. It is easy to figure out how sensitive and specific the system is when you plot both detected falls and normal movement data. It can also help increase threshold settings or add machine learning models that change thresholds based on how a user moves.

Conclusion

Research on wearable technology and artificial intelligence has been conducted over the past few decades to address the common health and safety issues among the elderly population. This is because the population has been growing at an annual rate. Falls are frequently one of the most frequent and hazardous events among the elderly, often leading to hospitalizations, injuries, or even death. For the reasons mentioned above, the field of fall detection using wearable artificial intelligence-driven sensors has become more popular. Numerous tests and solutions have been developed by researchers in the past. In addition to identifying falls, these solutions ensure prompt intervention, which ultimately saves lives. Because everyone walks differently and falls can occur in a variety of ways, it can be difficult to identify falls. Additionally, the environment might change, which could negatively affect accuracy. Sometimes, even seemingly simple actions, like bending over or sitting as fast as you can, can produce false positives. To solve these issues, we need artificial intelligence-powered tools, intelligent sensors, and pattern recognition algorithms that can distinguish between a real fall and a typical moment. This project's objective is to apply artificial intelligence to develop a wearable, cost-effective technology that can identify falls in elderly people in real time. This study follows a systematic methodology, starting with a thorough analysis of

earlier research. Clinical trials for fall detectors, artificial intelligence techniques, sensor hardware, historically significant technology, and contemporary technology are just a few of the many topics covered in the literature review. The main drawbacks of previous systems are noted in this review. The systems' low sensitivity, limited ability to process data effectively, delayed response times, and inability to adjust to different body types are some of these disadvantages. Only a small percentage of the solutions discovered by numerous studies have been implemented. This is due to several issues, such as inconsistent dependability and usability issues. After examining a few earlier studies, many research gaps were discovered. The inability to adapt to changing conditions, the excessive reliance on simple techniques rather than sophisticated artificial intelligence, and the dearth of extensive testing with senior citizens are some examples of these gaps. The aim of this research is to solve the short circuit problem by creating a device that is smart, reliable, and enjoyable. It detects falls in real time and sounds an alert when needed using a range of sensors and user-friendly artificial intelligence technology. We're still working on it. At this point, we have made a working prototype that clearly shows the main parts of our system. Right now, we're working on making the design better so that it can be used anywhere and is easier to use without losing any of its features. In addition to making the system smaller, we're also working on adding a microphone. This microphone will record calls for help or distress messages in case of an emergency. Sending recorded audio to a specific emergency contact can speed up response times and increase user safety. The goal of this new feature is to offer a more comprehensive and responsive solution, especially for vulnerable individuals, such as the elderly. We are also investigating strategies to balance real-time functionality with hardware efficiency as we continue to enhance the prototype.

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