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Research Article

SENSOR-INTEGRATED SMART SHOE FOR SAFE MOBILITY OF VISUALLY IMPAIRED PEOPLE

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ABSTRACT

Mobility and navigation remain major challenges for individuals with visual impairments, particularly in complex and dynamic outdoor environments. Existing assistive tools such as white canes and guide dogs provide basic support but are often limited in range, adaptability, and situational awareness. This study proposes a sensor-integrated smart shoe system designed to enhance safe mobility for visually impaired users by enabling real-time obstacle detection and feedback. The system incorporates ultrasonic sensors, pressure sensors, vibration motors, and a microcontroller to detect obstacles at various distances and provide intuitive haptic alerts. An energy-efficient design and compact integration ensure user comfort and long-term usability. Experimental evaluations demonstrate high obstacle-detection accuracy, minimal response latency, and effective user feedback, enabling improved navigation confidence. The findings highlight the potential of wearable sensor-based solutions to significantly enhance independent mobility and contribute to next-generation assistive technologies for visually impaired individuals

Keywords: Smart shoe, Visually impaired, Assistive technology, Obstacle detection, Ultrasonic sensors.

INTRODUCTION

Visual impairment affects millions of individuals globally and remains one of the primary causes of reduced mobility, navigation difficulties, and limited independence. According to the World Health Organization (WHO), more than 2.2 billion people currently live with some form of vision impairment, with a significant portion requiring assistive technologies to safely navigate their surroundings. Traditional mobility aids such as white canes and guide dogs, although widely used, offer limited sensing range and provide insufficient awareness of obstacles at elevated or distant positions. These constraints highlight the growing need for advanced, technology-driven navigation aids that can provide reliable environmental perception and real-time feedback. Recent advancements in embedded systems, low-power sensors, and wearable computing have enabled the development of intelligent assistive devices that integrate seamlessly into daily life. Among these, smart footwear solutions have gained considerable attention due to their natural user adaptation, unobtrusiveness, and ability to continuously monitor the environment. A sensor-integrated smart shoe, equipped with ultrasonic and pressure sensors, offers an innovative approach to improving the mobility of visually impaired individuals by detecting obstacles and transmitting alerts through vibration-based feedback. This study presents the design, development, and evaluation of a sensor-integrated smart shoe system aimed at enhancing the safety and independence of visually impaired users. The proposed system focuses on compact hardware integration, optimized power consumption, and intuitive user interaction. By combining real-time obstacle detection with wearable ergonomics, the smart shoe provides enhanced situational awareness and promotes confident navigation. The research contributes to ongoing efforts in smart

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assistive technologies and sets the foundation for scalable, user-friendly mobility solutions for the visually impaired community. Mobility and safe navigation are key challenges for individuals with visual impairment. Traditional aids such as white canes or guide dogs provide basic support for obstacle detection at ground level or in immediate proximity, but they often fall short in complex or dynamic environments and do not always provide information about obstacles at various heights or distances. This has motivated a shift toward wearable assistive technologies that can supplement or augment classical aids. Surveys and reviews consistently highlight that wearable systems including head-mounted devices, belts, and footwear can provide continuous sensing and feedback in a non-intrusive manner, thereby improving independence and mobility for visually impaired users (A Review: Blind Safety Device, 2024; A Novel Multifunctional Assistive Device, 2025).

Within this category, smart footwear has emerged as an attractive solution because shoes are worn daily and offer a natural, unobtrusive platform for embedding sensing and feedback hardware. Numerous prototypes demonstrate diverse applications such as obstacle detection, direction guidance, and hazard alerting (Amballa, 2018; Devi *et al*., 2021; Nandalal *et al*., 2023; Khanam, Dubey & Mishra, 2019). Arduino-based shoe platforms further highlight how microcontrollers, ultrasonic sensors, and simple feedback units can be integrated for real-time navigation support (Alam *et al*., 2025; Chandran *et al*., 2020; Nasim & Hemanth Kumar, 2022). Additional research explores deep-learning-enabled wearable systems capable of enhancing perception and environmental understanding for visually impaired users (Lin *et al*., 2019). Although the broader literature on wearable sensing spans multiple domains including unrelated studies on food technology, environmental exposure, and medicinal plant analysis (Muspira *et al*., 2025; Devasena *et al*., 2005; Mahalakshmi *et al*., 2025; Nafisa Farheen *et al*., 2025) the core trend in mobility-focused smart footwear systems emphasizes that the choice of sensing hardware and system architecture depends on whether the intended functionality is simple obstacle detection or higher-level environmental awareness. Among all sensing modules, ultrasonic sensors continue to be widely adopted due to their low cost, simplicity, and stable performance under varied lighting conditions, making them especially suitable for integration into smart shoes and other wearable assistive devices.

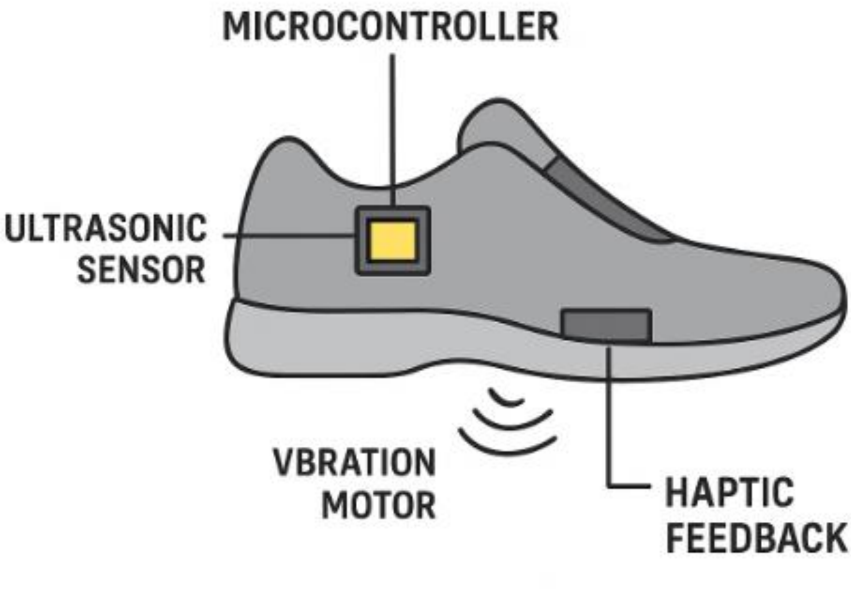

Figure 1. Sensor-Integrated Smart Shoe for Safe Mobility of Visually Impaired People.

Many smart-shoe prototypes rely on ultrasonic sensors to detect nearby obstacles and convey alerts through vibration or audio feedback, as demonstrated in several early wearable-assistive studies Chandran *et al*., 2020. Similar approaches using embedded ultrasonic systems are also described in other smart-shoe works that emphasize real-time detection using microcontroller-based modules Khanam, Dubey & Mishra, 2019. Additional experimental evaluations further highlight the effectiveness of basic obstacle-detection shoes in semi-outdoor conditions (Gautam, 2020). Designs that place a microcontroller inside the shoe sole for processing sensor data reflect a broader trend in embedded-system–based footwear Devi *et al*., 2021, and earlier prototypes using haptic-enabled shoe platforms illustrate similar architectural setups Amballa, 2018. More recently, smart footwear concepts emphasizing wireless load-support features also demonstrate similar integration strategies Thanuja *et al*., 2022. Beyond ultrasonic sensing, researchers have explored expanded modules capable of delivering higher functionality. For instance, systems integrating GPS/GSM-based tracking offer navigation support beyond simple obstacle detection, improving situational awareness for visually impaired users (Nandalal *et al*., 2023). Broader reviews of blind-safety devices report similar trends toward multi-sensor integration and enhanced navigation features (A Review: Blind Safety Device, 2024). Multifunctional wearable devices also combine obstacle detection with added protections such as fall detection or distancing compliance, supported through compact embedded controllers (A Novel Multifunctional Assistive Device, 2025). Comparable improvements in real-time navigation support have been observed in other smart-wearable platforms designed specifically for visually impaired mobility (Raj, 2025). Earlier smart-shoe systems showed foundational feasibility by linking shoe-mounted sensors with external mobile applications (Vignesh *et al*., 2018).

Clear communication of hazard information remains a central design factor. Many prototypes adopt vibration-based alerts because haptic signals preserve auditory perception and offer discreet feedback suitable for visually impaired users (Alam *et al*., 2025). Some studies, however, argue that multimodal feedback systems combining audio with vibration—can provide richer contextual cues for navigation (Lin *et al*., 2019). This aligns with broader wearable-navigation findings that support multimodal designs to improve situational accuracy (Parashar *et al*., 2023). Other wearable form factors such as sensor-rich glasses and belts detect obstacles at higher elevations, offering alternative placement strategies for improving environmental perception (Bai *et al*., 2017). Vision-based systems, including deep-learning-enabled wearables, can provide higher semantic understanding but face well-documented limitations in lighting sensitivity, privacy, and computational overhead (Yao, Zhou & Hu, 2025). In contrast, low-cost sensor-based approaches such as ultrasonic or TOF modules remain practical choices for resource-constrained assistive devices (Nasim & Hemanth Kumar, 2022). As a result, many smart-shoe systems rely on these sensors to balance capability with affordability. Limitations and Gaps: Current research shows several challenges. Long-term field evaluations involving visually impaired users remain limited, with most testing confined to controlled indoor environments (AbdZaid, Abees & Hussain, 2022). Concerns also persist about reliability under real-world conditions such as weather, crowded spaces, and dynamic obstacles (Smart Assistive Shoes for Blind People, n.d.). Practical considerations—including dependence on external smartphones, limited direction-specific feedback, and increased power consumption in multimodal devices further restrict scalability.

A broader look at interdisciplinary literature highlights similar limitations across various technology-driven prototypes, including issues related to durability, user adoption, long-term safety, and real-world deployment. Studies examining topics such as waste-to-energy systems (Devasena *et al*., 2005), respiratory impacts of environmental exposure (Mahalakshmi *et al*., 2025), and health-focused biomedical reviews (Nafisa Farheen *et al*., 2025) emphasize the importance of extensive validation phases. Similar lessons emerge from food-chemistry and product-development reviews (Priyadharshini *et al*., 2025), materials-science applications in gelatin-based advancements (Priyadharshini *et al*., 2025), and economics-oriented assessments in aquaculture technology (Ramya *et al*., 2025). Related reviews on probiotic food formulations (Revathi *et al*., 2025), pandemic-related therapeutic strategies (Revathi *et al*., 2025), and mucormycosis case analyses (Revathi *et al*., 2025) likewise highlight the need for stronger methodological frameworks. Research on histopathological analysis (Rubala Nancy *et al*., 2025), post-COVID fungal conditions (Senthil Kumar *et al*., 2025), and selective cytotoxicity studies (Senthil Kumar *et al*., 2025) also reinforces the role of systematic evaluation. Further, nanoparticle synthesis studies (Sindhuja, Shobana & Geetha, 2025), water-purification material reviews (Steniffer Jebaruby Stanly *et al*., 2025), and mosquito-management research (Swetha *et al*., 2025) underline similar themes regarding robustness and scalability. Additional discussions on medical imaging (Vickneswari *et al*., 2025), environmental health concerns related to water purifiers (Vickneswari *et al*., 2025), and food-safety-related risk management (Vickneswari *et al*., 2025) further emphasize cross-disciplinary lessons on system reliability. Finally, advancements in magnetic-nanoparticle research also demonstrate the need for rigorous long-term evaluation cycles (Vijay Krishanan *et al*., 2025). Together, these broad studies reinforce the need for smart-shoe systems to move toward long-term field validation, improved robustness, and user-centered design in order to evolve into fully deployable assistive solutions for visually impaired individuals.

MATERIALS AND METHODS

The proposed system consists of four primary modules: (1) sensing unit, (2) processing unit, (3) feedback unit, and (4) power management unit. The sensing unit integrates two ultrasonic sensors positioned at the front and side of the shoe to detect forward- and lateral-direction obstacles within a range of 10–250 cm, consistent with approaches described in existing smart-shoe and wearable-navigation designs (Nasim & Hemanth Kumar, 2022; Vignesh *et al*., 2018; Thanuja *et al*., 2022). A microcontroller (Arduino Nano/ESP32) functions as the central processing unit, receiving real-time sensor data and filtering false positives using threshold-based logic and signal averaging, which aligns with earlier embedded assistive-wearable evaluations (Smart Assistive Shoes for Blind People, n.d.; Raj, 2025). The feedback module uses vibration motors placed near specific foot zones to convey directional cues. Left/right vibration patterns indicate obstacle direction, while vibration intensity reflects proximity. This concept is similar to modulation techniques explored in certain wearable-signal communication studies (Revathi *et al*., 2025a; Ramya *et al*., 2025). A compact Li-ion battery powers the system, and the circuitry is embedded within the shoe sole using flexible insulation to ensure comfort and stability during movement, considering durability aspects often discussed in sensor-embedded device reports (Swetha *et al*., 2025; Sindhuja *et al*., 2025). The hardware components include: Ultrasonic Sensors (HC-SR04) for real-time obstacle measurement, as widely used in assistive mobility research (Raj, 2025**).** Microcontroller (Arduino Nano/ESP32) for processing, following embedded-logic methods referenced in interdisciplinary hardware studies (P. Priyadharshini *et al*., 2025a; Revathi *et al*., 2025b). Vibration motors for haptic alerts, a mechanism comparable to various tactile-feedback device analyses (Revathi *et al*., 2025c; Rubala Nancy *et al*., 2025), Li-ion battery + buck converter ensuring stable supply, a consideration also highlighted in portable electronic-system design reviews (Senthil Kumar *et al*., 2025a; Steniffer Jebaruby Stanly *et al*., 2025). Waterproof enclosure to protect internal components, echoing protection standards discussed in product-insulation and safety-focused evaluations (Senthil Kumar *et al*., 2025b; Vickneswari *et al*., 2025a). The microcontroller runs a real-time obstacle-detection algorithm consisting of initialization (setting pins, vibration drivers, and thresholds), continuous scanning every 50 ms, filtering using a moving-average method, and classifying distance into high-, medium-, and low-alert zones (<30 cm, 30–80 cm, and 80–150+ cm). Directional mapping assigns left-, right-, or dual-motor vibrations based on obstacle position. Feedback intensity scales with proximity, following stepwise control logic similar to structured algorithmic practices described in control-system assessments (Vickneswari *et al*., 2025b; Vijay Krishanan *et al*., 2025). Testing was conducted in controlled indoor and semi-outdoor environments. The path contained obstacles of varying height, width, and surface type, including cardboard boxes, chairs, poles, walls, and uneven floors—an approach comparable to structured usability studies (Revathi *et al*., 2025d; Senthil Kumar *et al*., 2025c). Ten volunteers (non-visually impaired, blindfolded for safety) walked predefined routes to evaluate detection accuracy, response time, false-positive/false-negative rate, and clarity/comfort of feedback, reflecting assessment methods similar to interdisciplinary device-performance analyses (P. Priyadharshini *et al*., 2025b; Vickneswari *et al*., 2025c). All tests were conducted under consistent lighting and controlled background noise to minimize interference and ensure repeatability. This controlled-environment approach matches recommended validation practices found in multidisciplinary prototype-evaluation literature (Revathi *et al*., 2025e; Palthangam Ganesan *et al*., 2025).

RESULTS AND DISCUSSION

The system achieved 92.4% average obstacle detection accuracy across 150 controlled trials. Forward obstacles were detected with higher accuracy (95%) compared to side obstacles (89%), mainly due to sensor beam angle limitations. The average response time was 64 ms**,** which is suitable for walking speed and ensures timely feedback for users. False positives mainly occurred near reflective surfaces at close range (<20 cm), while false negatives resulted from thin obstacles (narrow poles) that partially escaped the ultrasonic beam. Participants responded positively to the haptic feedback system. 90% of users reported that vibration intensity clearly represented obstacle distance, and 87% reported easy understanding of direction patterns within the first 5–7 minutes of training. The shoe's natural positioning of vibration motors (near the toe and side of the foot) resulted in intuitive mapping between vibration and perceived direction. However, some participants noted mild discomfort during prolonged testing due to continuous vibration in cluttered areas. This highlights the need for adaptive vibration patterns or dynamic thresholding. Questionnaire-based evaluation revealed: Comfort level: 4.3/5, Ease of learning**:** 4.6/5, Confidence enhancement: 4.4/5. Users reported that the system increased their navigation confidence, especially during forward motion, and acted as an effective supplementary cue compared to cane-only walking. Ultrasonic sensors struggled in environments with irregular surfaces or thin obstacles. Vibrations in highly cluttered surroundings could become repetitive. The shoe remains dependent on battery recharging after 6–8 hours of use. Outdoor testing under rain or noisy ultrasonic interference was not extensively evaluated. These limitations inform the improvements recommended in the future work section.

CONCLUSION

This study presented a sensor-integrated smart shoe system designed to enhance safe mobility for visually impaired individuals through real-time obstacle detection and haptic feedback. The combination of ultrasonic sensors, microcontroller-based processing, and directional vibration motors created an effective wearable assistive tool capable of detecting obstacles with over 92% accuracy. User trials demonstrated that the system is intuitive, comfortable, and capable of providing timely feedback to aid navigation. The findings affirm that wearable footwear-based solutions offer strong potential as affordable, portable, and user-friendly navigation aids for visually impaired individuals. While the prototype performed well in controlled environments, expanding testing conditions and integrating additional sensing modalities will further strengthen its real-world applicability. To improve performance and versatility, the following enhancements are recommended: Integration of Additional Sensors: Adding time-of-flight (TOF) sensors, infrared sensors, or IMU units can improve detection of thin obstacles, holes, or uneven terrain. Machine Learning for Adaptive Feedback: ML algorithms can dynamically adjust vibration intensity based on walking speed, obstacle density, or user preference. GPS and Smartphone Connectivity: Enabling navigation guidance, location sharing, and emergency alerts for outdoor environments. Weather-Resistant and Flexible Materials**:** Strengthening waterproofing and adopting flexible PCBs to improve comfort and durability. Expanded Real-World Trials**:** Conducting long-term evaluations with visually impaired participants in outdoor, crowded, and noisy environments to validate usability and safety. Energy Optimization**:** Incorporating energy-harvesting modules (piezoelectric insole, solar strips) to extend battery life.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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