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AI-Enabled Sensor-Fusion Smart Shoe for Navigation Assistance to Visually Impaired People: A Proposed Framework

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Abstract - *Safe and independent mobility remains challenging for people with visual impairment when obstacles, uneven surfaces, and wet areas are difficult to identify during walking. This paper presents a proposed footwear-based assistive framework that supplements, rather than replaces, established mobility aids. An ESP32 microcontroller is proposed as the central controller for integrating three directionally placed ultrasonic sensors, optional wet-surface sensing, local audio and vibration alerts, and optional location and remote-monitoring functions. The core operating concept is to acquire distance readings, validate them, compare them with configurable warning thresholds, and generate directional feedback. A GPS receiver may provide outdoor coordinates, while Wi-Fi, cellular communication, and an IoT dashboard may support caregiver notifications and status monitoring when configured and available. The architecture also depicts optional motion, temperature, and pulse-oximetry modules; these are not treated as confirmed core functions unless physically integrated and tested. A review of related smart footwear and wearable navigation approaches is used to identify the need for a modular design that prioritizes local obstacle alerts independently of cloud connectivity. The paper details the proposed architecture, component roles, working procedure, benefits, constraints, and an evaluation plan. Since experimental validation has not been reported, no detection accuracy, response-time, battery-life, or user-safety improvement is claimed.*

Keywords - Smart shoe, assistive technology, Internet of Things, ESP32, ultrasonic sensing, obstacle detection, GPS, haptic feedback.

1. INTRODUCTION

Safe and independent navigation is a continuing challenge for people with visual impairment, particularly in unfamiliar, crowded, or changing environments. Obstacles, changes in surface level, and wet areas may be difficult to recognize early enough to avoid them. Conventional mobility aids, including the white cane and guide dog, remain important; however, their capabilities are bounded by their physical design and the information they can convey. Wearable assistive systems have therefore explored combinations of sensors, embedded controllers, wireless communication, and audio or tactile feedback to provide supplementary environmental information [1], [3], [11].

Smart footwear is a potential wearable form because it places sensors near the walking path while leaving the user's hands available. The framework considered here uses an ESP32 controller and multiple ultrasonic sensors directed toward selected regions around the shoe. Sensor readings are evaluated locally, and the controller can activate spoken warnings and vibration alerts. GPS and communication modules are proposed as supplementary functions for location sharing and emergency notification, subject to signal availability and implementation.

The term "AI-enabled" in the paper title describes the intended scope for future intelligent extensions. The presently described core logic is sensor-based threshold evaluation; no trained AI model, dataset, or validated AI classification result is specified in the source paper. This distinction is retained to avoid overstating the current technical maturity.

2. PROBLEM STATEMENT AND RESEARCH MOTIVATION

Existing assistive devices and wearable navigation prototypes demonstrate the value of obstacle sensing and user alerts. Nevertheless, a user may need supplementary awareness of obstacles from more than one direction, hazards close to the ground, and location information that can be shared during an emergency. A single feedback channel may also be less useful in noisy environments or when the user cannot continuously listen to audio instructions.

The proposed work addresses the design problem of combining directional proximity sensing with two complementary local feedback modes in a shoe-mounted platform, while keeping remote monitoring optional. The principal design requirements are:

- Directional obstacle awareness through left-, right-, and lower/front-facing distance sensors.
- Immediate, non-visual feedback through audible prompts and vibration.
- Wearable, hands-free operation with sensing components positioned near the walking path.
- Optional location-based support through GPS and a cellular or Internet connection.

- Modular monitoring that does not make local obstacle warnings dependent on cloud availability.

The system is intended to supplement established mobility practices. Its practical usefulness will depend on sensor placement, threshold calibration, feedback intelligibility, power management, mechanical comfort, and testing in representative environments.

3. LITERATURE REVIEW / RELATED WORK

Research on assistive navigation includes smart shoes, sensor-based warning systems, wearable devices, and vision-based aids. Joyce et al. described an Internet of Things (IoT)-enabled smart shoe using ultrasonic and infrared sensing, an Arduino Nano controller, Bluetooth communication, and audio feedback [1]. Sivalakshmi et al. explored a rechargeable smart shoe with fall-detection and safety features, illustrating the inclusion of personal-safety functions in footwear [2]. Ikram et al. presented an IoT sensor-based obstacle detection and warning system for visually impaired users [3], while Gupta et al. discussed IoT-based intelligent shoes for visual assistance [4]. Senthil Kumar et al. investigated AI optimization and IoT integration in smart footwear [7]. Bari et al. focused on a low-cost smart-shoe approach for obstacle detection and location monitoring for deafblind users [8].

Other studies investigate wearable forms beyond footwear. Shwetha et al. studied a smart pendant for safe navigation [5], and Vigneshwari et al. described an assistive stick incorporating GPS and heart-rate monitoring [6]. Hersh reviewed wearable travel aids for blind and partially sighted people and discussed design and usability considerations [11]. IoT-based smart-shoe approaches were also reported by Almomani et al. [9] and Santhi Priya et al. [10].

Vision-based approaches provide a different design direction. Loresco et al. investigated indoor navigation glasses using deep learning and audio guidance [12]. Chen et al. presented a wearable assistive system combining object detection, distance measurement, and tactile presentation [13]. These studies illustrate alternative sensing and feedback strategies. Camera-based approaches can provide semantic information about objects and scenes, but may require additional image-processing resources. The proposed shoe instead emphasizes distance sensing and local embedded processing in its core configuration.

4. RESEARCH GAP AND COMPARATIVE ANALYSIS

The reviewed approaches cover obstacle detection, audio warnings, fall-related functions, GPS, tactile presentation, and vision-based recognition. The design opportunity addressed in this paper is a modular footwear architecture that combines multiple directional proximity inputs with audio-haptic feedback and treats remote monitoring as an optional extension. The key distinction is architectural integration, not a demonstrated performance advantage over prior systems.

Ultrasonic sensing can estimate the distance to nearby objects, but readings depend on target shape, angle, material, sensor orientation, and environmental conditions. GPS can provide outdoor coordinates but may be unreliable indoors or where satellite reception is weak. Cellular alerts require network coverage, while cloud monitoring requires an Internet connection. Accordingly, local obstacle warning is separated from optional remote services so that the intended local alert path does not depend on an active cloud connection.

5. PROPOSED SYSTEM ARCHITECTURE

The proposed architecture is organized around an ESP32 dual-core microcontroller. The input layer collects distance measurements and, when available, location and optional monitoring data. The controller validates incoming readings, evaluates configured conditions, and generates output signals. A voice output device and vibration motor provide local feedback. GPS and communication modules may support location sharing, emergency alerts, and remote monitoring when the relevant hardware, firmware, and services are configured.

The architecture has five functional layers: (i) input devices, (ii) processing and control, (iii) power supply, (iv) output devices, and (v) IoT and remote monitoring. Three ultrasonic sensors are assigned to left, right, and bottom/front detection positions. The diagram also depicts an ADXL345 accelerometer, DS18B20 temperature sensor, and MAX30100 pulse oximeter. These are optional extensions in the source description and must not be represented as implemented unless connected and tested. The water sensor mentioned in the abstract should likewise be included in the final hardware description only if it is part of the actual build.

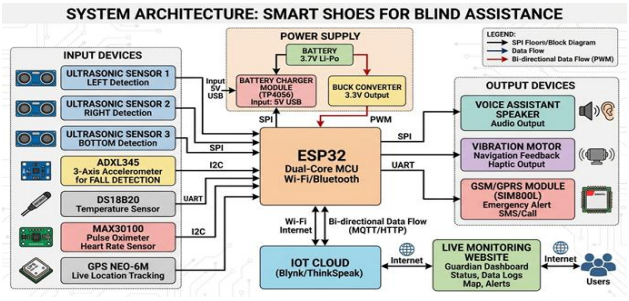

Fig. 1. System architecture of the smart shoe for visually impaired assistance. Optional sensors and communication functions are retained only if integrated and tested.

Table 1. Comparative overview of selected related approaches and the proposed framework

Approach	Sensing / input	Processing / feedback	Main focus and distinction
Joyce et al. (2025) [1]	Ultrasonic and infrared	Arduino Nano; Bluetooth; audio via earphones	IoT smart shoe and obstacle alerts; proposed framework uses ESP32 and multiple directional distance inputs.
Sivalakshmi et al. (2026) [2]	Shoe-mounted safety sensing	Rechargeable footwear system; safety alerts	Fall detection and safety; proposed framework emphasizes directional obstacle awareness and optional location support.
Ikram et al. (2025) [3]	IoT sensors	IoT-based processing and warning	Obstacle detection; proposed framework combines local audio-haptic alerts in a shoe-oriented architecture.
Bari et al. (2025) [8]	Obstacle and location sensing	Connected monitoring; alerts/location support	Low-cost detection and location monitoring; proposed framework combines multi-direction inputs and ESP32-controlled feedback.
Loresco et al. (2024) [12]	Camera / visual input	Deep learning; Edge TPU; audio guidance	Indoor navigation glasses; proposed core shoe design uses camera-free distance sensing.
Proposed framework	Three ultrasonic sensors; GPS and optional monitoring sensors	ESP32; Wi-Fi/GSM/IoT if configured; voice and vibration	Wearable obstacle alerts and optional location support; performance remains to be experimentally evaluated.

6. HARDWARE AND SOFTWARE REQUIREMENTS

The following components are identified in the source architecture. Their inclusion status must be confirmed against the physical prototype before the manuscript is submitted.

Ultrasonic sensors: Three units are proposed for left, right, and lower/front detection. Each measures distance by transmitting an ultrasonic pulse and measuring the echo return time. Placement and threshold calibration affect detection reliability.

ESP32 microcontroller: Acts as the central controller and coordinates sensor acquisition, threshold evaluation, alert activation, and supported communication. The exact pin assignment and interfaces depend on the final circuit.

Water sensor: Wet-surface detection is mentioned in the source abstract but is not shown in the supplied architecture diagram. The sensor model, placement, calibration, and implementation status must be confirmed.

GPS NEO-6M: Can obtain geographical coordinates from satellite signals for location display or emergency messages. A valid fix and suitable antenna placement are required; indoor performance may be limited.

3.7 V Li-Po battery, TP4056 charger, and buck converter: The battery supplies portable power, the charging module manages charging for a compatible single-cell battery, and the converter provides a regulated rail. The power design must meet each module's voltage and current requirements.

Voice assistant / speaker and vibration motor: Provide audible and tactile warnings. The final build must specify the audio hardware and validate that alert patterns are distinguishable and understandable.

SIM800L GSM/GPRS module: May send SMS messages or place calls to a designated caregiver. Operation depends on a valid SIM, network availability, suitable power delivery, and configured firmware.

IoT platform and monitoring website: Blynk or ThingSpeak are identified as possible platforms. Wi-Fi data transfer may use MQTT or HTTP depending on the selected implementation. A dashboard may display available status, logs, location, and alerts.

Optional ADXL345, DS18B20, and MAX30100: These modules can respectively provide acceleration, temperature, and pulse-oximetry data. They are optional monitoring extensions, not confirmed core navigation functions in the source paper.

Software: ESP32 firmware for sensor acquisition, validation, threshold logic, and output control; optional Wi-Fi/cellular communication code; and dashboard software if remote monitoring is implemented. The source does not specify a final firmware language, development environment, or deployed cloud configuration.

7. SYSTEM METHODOLOGY AND WORKING PROCEDURE

The methodology describes the intended sequence of operations and the role of each component. The system block diagram is shown in Fig. 1.

7.1 Input acquisition

The three ultrasonic sensors acquire distance readings from their configured directions. Each sensor transmits an ultrasonic pulse and measures the time required for the reflected signal to return. The ESP32 converts the measured time into a distance estimate. Readings should be checked for validity, and sensor placement and warning thresholds should be calibrated for the intended mounting geometry. GPS data are acquired when a valid satellite fix is available. Optional monitoring sensors are read only if included in the assembled system.

7.2 Processing and control

The ESP32 receives sensor readings through the interfaces supported by the selected modules, such as digital input/output, I^2C, or UART. Firmware is intended to validate or filter the readings, compare distance values with predefined thresholds, and determine whether a warning condition is present. The exact threshold values, filtering method, sampling interval, and direction-prioritization logic are not specified in the source and require implementation-level definition and testing.

7.3 Local feedback

When the programmed warning condition is met, the controller activates an audible message and/or vibration motor. Different vibration patterns may be assigned to different directions, provided that the patterns are tested for clarity and do not create ambiguity. The final implementation must identify whether audio is delivered through a speaker, Bluetooth headset, or another audio module.

7.4 Optional location and IoT functions

If GPS and GSM functions are configured, location information may be sent to a designated caregiver during an emergency. The ESP32 may also transmit selected sensor values, device status, and location data over Wi-Fi to an IoT service such as Blynk or ThingSpeak. A monitoring website may display available status information, data logs, map location, and alerts to authorized users. These remote functions are supplementary and should not be required for local obstacle alerts.

7.5 Overall working procedure

- The ultrasonic sensors acquire distance readings from the configured directions; the GPS receiver obtains location data when available.
- The ESP32 receives the readings and checks whether they are valid.
- The controller compares distance values with predefined thresholds to identify nearby obstacles.
- Based on the detected direction and programmed logic, the controller selects an audible warning and/or vibration pattern.
- If GPS and GSM functions are configured, location information can be sent to a designated caregiver during an emergency.
- Selected device data may be transmitted to the IoT cloud and displayed on the monitoring website.
- The battery, charging module, and voltage regulator provide and manage power for portable operation.

This workflow represents the intended design. Detection accuracy, response delay, communication reliability, battery duration, comfort, and usability must be measured experimentally before quantitative performance or safety claims can be made.

8. ADVANTAGES AND LIMITATIONS

8.1 Design-level advantages

- Hands-free assistance: sensing and alert functions are integrated into footwear.
- Multiple sensing directions: separate ultrasonic units can monitor selected left, right, and lower/front regions.
- Dual feedback: audio and vibration provide complementary ways to notify the user.
- Expandable platform: the ESP32 provides interfaces for compatible sensors and communication modules.
- Optional remote assistance: GPS, GSM, Wi-Fi, and cloud services can support location or status sharing when implemented.
- Camera-free core: the basic obstacle-warning approach can operate using distance measurements rather than continuous camera input.

8.2 Limitations and risks

- Ultrasonic readings can be affected by object angle, surface material, shape, environmental conditions, and sensor placement; some objects may be missed or measured inconsistently.

- Distance sensing alone does not identify object categories or provide semantic scene descriptions comparable to a vision-based system.
- GPS reception may be poor indoors; cellular and cloud functions depend on network coverage, connectivity, and service configuration.
- Battery capacity, total power consumption, charging safety, weight, enclosure protection, and footwear comfort have not been quantified.
- Audio and vibration patterns may be misunderstood unless designed and evaluated with intended users.
- No prototype test results, detection accuracy, latency, battery-life measurements, clinical evaluation, or user study are reported in the source paper. The system must not be treated as a replacement for a white cane or guide dog.

9. APPLICATIONS

Subject to implementation and validation, the proposed framework may be considered for supplementary obstacle awareness during indoor or outdoor walking, directional alerts near the user's feet, and optional caregiver location notifications during emergencies. The modular architecture may also serve as an educational or research platform for studying wearable sensing, embedded control, and assistive human–machine feedback. These are potential application areas rather than demonstrated deployment outcomes.

10. FUTURE SCOPE

Future work should begin with completing and documenting the core hardware build, including the exact sensor models, pin assignments, power budget, audio hardware, and enclosure design. The firmware should define sampling intervals, filtering, threshold calibration, and a clear priority policy when multiple sensors detect hazards simultaneously. Controlled experiments should then measure detection performance across object types, distances, angles, walking speeds, and environmental conditions. Response latency, false alarms, missed detections, battery life, connectivity reliability, and user comfort should be evaluated and reported transparently.

After the core system is validated, an AI-based hazard-classification module could be investigated as an optional extension. Such work would require a documented dataset, model selection, resource and energy analysis, and comparison against the baseline threshold-based approach. Additional sensors such as the accelerometer, temperature sensor, pulse oximeter, or water detector should be integrated only where their intended use is justified and their outputs can be validated. User-centred evaluation with appropriate ethical approval and accessibility expertise will be essential before any safety or independence claims are made.

11. CONCLUSION

This paper has presented a proposed sensor-fusion smart-shoe framework intended to provide supplementary navigation assistance to people with visual impairment. The design centres on an ESP32 controller, three directionally placed ultrasonic sensors, and two local feedback modes: audio and vibration. GPS, cellular communication, and IoT monitoring are presented as optional functions for location sharing and caregiver awareness. The architecture also identifies additional monitoring sensors as optional extensions rather than confirmed core features.

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