Real-Time Embedded Multi Sensor Alert System for Blind Navigation

G. V. Subrahmanyam[1]; Bhavana K.[2]; Tanusha Lakshmi Naga Devi D.[2]; S. N. S. D. Manjula T.[2]; Hani G.[2]; Sai Sri Ram B.[2.]

[1;2]Department of ECE, Sri Vasavi Engineering College, Tadepalligudem (A.P), India

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Abstract: Safe and independent navigation is still a major challenge for visually impaired individuals, especially in unfamiliar and crowded environments. To overcome this, this paper proposed an embedded real-time warning system for the blind person's navigation using a multi-sensor approach with the ESP32 microcontroller. The system has an ultrasonic sensor for obstacle detection, and a Motion Processing Unit (MPU) for detecting the user's motion and orientation, which further enhances navigation awareness. Collected sensor data is filtered with sensor fusion algorithms to enhance accuracy and minimise false alerts. The system gives the user real time warning about obstacles based on the distance to the obstacles, enabling the user to act fast and move safely. It is powered by a rechargeable battery with a Battery Management System (BMS) to manage the power usage in a safe and efficient manner. An easy control mechanism with a power switch is also provided for the easy control of the system and to save energy when not in use. The design is aimed to be low cost, lightweight and easy to use for everyday application. The system as a whole is designed to increase the safety, confidence and independence of visually impaired users by creating a simple and reliable navigation system.

Keywords: *Blind Navigation, Assistive Technology, Real-Time Alert System, Multi-Sensor System, ESP32 Microcontroller, Ultrasonic Sensor, Motion Processing Unit (MPU), Sensor Fusion, Obstacle Detection, Wearable Device, Low-Cost Design, Energy-Efficient System.*

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I. INTRODUCTION

Navigation is a daily activity of fundamental importance, but can be a major problem for the person who is visually impaired, especially in unfamiliar and crowded locations. Most traditional mobility aids (TMA) like white canes can only sense obstacles within a short distance, and cannot tell the user much about the surroundings [20]. This constraint will impact the user's mobility and safety to move freely and safely, highlighting the importance of advancing assistive technologies.

Intelligent navigation aids have been developed in recent years with the help of the new developments of embedded systems and sensor technologies. To improve mobility for the visually impaired, a number of wearable assistive devices and electronic travel aids have been suggested that can identify obstacles and report to the user in real time [14, 17]. They are designed to enhance situational awareness and minimize the potential for accident occurrence during vessel navigation.

One of the most commonly used sensors in these types of systems is the ultrasonic sensor which is easily installed, very low cost, and provides reliable distance measurement. They are especially good for identifying obstacles in the way of the user. The drawbacks, however, of using a single sensor-based system are that the accuracy and reliability of the system may be compromised in different environments.

To overcome these drawbacks, multiple-sensor approaches have been developed, combining ultrasonic sensors with the motion sensors, such as MPU, to improve system performance [8][12]. The motion sensors are another source of data con-cerning orientation and movement, that adds to understanding of the environment. Moreover, sensor fusion methods allow a successful fusion of the data gathered from several sensors which helps to reduce measurement errors and decrease false alarms [11], [18].

Furthermore, embedded systems can be combined with IoT technologies so that data can be processed in real time and quick responses can be provided; this is essential for assistive navigation applications [4], [13]. The systems are generally portable, energy efficient and cost effective making them applicable to everyday life for the visually impaired [6].

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This work aims at the development of a real-time embedded multi-sensor navigation system based on an ESP32 microcon-troller, an ultrasonic sensor and an MPU sensor. A ultrasonic sensor is used to detect the presence of obstacles and the MPU sensor is used to detect the motion and orientation. The ESP32 collects sensor data and sends out alerts to the user as soon as they are needed. The system is programmed in Embedded C/C++ with Arduino IDE, guaranteeing efficient integration and real-time operation.

The system is powered by a rechargeable battery, making it portable and able to be used over an extended period of time. This project aims to create an assistive navigation system that enhances the safety, independence and mobility of visually impaired people, is light in weight and low cost, and is efficient.

Many problems remain to be solved when it comes to reliability, usability and costs, although great strides have been made in this area. Some current solutions use complex elements like cameras and LiDAR, resulting in higher costs and power usage. This makes them less useful for everyday use, especially in underdeveloped countries.

Table 1 Literature Review

No	Paper Title	Author & Year	Method Used	Future Scope
1	Wi-Fi Enabled Smart Ultra-sonic Glasses for the Visu-ally Blind	Ahmed et al., 2023	Ultrasonic Sensors + Wi-Fi + Embedded System	The system can be improved by increasing sensing range and adding advanced sensors for better detection.
2	Wearable Obstacle Avoidance Electronic Travel Aids: A Review	Xu et al., 2023	Multi-sensor systems (Ultrasonic, Camera, LiDAR, IMU)	Future work can focus on reducing cost and improving real-time performance.
3	Survey on Outdoor Navigation Applications for Visu-ally Impaired	El-Taher et al., 2023	GPS + Smartphone Applications	Can be enhanced by integrating real-time obstacle detection systems.
4	Low-Cost Navigation System for Visually Impaired	Al-Khatib 2020 etal.,	Ultrasonic Sensor + Micro-controller	Can be improved using multi-sensor fusion for better accuracy.
5	Embedded Wearable Navigation using Ultrasonic and IMU	Garcia et al., 2022	Ultrasonic + IMU + Embedded System	Future improvements can focus on reducing complexity and power usage.
6	Smart Cane with Obstacle Detection and Navigation	Mehta et al., 2021	Ultrasonic Sensor + Embedded System	Can be enhanced with long-range detection and better feedback methods.
7	Obstacle Avoidance using Ultrasonic Sensors	Borenstein 1988 etal.,	Ultrasonic Sensor	Can be upgraded using modern sensors and intelligent decision-making.
8	Low-Power Multi-Sensor Fusion System for Blind Assistance	Gupta et al., 2022	Multi-Sensor Fusion	Future work can focus on improving efficiency and reducing processing load.
9	Sensor Fusion-Based Navigation System	Lee et al., 2021	Ultrasonic + IMU	Can be improved using advanced calibration techniques.
10	IoT-Based Smart Assistive System for Visually Im-paired	Hossain et al., 2021	Sensors + IoT	Reducing internet dependency and im-proving offline performance.

II. TECHNICAL CONTRIBUTIONS

The key findings of this work are presented as follows:

- *Real-Time Navigation System*

A real-time navigation system is developed to help the blind or visually impaired to move safely in familiar/ unfamiliar en-vironment. Like existing electronic travel aids [20] the system gives instant feedback to the user, and enhances mobility and independence.

- *Multi-Sensor Integration*

The system proposed consists of an ultrasonic sensor and a motion processing unit (MPU) to improve the detection of obstacles and track the user's movement and orientation. This multi-sensor approach has been proven to enhance navigation performance than single-sensor approaches [8, 12].

- *Sensor Fusion Approach*

Simple sensor fusion method is applied to fuse the data from various sensors. Provides better detection accuracy and less false alarms, as demonstrated in recent multi-sensor fusion studies [11], [18]

- *Efficient ESP32-Based Implementation*

The system is implemented with the help of an ESP32 microcontroller, which allows for fast processing speed, real-time response, and efficient management of sensor data. Assis-tive technologies are typically implemented using embedded systems because of their reliability and performance charac-teristics [6, 13].

- *Energy-Efficient Design*

It is powered by a rechargeable battery that has a Battery Management System (BMS) and a power switch for safe and efficient power usage. For wearable assistive devices, low-power embedded solutions are key [11].

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➤ *Low-Cost and User-Friendly Design*

The system is designed to be user friendly, lightweight and inexpensive. This can be used by visually impaired people everyday, which is an important requirement for assistive technologies that are affordable [6]. Aside from the above contributions, the system is designed in a way that enables the continuous real-time monitoring of the system, enabling users to navigate safely without interruption [20].

III. METHODOLOGY

The system employs an ESP32 microcontroller and ultra-sonic sensor with MPU sensor for obstacle detection and motion tracking. Once the ESP32 is initialized, they will be reading data from both sensors, performing simple sensor fusion to achieve higher accuracy.

It checks the distance measured against a pre-defined distance. When an obstacle is detected, an alert is generated, otherwise the system is continuously monitoring. The process is recursive, and is operated in real time.

➤ *Flowchart*

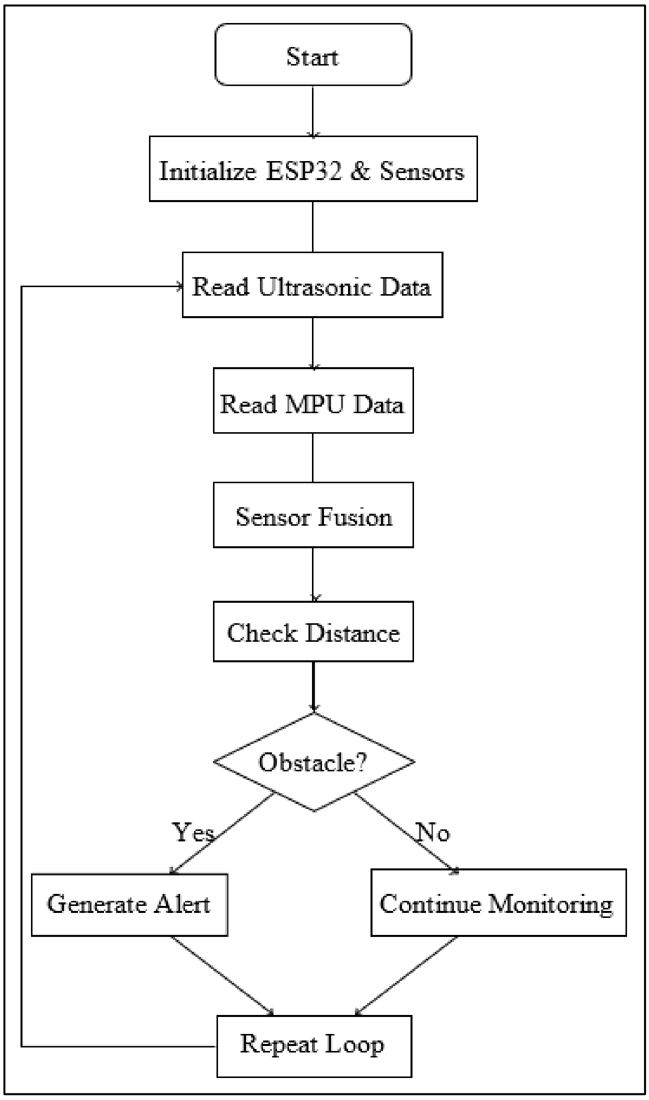

Fig 1 Flowchart of Proposed System

IV. METHODOLOGY–DETAILED BLOCK EXPLANATION

➤ *Start*

When power is applied via a rechargeable battery, then the system turns on. The ESP32 microcontroller turns on, loads program into the microcontroller's memory, and gets ready to run the instructions. It is noteworthy for embedded assistive devices because they are meant to be run nonstop without the user's involvement.

➤ *Initialize ESP32 and Sensors*

In this step, all the connected components, such as ultrasonic sensor and MPU sensor are configured by ESP32. The trigger pin and echo pin of the ultrasonic sensor are defined and the communication to the MPU sensor is made via I2C protocol. When properly initialized, all sensors are calibrated and thus supply accurate and reliable data during operation.

➤ *Read Ultrasonic Sensor Data*

The ultrasonic sensor is used to detect the distance to obsta-cles in its range by sending out ultrasonic waves and measuring the time it takes for them to return. The system measures the distance between the user and the object using the speed of sound. This step can be used to get the information about obstacles in the environment in real time.

➤ *Read MPU Sensor Data*

The MPU sensor measures various forms of motion includ-ing acceleration and angular velocity. This assists the system in comprehending.

The direction, orientation and movement of the user changes Once the system can determine if the user is moving or stationary, it can inform the user of the "moving" state and make appropriate decisions.

➤ *Process Sensor Data (Sensor Fusion)*

In this stage, the ESP32 combines the data obtained from the ultrasonic and MPU sensors. This is called sensor fusion and enhances accuracy and minimizes false alerts. Using several sensors in combination, the system can Make better decisions in various situations.

➤ *Check Distance Threshold*

The processed data is then compared to a threshold value which is usually set at about 100 cm. This comparison is useful for the system to decide if an obstacle is in the way and needs to be addressed. The threshold-based checking provides fast and effective real-time decision making.

➤ *Decision: Obstacle Detected*

The system determines whether the distance measured is below the threshold. If the distance is equal to or greater than threshold, then no obstacle is detected nearby, and the system continues monitoring. When the distance is below the set threshold, the system detects the obstacle and continues to determine the distance from the obstacle.

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- *Very Close Distance (¡ 20 cm)*

When a distance less than 20cm is detected, then the system recognizes that there is a very close obstacle. In such an instance a continuous buzzer sound will be produced to alert the immediate danger. This is a strong alert that assists the user to respond immediately and prevent collisions.

- *Medium Distance (20–50 cm)*

When these distances are from 20cm to 50cm, the system beeps quickly. This means that the obstacle is close by and is coming towards them, which means that the player has enough time to move around it.

- *Far Distance (50–100 cm)*

A slow beep sound will be emitted by the system if the distance is in the range of 50cm to 100cm. This is an early warning indicator that lets the user know of a far away obstacle in order to prepare for it ahead of time.

- *Continue Monitoring*

If no obstacle is detected or after generating the appropri-ate alert, the system continues to monitor the environment. Sensors are used continuously to detect any changes of sur-roundings, ensuring user safety.

- *Repeat Loop*

The whole process is repeated in a loop. The ESP32 con-tinuously receives data from the sensors, processes it, checks the conditions, and stores the results and instantaneously up-dates alerts. It provides a looping operation, which guarantees continuous flight and navigation support.

V. EXPERIMENTAL SETUP

The experimental setup is made up of an ESP32 micro-controller, an ultrasonic sensor, a MPU sensor and a buzzer. It is powered by a rechargeable battery, so it's portable. The ultrasonic sensor is mounted in front for the purpose of object detection, the MPU sensor is used for the purpose of the detection of movement and orientation. Both sensors are connected to the ESP32, which reads their values, tracks them and activates the buzzer to trigger alerts. All parts are securely connected for accurate readings. The system is tested under various environments to ensure that it performs well in identifying obstacles and giving timely warnings.

Fig 2 Hardware Assembly of the Proposed System

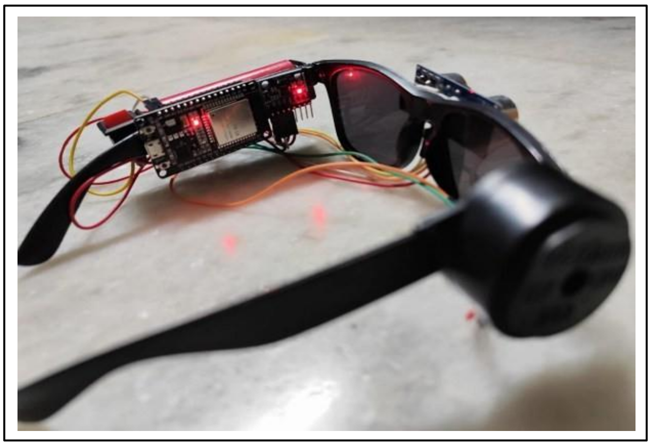

Fig 3 Experimental Setup for Real-Time Obstacle Detection System

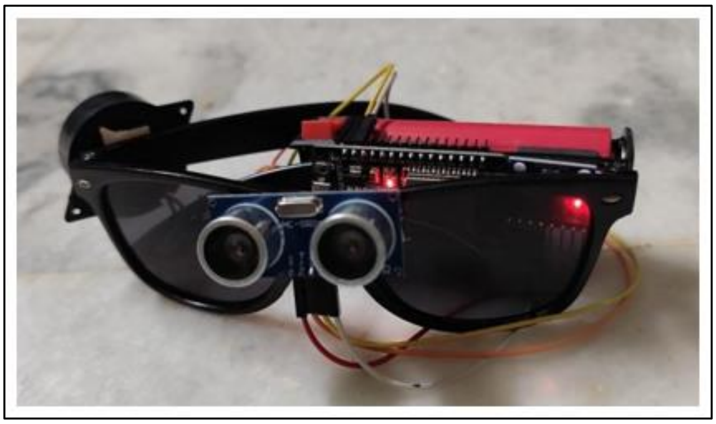

Fig 4 Experimental Hardware Arrangement

VI. RESULTS AND DISCUSSION

The output of the proposed system is visibly shown in the realtime picture given below where the distance and falls detection messages are continuously presented through serial monitor. The user determines the distance to objects and people in the vicinity of the ultrasonic sensor. If the distance is large (e.g., 188 cm), this means that there is no obstruction, and the system is in a normal state.

As the inter-distance of the system decreases to very small values (e.g., 1-10 cm), the system will sense the presence of a nearby object and switch on the buzzer for warning the user. The intensity of the alert depends on the distance, and makes it easier for the user to understand how close the obstacle is. Meanwhile, the MPU sensor tracks the direction of move-ment and is able to sense a sudden change in orientation or acceleration. If this unusual movement is detected, the system alerts the user to this with the message "Fall Detected."

If the obstacle and the fall are detected at the same time then the system will produce a strong alert in case of a critical scenario ("Obstacle + Fall Detected → BUZZER ON": This means that there is immediate danger.)

The result shows that the combination of ultrasonic and MPU sensor functions efficiently in the system. There are advantages of using multisensor fusion as it enhances the accuracy, minimizes the number of errors and offers reliable alerts in real-time, thus increasing the safety and navigation capability of a visually impaired user cost-effective in order to make it accessible to more people. Additional sensors can be integrated with motion sensors (MPU/IMU) to enhance navigation and movement tracking. Feedback systems can be enhanced by adding voice alerts along with buzzer or vibration. Lastly, the system is capable of working effectively both indoors and outdoors. Integration of motion sensors (MPU/IMU) with additional sensors can improve navigation and movement tracking. Feedback systems can be enhanced by adding voice alerts along with buzzer or vibration. Finally, the system can be extended to work effectively in both indoor and outdoor environments.

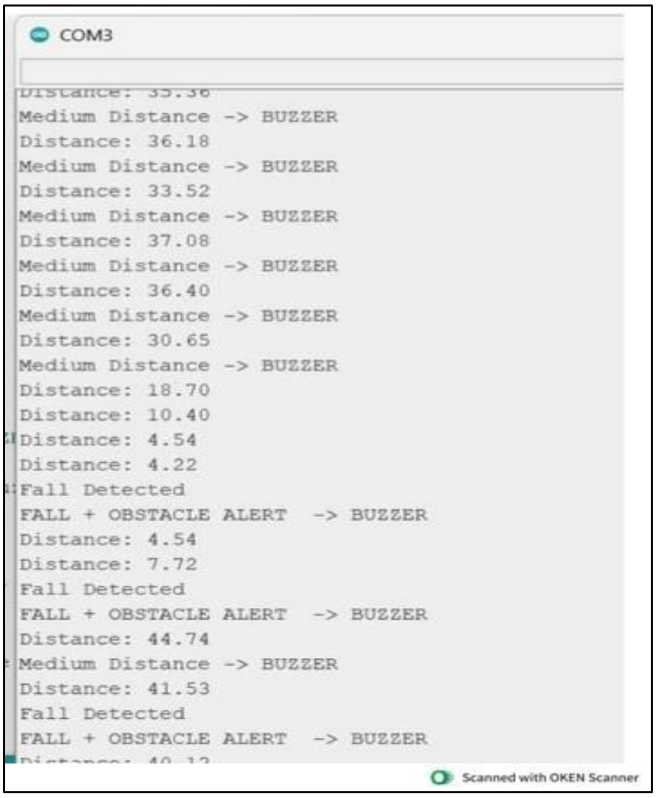

Fig 5 Real-Time Serial Output Showing Obstacle Detection Levels and Fall Alerts with Buzzer Activation.

VII. CONCLUSION AND FUTURE SCOPE

The proposed system is based on an ESP32 microcontroller, an ultrasonic sensor, and an MPU sensor to detect obstacles and monitor the movement. The system is real-time and constantly reads the sensor data and provides alerts depending on the distance of the obstacles. Multi level alert system (continuous, fast and slow beep) helps the user to know the distance of the obstacles easily. The system works by using both sensors' data to capture a more complete picture and decrease detection errors. Overall, the system is simple and inexpensive for assisting navigation, and effective. It improves user safety by making it more secure to operate timely alerts and increasing awareness of the surroundings.

Future improvements can be directed towards improving the performance and usability of the system. Obstacle detection can be improved:

Through the use of advanced vision based techniques that involve cameras and deep learning for improved object recognition. Possibility of creating more advanced wearable navigations to make the system user-friendly and comfortable for blind users. Further, multi-sensor fusion techniques could be developed to enhance the accuracy and decrease the number of detection errors. The use of systems based on the Internet of Things (IoT) can help with real-time processing and decision-making. The system can be designed to make the system more.

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