Austin Journal of Public Health and Epidemiology

Open Access

Austin Publishing Group

Research Article

Development of a Compact, Affordable Ultrasonic-Based Assistive Cane for Improved Mobility of Visually Impaired Individuals

Riyadh Abdullah Alzahrani[1]*, Hamad Hassan Alqahtani[1], Saeed Mohammed Alqahtani[1], Turki Saeed Alshahrani[1], Abdullah Salem Al Inkis[2] and Mohammed Ali Asiri[2]

[1]Department of Medical Engineering, Armed Forces Hospital, Najran, Saudi Arabia

[2]Department of Health Education, Armed Forces Hospital, Najran, Saudi Arabia

***Corresponding author:** Riyadh Abdullah Alzahrani, Department of Medical Engineering, Armed Forces Hospital, Najran, Saudi Arabia

Email: abedazhot@gmail.com

Received: December 08, 2025
Accepted: December 24, 2025
Published: December 29, 2025

Abstract

Visually impaired individuals face significant challenges in navigating their environment safely and independently, and traditional white canes, while widely used, have limitations such as the inability to detect obstacles above waist level. To address these challenges, this study aimed to develop a compact, affordable ultrasonic-based assistive cane capable of detecting obstacles and providing real-time feedback through vibration and sound. The device employs four strategically positioned ultrasonic sensors to monitor overhead, frontal, and ground-level obstacles, controlled by an Arduino microcontroller housed in a 3D-printed casing. The system provides users with haptic and auditory alerts that vary in intensity according to the proximity of obstacles, enhancing spatial awareness and safety. Simulations performed on the Tinkercad platform confirmed the correct functioning of the sensor feedback logic, while real-world testing of the prototype revealed minor discrepancies, including processing delays and sensor blind spots, which were partially mitigated through software filtering. Despite these limitations, the prototype demonstrated several strengths, including affordability, lightweight design, portability, and extended battery life exceeding eight hours of continuous use. Design and assembly challenges, such as large casing size due to through-hole components and manual wiring, highlighted areas for improvement in future iterations. Overall, the study demonstrates that ultrasonic-based assistive devices can provide effective multi-level obstacle detection and represent a promising, low-cost alternative to traditional white canes. With further refinement, including miniaturized electronics, improved sensors, and additional navigation features, such devices have the potential to significantly enhance independent mobility, safety, and quality of life for visually impaired users.

Keywords: Accessibility; Assistive; Cane; Mobility; Navigation; Sensors; Ultrasound

Introduction

Visual impairment is a growing global health concern that continues to impact the independence, safety, and quality of life of millions of individuals. According to the World Health Organization (WHO), approximately 1.3 billion people live with some form of visual impairment, including 36 million who are completely blind [1]. While the burden is highest in developing countries, industrialized nations are also facing increasing rates of blindness due to aging populations. For instance, in the United States alone, the population aged 65 and above is projected to rise from 46 million to more than 98 million by 2060, significantly increasing the prevalence of age-related visual decline [2]. Reduced visual acuity has been shown to negatively affect gait, mobility, balance, and walking speed, making safe and independent navigation a daily challenge for visually impaired individuals. For decades, the conventional white cane has served as the most widely used assistive tool for navigation among visually impaired people. Its popularity stems from its simplicity, low cost, and ability to provide tactile information about the immediate environment, particularly obstacles located at ground level such as steps, curbs, and furniture. Additionally, the white cane serves as a recognizable symbol that notifies others that its user is visually impaired, promoting social awareness and caution in public settings [3]. Despite these advantages, traditional canes have major limitations. They cannot detect obstacles above waist level such as hanging signs, tree branches, or vehicle mirrors, leading to frequent head and upper-body collisions. A previous study involving 300 blind participants reported that 40% experienced head-level collisions at least once per year, highlighting the need for enhanced navigation aids that ensure greater safety [4]. Advancements in assistive technology have led to the development of Electronic Travel Aids (ETAs), which aim to supplement or enhance the function of the traditional white cane. ETAs use sensors commonly ultrasonic sensors to detect obstacles, then convey information to the user through haptic or auditory feedback [5]. These devices offer a significant advantage by detecting obstacles at a distance and above ground level, thereby supporting more independent, confident, and safe mobility. However, currently available ETAs such as the UltraCane and MiniGuide remain costly and are not accessible to most visually impaired individuals, particularly in low-income communities. Moreover, many ETAs

Citation: Riyadh Abdullah Alzahrani, Hamad Hassan Alqahtani, Saeed Mohammed Alqahtani, Turki Saeed Alshahrani, et al. Development of a Compact, Affordable Ultrasonic-Based Assistive Cane for Improved Mobility of Visually Impaired Individuals. Austin J Public Health Epidemiol. 2025; 12(3): 1183.

are not ergonomically designed, bulky, or require pairing with a traditional cane to provide sufficient navigation data, limiting their practicality for everyday use [6]. Given the limited options for affordable and user-friendly navigation aids, there is a need to develop a cost-effective, compact, and efficient electronic cane alternative suitable for daily use. The rationale of this research is based on the belief that electronic assistive devices represent the next generation of mobility support, offering greater functionality, increased safety, and improved user experience compared with traditional white canes [7]. The current study proposes the development of an ultrasonic-based smart assistive cane capable of detecting obstacles and alerting users through vibration and sound feedback. It is hypothesized that such a device will be more convenient, easier to use, and more functional than conventional canes, while remaining affordable for the average user. The main objectives of this study are: 1) to produce an assistive device that detects obstacles for visually impaired individuals, and 2) to warn users of these obstacles through vibration and sound. The design aims include creating a compact, lightweight, affordable, rechargeable device capable of operating for a full day on a single charge, ensuring suitability for daily, long-term use.

Literature Review

Petsiuk et al. [8] introduced an innovative ultrasonic-based navigation system designed as a wearable bracelet to support independent mobility among individuals with visual impairment. The proposed device utilizes digitally distributed manufacturing and low-cost components, enabling production through 3D printing or milling at an affordable cost.

The system detects obstacles within a four-meter range and provides distance information to the user through haptic feedback using varying vibration patterns. One of its main advantages is its simplicity, as it does not require extensive calibration or training, allowing it to be used as an assistive add-on to traditional mobility tools such as the white cane. In trials involving blindfolded participants, the system demonstrated the ability to support basic navigation, including orientation in unfamiliar environments, bidirectional navigation, and collision avoidance with pedestrians. Although promising in demonstrating the potential of ultrasonic feedback for mobility, the study relied mostly on non-visually impaired participants, raising concerns about the validity of the results for real-world use among individuals who are blind [9]. In contrast, Dos Santos et al. [10] emphasized the importance of testing assistive mobility devices with authentic blind users rather than relying primarily on blindfolded sighted participants, a limitation seen in much of the previous research. Their study compared the usability and performance of an ultrasonic-based electronic cane with a traditional white cane.

The findings revealed that walking speed was significantly slower when using the electronic cane compared to the traditional white cane, suggesting that additional training may be necessary for efficient use of electronic mobility aids. Notably, visually impaired participants demonstrated faster performance than blindfolded individuals, indicating that blindfolded users are not appropriate substitutes for experienced cane users. While both devices showed similar results in detecting ground-level obstacles, the electronic cane successfully detected 79% of suspended obstacles, confirming a key advantage over the traditional white cane. The authors concluded that electronic cane innovations require longitudinal studies with trained blind participants to fully evaluate device effectiveness, learning curves, and real-world usability.

Methodology

Device Design and Working Principle

This study aims to develop an electronic assistive device to serve as an enhanced alternative to the traditional white cane for visually impaired individuals. The device is designed to be held at waist level, enabling users to receive continuous sensory feedback regarding obstacles in their surroundings. The system utilizes four ultrasonic sensors strategically positioned to detect obstacles at different heights: overhead, frontal, and ground-level. The first ultrasonic sensor is angled upward to detect overhead obstacles that pose a collision risk to the user's head and upper body. Although the sensor can measure distances up to 4.5 meters, the warning system is limited to only activate when an object falls within the head-level danger zone. Anthropometric ratios were applied to determine this threshold. Human body measurement standards indicate that the distance from the waist to the floor represents 48.5% of total height, leaving 51.5% above the waist. Using the average male height in Saudi Arabia (170 cm), the waist-to-head distance is approximately 88 cm. With the sensor tilted at 45°, trigonometric calculations estimate a horizontal detection distance of ~125 cm. To enhance safety, an additional 10 cm margin was integrated into the detection limit to ensure timely user alerts.

A second sensor is positioned horizontally to detect frontal obstacles. The system continuously monitors the distance to objects ahead and provides progressive feedback: the closer the object, the stronger the vibration and the higher the warning frequency. This ensures that users receive real-time spatial awareness as they approach obstacles. The third and fourth sensors are positioned to simultaneously detect ground-level hazards, including ascending or descending stairs, curbs, or uneven surfaces. They are fixed at a 45° angle relative to each other. The lower sensor measures the distance to the ground, forming the adjacent side of a right-angle triangle. Given the fixed angle and adjacent value, the expected value of the hypotenuse measured by the second sensor can be calculated by the microcontroller. Any deviation beyond ±5 cm indicates a surface irregularity, triggering an alert with a distinct vibration and sound pattern to differentiate it from overhead and frontal warnings. The device also includes three external buttons allowing the user to switch the system on/off and to select preferred feedback mode (sound, vibration only, or both) depending on the surrounding environment.

Electronic Components and Power System

The system is powered by a rechargeable lithium-polymer battery with a nominal voltage of 3.7 V. Since the Arduino microcontroller requires a minimum of 7 V for optimal operation, a voltage booster module was integrated to elevate the voltage supply from 3.7 V to 7 V. A dedicated charging and protection circuit was installed to regulate the battery's charging current and voltage, preventing overcharging or thermal damage [11].

Sensory Feedback Mechanism

Two types of sensory feedback are provided: vibration (haptic) and sound (auditory). A vibration motor generates haptic feedback with varying intensities depending on the distance of the obstacle. As

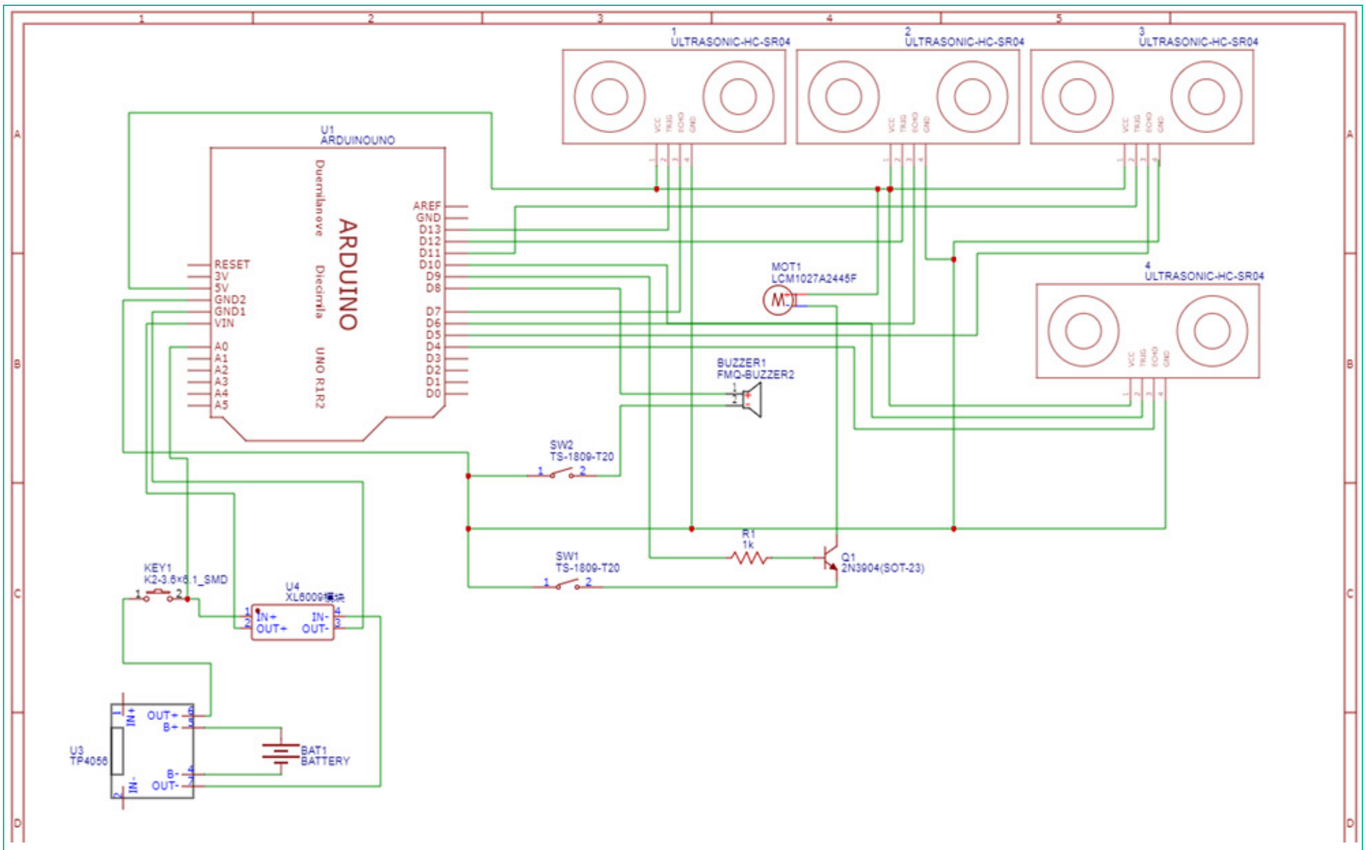

Figure 1: Circuit diagram.

vibration motors require at least 2.5 V to activate and can operate up to 5 V, pulse width modulation (PWM) is used to regulate output. The PWM signal range (0–255) was calibrated such that values between 127 and 255 produce a proportional increase in intensity as the user approaches an object. A piezoelectric buzzer provides auditory cues, with distinct tones assigned to each sensor alert type to prevent confusion. A unique alert pattern is also programmed to notify users of low battery status and during system startup [12].

Feasibility and Risk Analysis

The project did not present financial feasibility concerns, as all prototype components were supplied by the college. However, the ultrasonic sensors used have inherent limitations, including a short blind zone in which distance measurement is unreliable. To reduce false readings, software filtering techniques were implemented to discard improbable values. While this improved performance, it also slightly reduced sensitivity, representing a compromise between accuracy and stability. Future versions may require more advanced filtering or alternative sensor technologies to increase reliability.

Circuit Diagram

We connected the circuit as shown in figure 1 below.

System Block Diagram

The system works by sensing surrounding environment and measuring battery voltage and then processing this data to decide on the appropriate feedback to give to the user as shown in figure 2.

Software

The microcontroller begins operation by initializing all variables, input/output ports, and system components. Upon successful startup, the user receives an initial feedback signal indicating that the device has been powered on. This start-up feedback is executed once at the beginning of the program. After initialization, the microcontroller enters a continuous loop in which it monitors both battery voltage and sensor readings in real time. Based on the acquired data, the system determines whether an alert should be issued to the user. This loop repeats continuously throughout device operation until the user switches the device off. The overall process flow is illustrated in Figure 3.

Simulation

A preliminary simulation of the device was carried out using the Tinkercad platform. Although Tinkercad does not support simulating certain components specifically the charging circuit and voltage boosterthis limitation did not affect testing of the core functionality.

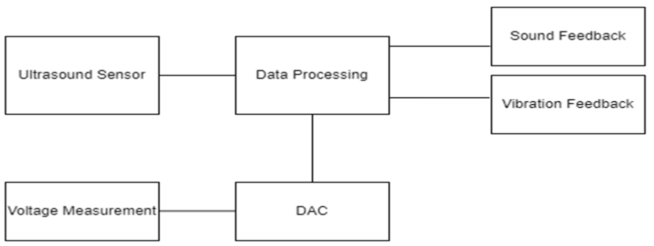

Figure 2: System Block Digram.

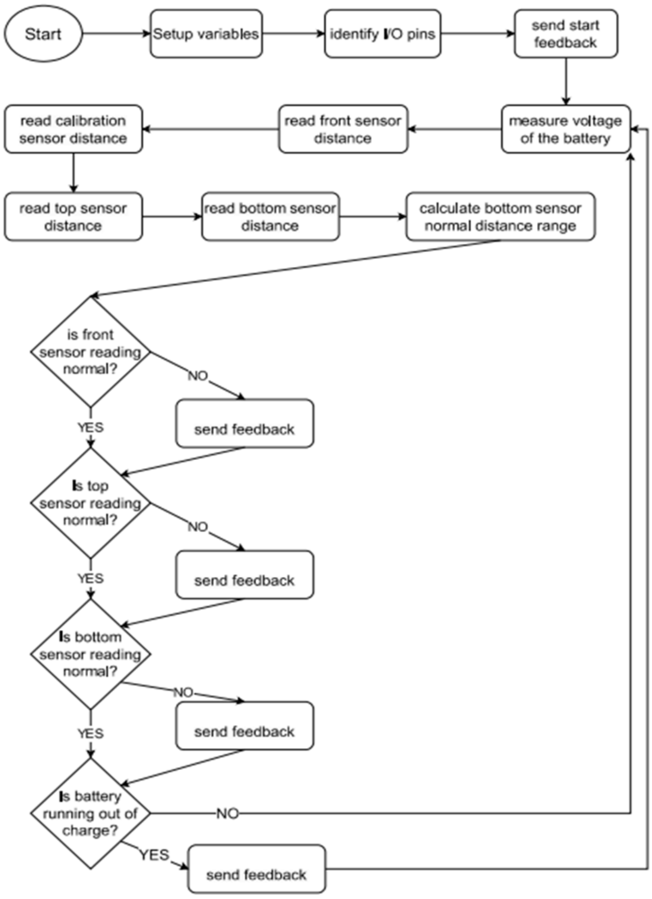

Figure 3: Software Flow Chart.

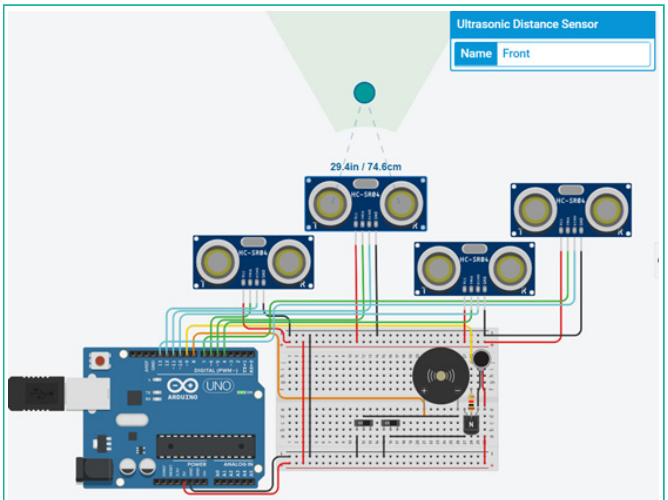

Figure 4: Simulation for front sensor.

The simulation focused on validating the ultrasonic sensor readings and the corresponding feedback responses. The results were consistent with the theoretical design expectations. As illustrated in Figure 4, when the front ultrasonic sensor detected an obstacle at a distance of less than 100 cm, the system successfully activated both vibration and auditory feedback, confirming the correct execution of the programmed logic.

Case Design

The device casing was designed using SOLIDWORKS 2022 to produce a three-dimensional model that accommodates all internal components and meets the functional requirements of the system. SOLIDWORKS was selected due to its widespread use among professional designers and engineers, its high accuracy in generating complex designs, and its extensive range of tools for modeling, assembly, and technical drawing. Although the software requires a steep learning curve for beginners, numerous online tutorials and training resources supported the design development process. Approximately two weeks were dedicated to learning the basic functions of the software and practicing simpler models prior to initiating the device design [13].

During the initial design phase, several challenges were encountered, particularly in sketching and dimensioning. Errors in defining angles and constraints in the early sketches resulted in complications during subsequent design steps, as modifications to initial lines become restricted once features are applied. This emphasized the importance of establishing a fully constrained and error-free initial sketch, as inaccuracies at this stage propagate through the remainder of the design. In addition, failure to properly close a sketch or terminate a tool before proceeding to the next function led to unintended geometry or system errors, occasionally requiring a complete redesign to isolate and correct the issue. These challenges highlight the need for precision, focus, and step-by-step validation throughout the design process [14].

Given that the proposed device incorporates four ultrasonic sensors, each with a specific orientation and function, the design was developed to ensure correct sensor positioning and alignment according to operational requirements. The casing was modeled to house all electronic components securely while remaining portable and user-friendly. However, as this design represents a preliminary prototype, the overall size of the casing was relatively large due to the physical dimensions of components used. For example, each ultrasonic sensor measures approximately 45 mm in length and 20 mm in width, in addition to other sizable electronic modules integrated into the system. The initial SOLIDWORKS model of the device enclosure is shown in Figure 5.

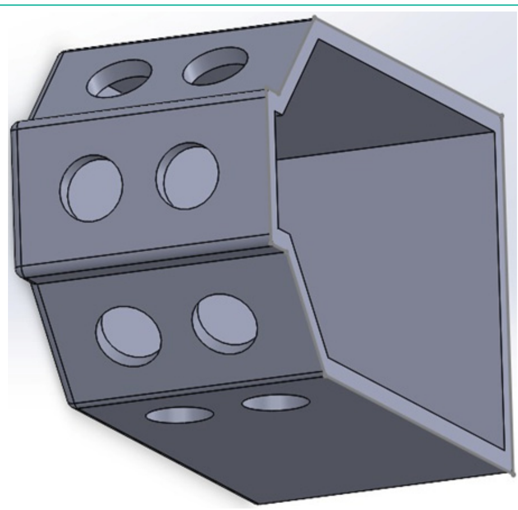

Figure 5: Big piece of the case model.

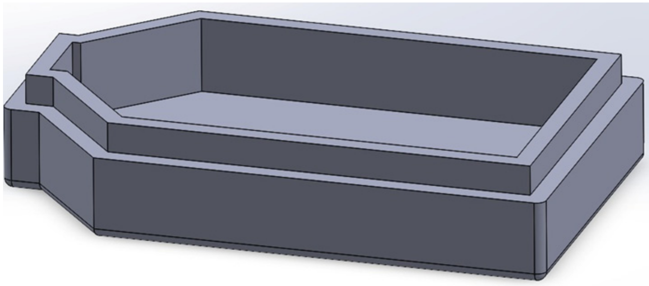

Figure 6: Cover piece of the case design.

The device cover was designed to be side-mounted to facilitate easier assembly of internal components and to accommodate the relatively large size of the parts. This design choice also optimized the 3D printing process by minimizing the need for support structures, which can introduce defects or compromise dimensional accuracy due to printer limitations or material properties. The side-mounted cover thus ensures a simpler, more reliable assembly while maintaining the integrity and functionality of the printed parts, as illustrated in Figure 6.

The material used in printing was PLA.

Results

Simulation vs. Prototype Performance

The initial simulation of the device, conducted using Tinkercad, demonstrated the theoretical functionality of the ultrasonic sensors and feedback mechanisms. During simulation, the system responded accurately to obstacle detection without any noticeable delay or errors. For instance, when the front sensor detected an object within 100 cm, the device successfully provided both vibration and auditory feedback, confirming that the logic and response algorithms operated as intended (see Figure 4). Similarly, the haptic and sound feedback mechanisms for the top and bottom sensors also functioned correctly in the simulation, with intensity levels corresponding to object proximity as programmed [15]. These results suggested that, in theory, the proposed design could deliver real-time, multi-sensor feedback for safe navigation.

However, when the actual prototype was constructed and tested, several discrepancies between simulation and real-world performance became apparent. Notably, the system experienced processing delays, particularly when performing trigonometric calculations for the bottom two sensors, which are responsible for detecting ground-level obstacles such as stairs or curbs. These delays occasionally resulted in delayed or false feedback, which could compromise safety. Additionally, the ultrasonic sensors exhibited blind zones small areas immediately adjacent to the sensor where obstacle detection was unreliable. While these effects were partially mitigated by adjusting the code and filtering out improbable readings, they could not be completely eliminated, highlighting a limitation of the hardware and microcontroller processing capacity [16].

Prototype Usability and Performance

Despite these technical challenges, the prototype demonstrated several practical strengths. The total cost of components was approximately 200 Saudi Riyals, making the device affordable for the average consumer. The assembled prototype, although larger than initially intended due to component size and design constraints, remained lightweight and could be comfortably held in one hand, which is essential for mobility and user convenience. The rechargeable lithium-polymer battery performed well, providing over eight hours of continuous operation and a full recharge in less than 30 minutes. These characteristics confirm that the device meets key design objectives related to affordability, portability, and usability [17].

Figure 7: Switches mounting in the case.

During assembly, some unexpected modifications were necessary. For example, the initial CAD design did not account for openings for the external switches. These holes were added manually after 3D printing, as shown in Figure 7. Additionally, the case size had to be increased to accommodate through-hole mounted electronic components, which were chosen due to limited experience with printed circuit board (PCB) design. Using a PCB or surface-mount components could have significantly reduced the size of the prototype, improving compactness and ergonomics [18].

Design and Assembly Considerations

The device casing, designed in SOLIDWORKS 2022, served as both a protective enclosure and an ergonomic holder for the four ultrasonic sensors, microcontroller, battery, and feedback components. The cover was side-mounted to simplify assembly and reduce the need for support structures during 3D printing, minimizing potential printing defects (Figure 6). Although the preliminary design was relatively large, it successfully housed all components while maintaining a functional, user-friendly form factor [19].

Assembly required careful placement of each component to ensure correct sensor orientation, as each ultrasonic sensor has a specific detection angle and operational function. Errors in component alignment could compromise the detection range and feedback accuracy [20]. After assembly, the system was tested for both sensor alignment and feedback consistency, ensuring that each sensor

Figure 8: Prototype after assembly.

triggered the correct vibration and auditory signal based on obstacle location. The final assembled prototype is shown in Figure 8.

The comparison between simulation and prototype results revealed several key findings. The Arduino microcontroller performed slower than anticipated during simultaneous calculations for multiple sensors, resulting in minor feedback delays that could impact real-world navigation. Additionally, the ultrasonic sensors exhibited inherent blind zones, which affected obstacle detection near the device; while software filtering reduced these effects, they remain a limitation of the current hardware. On the positive side, the prototype is lightweight, functional, and affordable, meeting the project's primary design objectives, and can be comfortably held in one hand while operating for an entire day on a single charge. Design and assembly constraints, including limited CAD experience and the use of through-hole components, resulted in a larger-than-intended casing; future iterations could employ PCBs and surface-mount technology to achieve a more compact form [21]. Overall, the results demonstrate that the proposed ultrasonic-based assistive device effectively delivers multi-sensor feedback and serves as a feasible, low-cost, and user-friendly alternative to the traditional white cane, although further optimization is necessary to improve responsiveness, sensor coverage, and portability.

Discussion

Visually impaired individuals continue to rely heavily on the traditional white cane for navigation, yet there is a growing need for alternative assistive devices that are affordable, functional, and aligned with modern technology. Advances in sensor technologies such as ultrasonic sensors, infrared sensors, cameras, and sonar, offer opportunities to enhance mobility and safety for visually impaired users. In this research, an ultrasonic sensor-based assistive device was designed and prototyped as a potential alternative to the white cane. The ultrasonic sensors demonstrated strong promise in detecting obstacles at multiple levels and providing both auditory and haptic feedback [22]. While the prototype successfully delivered the intended functionality, several minor challenges were observed that could be addressed in future iterations to further improve performance and user experience [23]. Several limitations were encountered during the design and development process. First, no single simulation platform allowed for testing all device components simultaneously, which required reliance on online user experiences and third-party evaluations to predict device behavior. Second, obtaining detailed technical specifications for some components was challenging, and we often had to rely on user-reported performance data rather than official manufacturer documentation. This reliance introduced some uncertainty regarding component performance, particularly in sensor range and responsiveness. Additionally, the team had limited experience with computer-aided design (CAD) and 3D printing, which constrained the complexity and compactness of the device casing. The use of through-hole components and manual wiring further increased the overall size and weight of the prototype, highlighting the need for more advanced electronic design techniques such as printed circuit boards (PCBs) in future designs.

Despite these limitations, the prototype demonstrated several strengths. The device successfully integrated four ultrasonic sensors to provide multi-level obstacle detection, translating sensor data into distinct vibration and auditory feedback. The battery system allowed for extended operation, and the prototype remained lightweight and portable, capable of being held in one hand. The total cost of components was approximately 200 Saudi Riyals, making the device potentially accessible to a wide range of users. These results confirm that ultrasonic sensor-based devices can serve as a viable, low-cost, and user-friendly alternative to the traditional white cane, offering additional functionality such as detection of suspended obstacles that a conventional cane cannot provide.

Future work on the device could address both hardware and software limitations to improve performance and usability. Incorporating a printed circuit board would enable better cable management, reduce size and weight, and simplify assembly. High-quality sensors could minimize blind spots, enhancing reliability and user confidence. Replacing the piezoelectric buzzer with a Bluetooth speaker could reduce noise disturbance to surrounding individuals, while additional features such as GPS tracking, voice commands, and voice feedback could further support independent navigation and safety. Integration of a gyroscope could allow sensor readings to adapt to changes in device orientation, rather than relying on fixed sensor angles, improving accuracy in real-world use.

Conclusion

In conclusion, the development of an ultrasonic sensor-based assistive device represents a significant step toward modern alternatives to the traditional white cane. While current prototypes have limitations, including sensor blind spots and the need for battery recharging, they offer considerable advantages in functionality, portability, and affordability. With ongoing advancements in battery technology, microcontroller processing power, and miniaturization, such devices have the potential to become mainstream solutions for visually impaired individuals. Future iterations that incorporate compact design, advanced sensors, and additional navigation features could significantly enhance independent mobility, safety, and quality of life for users, marking a substantial technological evolution in assistive mobility devices.

References

1. Vision Loss Expert Group of the Global Burden of Disease Study. Global estimates on the number of people blind or visually impaired by glaucoma: A meta-analysis from 2000 to 2020. Eye. 2024; 38: 2036.

2. Swenor, B. K., Lee, M. J., Varadaraj, V., Whitson, H. E., & Ramulu, P. Y. Aging with vision loss: a framework for assessing the impact of visual impairment on older adults. The Gerontologist. 2020; 60: 989-995.

3. Bäckman, M. Living with an iconic aid: The case of the white cane. Culture unbound. 2023; 15.

4. Khan, S., Nazir, S., & Khan, H. U. Analysis of navigation assistants for blind and visually impaired people: A systematic review. IEEE access. 2021; 9: 26712-26734.

5. Khan, I., Khusro, S., & Ullah, I. Technology-assisted white cane: evaluation and future directions. PeerJ. 2018; 6: e6058.

6. Kim, I. J. Recent advancements in indoor electronic travel aids for the blind or visually impaired: a comprehensive review of technologies and implementations. Universal Access in the Information Society. 2025; 24: 173-193.

7. Bateni, H., & Maki, B. E. Assistive devices for balance and mobility: benefits, demands, and adverse consequences. Archives of physical medicine and rehabilitation. 2005; 86: 134-145.

8. Petsiuk, A. L., & Pearce, J. M. Low-cost open source ultrasound-sensing based navigational support for the visually impaired. Sensors. 2019; 19: 3783.

9. Freeman, E., Wilson, G., Vo, D. B., Ng, A., Politis, I., & Brewster, S. Multimodal feedback in HCI: haptics, non-speech audio, and their applications. In The Handbook of Multimodal-Multisensor Interfaces: Foundations, User Modeling, and Common Modality Combinations. 2017; 277-317.

10. Dos Santos, A. D. P., Loureiro, M., Machado, F., Frizera, A., & Medola, F. O. NavWear: design and evaluation of a wearable device for obstacle detection for blind and visually impaired people. Disability and Rehabilitation: Assistive Technology. 2025; 1-15.

11. Peyghami, S., Palensky, P., & Blaabjerg, F. An overview on the reliability of modern power electronic based power systems. IEEE Open Journal of Power Electronics. 2020; 1: 34-50.

12. Zivotofsky, A. Z., & Hausdorff, J. M. The sensory feedback mechanisms enabling couples to walk synchronously: An initial investigation. Journal of neuroengineering and rehabilitation. 2007; 4: 28.

13. Trojan, J., Trebuňa, P., Svetlík, J., & Kopec, J. Case Study: Component Design for Streamlining the Manufacturing Process Using 3D Printing. Processes. 2025; 13: 1282.

14. Kazi, R. H., Grossman, T., Cheong, H., Hashemi, A., & Fitzmaurice, G. W. DreamSketch: Early stage 3D design explorations with sketching and generative design. In UIST. 2017; 14: 401-414.

15. Hennig, A. N. D. R. E. A. S., Hentschel, A. N. J. A., & Tyack, J. A. M. E. S. Performance prototyping–generating and simulating a distributed IT-system from UML models. Al-Dabass. 2003; 1: 1.

16. Joundi, J., Baccarne, B., Robaeyst, B., Bombeke, K., De Marez, L., & Saldien, J. Comparing Virtual and Real-Life Rapid Prototyping Methods for User Testing Smart City Interfaces: A Case Study. Applied Sciences. 2024; 14: 9918.

17. Vijayakumar, V., Anothumakkool, B., Kurungot, S., Winter, M., & Nair, J. R. In situ polymerization process: an essential design tool for lithium polymer batteries. Energy & environmental science. 2021; 14: 2708-2788.

18. Lanin, VL, Emel'yanov, VA, Petuhov I. Chapter 1. Assembly and Mounting of Electronic Devices: Advancements in Technology and Equipment. Surface Engineering and Applied Electrochemistry. 2024; 60: 269-288.

19. Chanchiewvichai, W., Rianmora, S., & Patmayothin, N. Designing everyday essentials: a guide for user-friendly accessibility using Quality Function Deployment. Cogent Engineering. 2024; 11: 2387826.

20. Park, J., Je, Y., Lee, H., & Moon, W. Design of an ultrasonic sensor for measuring distance and detecting obstacles. Ultrasonics. 2010; 50: 340-346.

21. Bradley, R. Design and manufacturing of educational fiber extrusion device and smart factory. Massachusetts Institute of Technology. 2023.

22. Mocanu, B., Tapu, R., & Zaharia, T. When ultrasonic sensors and computer vision join forces for efficient obstacle detection and recognition. Sensors. 2016; 16: 1807.

23. Baumer, D., Bischofberger, W., Lichter, H., Zullighoven, H. User interface prototyping-concepts, tools, and experience. In Proceedings of IEEE 18th International Conference on Software Engineering. 1996; 532-541.