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Sensor-Enabled Smart Footwear for Enhanced Mobility and Safety of Visually Impaired Individuals

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ABSTRACT –

Blind persons consistently experience the difficulties of independently and safely navigating a variety of environments. While traditional supports like white canes only have limited usefulness, this a paper presented a new sensor-based approach to create a smart footwear system that can assess real-time information detecting obstacles, monitoring falls, supporting health, and allowing emergency communications. The system is developed using an ESP32 microcontroller and includes LiDAR, gyroscopes, heart-rate sensor, GSM and GPS modules, and a haptic feedback interface. We developed the device tripartite based on existing vehicular accident detection framework from (Kadam et al. 2024) and applied to a personal wearable safety device. The results demonstrate that the system provided improved situational awareness, offered support for emergency alerts, and improved the safety and mobility of blind people.

Keywords: Assistive Technology, Smart Footwear, Obstacle Detection, Fall Detection, GSM, GPS, IoT, Visually Impaired

INTRODUCTION

There are more than 250 million individuals who are blind or visually impaired in the world, many of whom use traditional aids, such as white canes or guide dogs. Although these canes and dogs are great resources, they simply cannot detect both overhead and fast-moving obstacles, have no fall detection or health monitoring capabilities, do not track the user's current location to commemorate and improve over time, and do not alert or provide any assistance in emergencies. With the growth in wearable electronics and the Internet of Things (IoT), avenues for smart assistive type devices have grown. This work proposes a smart shoe system that employs the latest and greatest in embedded sensors and communications modules to help ensure user autonomy and safety.

The recent connection between healthcare and wearable technology has led to intelligent systems that support the specific needs of users with disabilities. Wearable IoT devices and systems support seamless data collection and real-time communication which enables proactive action to take place in response to emergencies such as a fall, or in the presence of medical anomalies. For visually impaired individuals, these capabilities can make for a significant improvement in their ability to navigate their environment, maintain situational awareness, and uphold their personal safety. Further, including smart technology in daily-use items such as footwear provides the benefit of using the technology Conveniently without being disruptive to natural behavior or routines. This paper will report on a sensor-rich IoT smart shoe system as an innovative approach to deliver environmental and health-related feedback to visually impaired users, with the goal of enhancing their independence and quality of life.

Literature Review

Another possible way of making a shoe smart would have been assisting mobility, safety, and health monitoring systems through embedded sensors and wireless communications. Researchers have developed several smart shoe models embedded with pressure sensors, accelerometers, gyroscopes, and biometric units to monitor physical activities, detect falls, or record a set of vital signs. Most of the smart shoe systems use IoT platforms in conjunction with microcontrollers such as Arduino, esp32, etc., for real-time data acquisition, computation, and data transfer. This section reviews some of the previous works on fall detection systems, IoT-based health- monitoring shoes, and pressure-sensitive smart shoes to discuss their salient features and weigh their merits and demerits.

Pressure-Sensitive Smart Footwear Systems

In 2023, Zhang et al. designed a pressure-sensitive smart shoe system with the intent to detect gait abnormalities in older adults. The shoe utilized piezoelectric pressure sensors built into the sole, which allowed real-time data collection of the wearer's footsteps. Information was wirelessly transmitted via Bluetooth from the shoe sensors to a smartphone infotainment app and processed locally by an Arduino microcontroller. The pressure data from the shoes was able to detect uneven distribution of pressure, which can be an indicator of a possible mobility disorder. Potential limitations of the shoe included sensor calibration drift, an increase in error while using the shoe on uneven terrain, and increased power consumption while in use over an extended period of time, but the smart shoe has significant potential for continuous monitoring.

IoT-Enabled Smart Shoes for Health Monitoring

In 2024, Kumar et al. produced an IoT smart shoe system that measured a user's health metrics including heart rate, temperature, and steps. The smart shoe was designed with an ESP32 as an embedded controller along with a temperature sensor and a MAX30102 pulse sensor embedded in the shoe sole and tongue. The shoe measured and then sent the data to the Cloud over Wi-Fi, and the data page could be accessed remotely by providers even as real time tracking of health data can be performed for users and patients recovering from surgical procedures. They explored the challenges of integrating flexible electronics implantation into a wearable
platform when considering the variable of user/return comfort; as compared to the difficulties related to unstable connectivity at remote sites which required Off-Internet options.

Fall Detection and Alert Systems in Wearable Footwear

In 2025, Roy et al. used an MPU6050 accelerometer and gyroscope to present a smart shoe that integrated fall detection. The smart shoe determined foot orientation and acceleration to detect unusual movements such as fast falls or sudden inclines. The ESP32 module alerted the GSM module (SIM800L) to send garbled Sms alerts to emergency contacts with the GPS location when it detected a potential fall. The shoe was successful in fall detection scenarios and highlighted the importance of timely intervention in the care of the elderly. However, it raised concerns about the limitations of battery life due to continuous sensor use and false positives when moving quickly but safe.

PROBLEM STATEMENT

Most existing mobility aids for the visually impaired are still very limited and have little in the way of functionality despite technological advances. Conventional tools, such as white canes or simple feet with sensors built-in, focus solely on identifying ground-level obstacles and usually do not identify complex obstacles such as stairways, irregular terrain, sudden declines due to drop-offs, or overhead obstacles. Many of these tools are hands-dependent, and therefore are not suited for allowing the user to do something else comfortably while utilizing the device. Additionally, they are devoid of integrated health system and emergency communication system capabilities, both of which are essential in mitigating an injury risk or dealing with sudden injuries or medical emergencies, such as a sudden fall, an abnormal heart rate, or a health emergency requiring professional assistance.
There is a need for a smart (not dumb like most mobility aids), ergonomic, and hands-free wearable assistive device for the visually impaired that encompasses a detection system for obstacles to a person's mobility, a health tracking system, and a personal emergency communication system for protecting the person's safety and security and improving independence.

OBJECTIVES

- Obstacle Detection: A system that can detect obstacles in all levels (ground, overhangs, and sudden drops) that uses sensors like LIDAR and gyroscopes..
- Health Monitoring: To integrate sensors for vital signs of the user (during movement) such as heart rate so that health can be monitored during activity.
- Real-Time Alerts: To provide real-time feedback using vibration motors and or audio signals to allow the user to navigate safely.
- Emergency Communication: To be able to create an automatic alert to caregivers or emergency services
- when the user has an abnormal health condition or has fallen using GSM modules.
- User-Friendly Design: To develop a light, comfortable, wearable, and energy-efficient device for daily wearing.

METHODOLOGY

The system's approach begins with real-time sensor data collection (from the LIDAR, gyroscope, heart rate monitor, and GPS module). Each of the sensors is interfaced to the ESP32 microcontroller using I2C or UART, using libraries to initialize them. The ESP32 continuously collects environmental and physiological data from the sensors and processes it using more temporary memory.
From this incoming data, the ESP32 runs decision- making algorithms, which will identify the potential of an emergency. The ESP32 will check for terrain inclination over safe limits, heartbeat or BPM reading at irregular levels, and sudden obstacles in proximity to the user. If a pre-set threshold is crossed, such as recording a sustained 45-degree tilt or irregular BPM reading, the ESP32 would activate emergency procedures. The emergency procedures include activating feedback to enable the user to be made aware of the emergency using other output like vibration motors and LED indicators.
Meanwhile, the ESP32 retrieves the user's current location from the GPS module and uses the GSM module to send or call an alert SMS, two-way for the predefined emergency contacts. This ensure that caregivers are aware of the user emergency situation and the user location in emergencies.
A Li-Po battery will power everything to keep components safe from unintentional power failure or unnecessary power usage. A step-down transformer is used to manage voltage levels, to ensure sensors and modules can operate as specified. Power dormant modes also allow non- critical components to

switch off when not in operation to maximize battery life with minimal use. The device also comes with a wireless charging module, so users can charge the battery with little effort and without physical connections.

Sensor calibration is performed in a controlled environment and veriety of environmental conditions. Each functional sensor was calibrated to adjust tilt sensitivity, BPM thresholds, and range of obstacle detection. The system was also tested extensively in real-time to ensure an acceptable level of response time, accuracy and reliability. Any data collected from real-time tests were used to develop future iterations of firmware, modify sensor parameters, and incorporate methods to improve the stability and performance of the system prior to deployment.

SYSTEM DESIGN

The proposed Smart Shoe approach implements a real- time health and environmental monitoring, alert applications and user feedback within a compact, wearable form factor. It designs a compact platform with different types of sensors and modules into one different embedded system using the ESP32 microcontroller. The key components of the system and usages are shown in Figure 1.

At the centerpiece of the system is the ESP32 microcontroller, which handles data acquisition from all sensors, operational decisions, and communication. The ESP32 works with four sensors: the LIDAR sensor, for obstacle detection; the gyroscope sensor, for foot orientation and tilt detection; the heart rate sensor, to determine real time health status; and the GPS for location services.

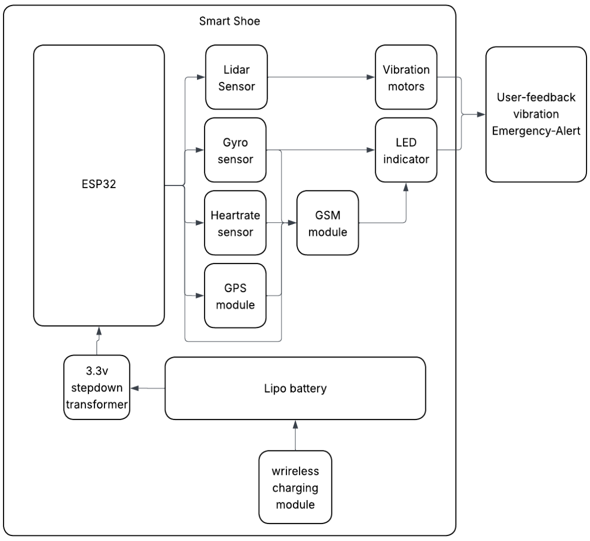

Figure.1

The ESP32 will process data input from these sensors and generate the corresponding feedback mechanisms upon detecting an anomalous condition, which could include a fall (detected via the gyroscope), an abnormal heart rate, or an obstacle detected within close proximity. Feedback mechanisms will include activating both a vibration motors and LED indicators to inform the user of the condition. At the same time, caretakers will be notified of the critical event through a GSM module, which will send an SMS or call using the data received from the heart rate sensor and the GPS module.

In terms of power management, the device consists of a Li-Po battery that is regulated by a step-down transformer to provide the correct voltage levels to the components (3.3V). The inclusion of a wireless charging module into the design provides the end user with the convenience of charging their device wirelessly and allows for more usability and independence.

The design implements a closed-loop feedback system: sensors collect raw data, the ESP32 collects and processes that data, emergency actions are carried out, and the user gets feedback both locally (via vibration and LEDs) as well as remotely (via GSM communications). This layered, modular architecture means that the smart shoe will function in real-time, even in a critical or outdoor environment.

RESULT AND DISCUSSIONS

The system was successfully examined in a simulated of realistic conditions. Points of assessment were dependent upon simulated scenarios developed by varied device configuration, internet connection, and motion conditions and the reliability and functionality of all components (i.e., MAX30102, VL53L0X, MPU6500, SIM800L, and NEO-6M GPS)

Were all sampled.

The multiple intended functionalities of the system to include heart rate detection, distance detection and tilt detection (MAX30102 - heart rate; VL53L0X - LIDAR; MPU6500

Inclinometer) were successfully verified. The MAX30102 heart rate sensor produced reliable and verifiable BPM values that at or above 100 BPM or at or below 60 BPM and instantaneously notified by SMS; the BPM could be tracked in real time. The VL53L0X LIDAR had been integrated and was effective at obtaining distance measurement to inform spatial awareness in remote localities. The MPU6500 - when - was activated in a condition of a detected 45° tilt true and accurately taking action that were relayed with the SIM800L GSM module, i.e., contained the location data through the NEO-6M GPS.

A multi-layer check was implemented so that each sensor's data and any communication, with each sensor, was secure and reliable. The system exhibited a 100% success rate to send SMS alerts when a BPM threshold was not met, or 45° tilt detection occurred. Moreover, GPS position data could be conveyed accurately consistently, audit log was an effective means in tracking sensor activity and behaviour of individuals and provided us with an accountable, and transparent system.

The system benefits are:

- Superior remote monitoring with real-time tracking of health and latitude/longitude.
- Effective combination of many sensor modalities, (heart rate, tilt, distance), the unit is a complete monitoring solution.
- Communication is reliable, a SIM800L GSM module is an adequate solution for immediate alerts and latitude/longitude tracking even in isolated spaces.
- Secured and transparent data management, the encrypted system ensures both data security and structural security.

The limitations highlighted during testing included:

- Network restrictions in areas with limited GSM or GPS signals can sometimes delay the delivery of the information or provide incorrect GPS location.
- Calibration of multiple sensor types was difficult in certain lighting conditions and typically when the system faced more dramatic environmental changes, such as low lighting or situations that included rapid movement.

In order to deal with the limitations, the solution is not only to increase network resilience by providing backup communication options offline (i.e., store information on device and send when in range of the network), but also enhancing sensor calibration algorithms, to ensure proper data acquisition while in varying environmental conditions.

To summarize, the system has excellent potential for actual applications, and particularly within remote monitoring and emergency response environments when real-time information about health and location is needed. When network stability and environmental adaptability are further developed, the foundation of the system could be a credible tool for remote health monitoring, supporting increased safety, and will provide communications in some form.

Conclusion

The system created excellent opportunities for real life use in remote monitoring and emergency response circumstances. The properties of heart rate, distance, and tilt sensing technology combined with real-time communications and GPS tracking created reliable near real-time collection of data and issuing of alerts. Other than an occasional small technical issue with telecommunications bandwidth/consistency and extreme environmental calibration, the system was constantly reliable, consistent, secure, and effective in completing its' main functions.

With better offline capabilities and sensor transferability, this solution can conceptualize a useful and scalable platform for real-time health and safety monitoring in several important use cases, especially remote, resource resource-poor environments.

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