

Human-Centred Design and Evaluation of a Low-Cost Smart Cane for Independent Mobility of Visually Impaired Users

Ankita Kumari ^{a*}, Ruchi Gaur ^b

a Student, Department of UX & DPD, School of Design, World University of Design, Sonipat

b Assistant Professor, Department of UX & DPD, School of Design, World University of Design, Sonipat

Abstract - Independent mobility is an important aspect of daily life for visually impaired people. The conventional white cane helps users identify obstacles through physical contact, but it provides limited warning about obstacles before they are reached. This study presents the design and evaluation of a low-cost smart cane developed to provide early obstacle awareness through ultrasonic sensing and haptic feedback.

The study follows a human-centered design approach, with emphasis on usability, accessibility, safety, and ease of interaction. The proposed prototype uses an Arduino Uno with ultrasonic sensors to detect obstacles and provides alerts through vibration, supported by an LED indicator. The design process included problem identification, concept development, hardware selection, circuit design, prototyping, programming, structural development, assembly, and real-world testing. Initial testing was carried out with different stationary and moving objects to examine obstacle detection and to adjust the sensitivity of the system and reduce unnecessary alerts.

The study further proposes user-based evaluation to understand how effectively users can interpret the haptic feedback and how the device supports their perceived safety, confidence, and independent mobility. Rather than focusing only on the technical functioning of the device, the study considers the interaction between the user and the assistive technology.

The research aims to identify the strengths and limitations of a low-cost smart cane and provide design recommendations for improving its usability and practical application. The study contributes to the growing field of assistive technology by exploring how simple sensing and haptic feedback can be integrated into a familiar mobility aid to provide additional support for visually impaired users.

Keywords: Smart Cane, Human-Centered Design, Haptic Feedback, Assistive Technology

1. Introduction

Independent mobility is a fundamental part of everyday life, allowing people with visual impairment to travel, access public spaces, participate in education and employment, and perform daily activities with greater autonomy. Visual impairment has remained a major global concern, with millions of people experiencing blindness or varying degrees of vision loss. Estimates by Pascolini and Mariotti (2012) highlighted the large global burden of visual impairment, while more recent evidence shows that the number of people affected by blindness and vision impairment has continued to increase over the past three decades (Steinmetz et al., 2021). For people with little or no

vision, safe movement depends greatly on their ability to obtain information about the surrounding environment.

Before the development of modern assistive technologies, visually impaired people mainly relied on environmental awareness developed through experience, assistance from other people, guide dogs, and mobility canes. Canes have been used as mobility aids for centuries; however, the modern white cane developed as an important mobility and identification tool during the early twentieth century. James Biggs, a photographer from Bristol who lost his sight following an accident, is widely associated with the introduction of the white cane in 1921. He painted his walking stick white so that it could be more easily seen by motorists. During the 1930s, the use of the white cane spread more widely, including through initiatives by Lions Clubs in the United States, where it became associated with independent mobility and pedestrian safety (Lions Clubs International, 2026).

The conventional white cane remains an important and widely used mobility aid. It enables users to identify obstacles and changes in the walking surface through physical contact and tactile information. However, its ability to provide information about obstacles before contact is limited. This limitation has encouraged researchers and designers to explore electronic and digital technologies that can extend the user's awareness beyond the physical reach of the cane. Developments in assistive technology have included computer vision, wearable systems, spatial interfaces, and haptic feedback mechanisms (Yasin et al., 2013; Arakeri et al., 2018; Tapu et al., 2020).

Haptic feedback has received particular attention because information can be communicated through touch and vibration rather than relying entirely on vision or hearing. Shull and Damian (2015) describe haptic wearables as technologies capable of sensory replacement and augmentation, while studies such as Bau and Poupyrev (2012) and Mon and Yap (2012) demonstrate the potential of tactile interaction for communicating information to users with visual impairment. Spatial tactile feedback has also been explored for representing geographical information to visually impaired users (Yatani et al., 2012). These developments have contributed to the emergence of smart mobility aids that combine sensing technologies with tactile, auditory, or multimodal feedback.

Current smart cane research extends the basic function of the traditional cane by incorporating sensors that can detect objects before physical contact. Ultrasonic sensors, for example, estimate the distance of an obstacle by transmitting sound waves and measuring the returning signal. Other systems use infrared sensors, cameras, LiDAR, GPS, computer vision, and combinations of these technologies (Tapu et al., 2020; Mai et al., 2023). Recent research has also explored wearable haptic

systems and robotic canes for navigation and obstacle avoidance (Barontini et al., 2021; Agrawal et al., 2022). These technologies can provide users with additional environmental information, but increasing technological complexity can also raise concerns related to cost, usability, comfort, cognitive load, and practical adoption.

The development of assistive mobility devices should not focus only on technical performance. A human-centred approach is necessary to understand whether the technology is useful, understandable, comfortable, and suitable for everyday mobility. The present study addresses this need through the design and evaluation of a low-cost smart cane that uses ultrasonic sensing and haptic feedback to provide early obstacle awareness. The study examines the device from both technical and user perspectives, with the broader aim of supporting safer and more independent mobility for visually impaired users.

2. Literature Review

2.1 Assistive Technology and Independent Mobility

Independent mobility is a major concern for people with visual impairment, as difficulties in identifying obstacles, changes in walking surfaces, and unfamiliar environments can affect their safety and confidence. Traditionally, the white cane has remained one of the most important mobility aids because it allows users to detect changes in the environment through physical and tactile contact. However, the information available through a conventional cane is largely limited to objects within its physical reach. The development of assistive technology has therefore focused on extending environmental awareness through electronic sensing and alternative forms of feedback.

The development of electronic travel aids has introduced technologies that can provide information about obstacles before physical contact. Yasin et al. (2013) reviewed computer vision techniques designed to support blind and visually impaired people and highlighted the potential of image-based systems for environmental understanding. Similarly, Arakeri et al. (2018) explored computer vision as an assistive technology for visually impaired users, demonstrating how cameras and image-processing techniques can be used to identify environmental information. These approaches represent an important shift from purely mechanical mobility aids towards technology-supported environmental perception.

Tapu et al. (2020), in their state-of-the-art survey, examined a wide range of wearable assistive devices for visually impaired users. Their review shows that assistive technologies have increasingly been developed to support navigation in both indoor and outdoor environments, using different sensing and feedback approaches. However, the authors also emphasize the strengths and limitations of different systems and the importance of evaluating assistive devices according to the needs of the blind community.

2.2 Evolution of Smart Mobility Aids

The development of smart mobility aids has moved from relatively simple obstacle-detection systems towards more complex navigation technologies. Early electronic systems commonly used ultrasonic or infrared sensors to estimate the distance between the user and nearby obstacles. More recent

systems incorporate cameras, RGB-D sensors, LiDAR, GPS, inertial sensors, machine learning and sensor fusion. A recent review of smart cane technology describes this progression from basic ultrasonic obstacle detection towards systems capable of object recognition, environmental mapping and navigation assistance.

The advantage of sensor-based systems is that they can provide information before the user physically reaches an obstacle. However, increasing technical sophistication does not necessarily result in better user experience. Complex systems may increase cost, weight, power requirements and the amount of information that the user needs to interpret. Tapu et al. (2020) similarly identify the need to consider both technological capabilities and practical limitations when evaluating assistive devices.

For this reason, a low-cost smart cane based on relatively simple sensing technology remains relevant. Rather than attempting to replace existing mobility practices, such a device can be designed as an additional layer of environmental awareness while retaining the familiar form and use of the conventional cane.

2.3 Haptic Feedback for Visually Impaired Users

Haptic interaction has become an important area within assistive technology because information can be communicated through touch and vibration. Unlike visual feedback, haptic feedback does not require the user to look at a display. It can also provide information without occupying the auditory channel, which may be important when users need to listen to environmental sounds while walking.

Bau and Poupyrev (2012) demonstrated the potential of tactile feedback for augmented interaction through the REVEL system, showing how surface-based tactile sensations can communicate information to users. Mon and Yap (2012) similarly investigated the use of a haptic interface for learning by visually impaired children, demonstrating the potential of tactile interaction as an alternative means of accessing information. Yatani et al. (2012) further explored spatial tactile feedback for representing geographical information to visually impaired users.

Shull and Damian (2015) provide a broader perspective on haptic wearables, describing their applications in sensory replacement, sensory augmentation and training. Their work is particularly relevant to smart mobility aids because it establishes haptic feedback as more than an interface technique; it can act as an alternative channel through which environmental information is conveyed.

Recent research has continued to explore haptic feedback for navigation. Barontini et al. (2021) developed a wearable haptic navigation system in which feedback was used to support obstacle avoidance and indoor navigation. Importantly, their approach involved continuous feedback from visually impaired users during the development process. Their experiments with visually impaired participants and blindfolded participants showed that the system could provide useful support during indoor navigation.

2.4 Human-Centered Design in Assistive Mobility

Although technological development has produced increasingly sophisticated assistive devices, research indicates that technical performance alone does not determine whether a device will be accepted and used in everyday life. Barontini et al. (2021) specifically point out that limited involvement of actual end users during conceptualization and design can contribute to poor real-world acceptance of technological travel aids. Their study demonstrates the value of involving visually impaired people throughout the development process rather than evaluating the technology only after the prototype has been completed.

This finding is particularly relevant to the present study. A smart cane is not simply an electronic product; it becomes part of a person's physical interaction with the environment. Therefore, factors such as weight, grip, comfort, feedback interpretation, alert frequency, confidence, and ease of use can influence the overall experience. A technically accurate sensor may still be unsuitable if its feedback is confusing or produces too many unnecessary alerts.

The human-centered approach therefore shifts attention from "Can the device detect an obstacle?" to broader questions such as "Can the user understand the alert?", "Does the alert support decision-making?", and "Is the device practical for everyday mobility?" This perspective provides the foundation for evaluating the proposed smart cane not only in terms of sensor performance but also in terms of usability and perceived usefulness.

2.5 User-Centred Evaluation of Assistive Devices

User evaluation is increasingly important in assistive technology research. Tapu et al. (2020) emphasize evaluation criteria developed in relation to the needs of the blind community, indicating that the assessment of assistive devices should extend beyond technological specifications.

Barontini et al. (2021) provide a strong example of this approach by involving visually impaired users during development and subsequently examining the effectiveness of the navigation system. Recent research in wearable mobility aids also continues to identify haptic and sensory-substitution technologies as important research directions, while highlighting the need to consider the interaction between technological capability and individual user needs.

This suggests that evaluation of a smart cane should include both technical measures and human factors. Technical measures may include detection distance, detection accuracy, response time and false-positive rates. Human-centred measures may include perceived usefulness, ease of understanding feedback, comfort, confidence and willingness to use the device.

2.6 Emerging Gaps

The literature demonstrates substantial progress in electronic travel aids, computer vision, wearable systems and haptic navigation. However, there remains a practical challenge in translating technological possibilities into simple, affordable and user-centered mobility solutions. Advanced systems increasingly incorporate cameras, AI, LiDAR, mapping and multimodal feedback, but such systems may introduce additional cost, complexity and hardware requirements.

At the same time, studies of haptic navigation demonstrate the value of tactile feedback, but many proposed systems focus on sophisticated wearable or navigation platforms rather than enhancing the familiar form of the conventional cane. Barontini et al. (2021) also highlight the importance of involving visually impaired users throughout the design process, suggesting that user participation should be central rather than an afterthought.

Therefore, the research gap identified for the present study is the need to examine how a relatively simple, low-cost smart cane using ultrasonic obstacle detection and haptic feedback can be designed and evaluated from a human-centered perspective. The focus is not only on whether the prototype can detect obstacles, but also on whether the feedback is understandable, useful and suitable for supporting independent mobility.

3. Research Gap

Recent research shows a clear progression from conventional white canes towards electronic travel aids using ultrasonic sensing, computer vision, LiDAR, wearable sensors and haptic feedback. Advanced smart canes are now capable of obstacle recognition and navigation using combinations of LiDAR, RGB-D cameras, IMUs, GPS and embedded processors (Mai et al., 2024). Similarly, recent assistive systems have explored deep learning combined with audio and haptic feedback for real-time obstacle detection (2024).

However, technological sophistication does not necessarily translate into better usability. Earlier research by Kim and Cho found that although smart canes could improve obstacle avoidance compared with conventional canes, users experienced problems related to sensor direction, cane weight, floor-level detection and feedback. Their study therefore emphasized the need for usability-oriented design guidelines.

Recent research continues to support this concern. Ricci et al. (2024) found that haptic feedback could reduce collisions during navigation, but participants using haptic feedback alone also showed hesitation and increased task completion time in a complex environment. The study consequently recommends consumer-oriented and progressively realistic testing of assistive technologies. Similarly, studies of haptic navigation have shown that the form and pattern of vibration can influence user preferences and interaction with the mobility aid.

Another important development is the increasing use of sophisticated sensing technologies. For example, Mai et al. (2024) developed a smart cane integrating 2D LiDAR, RGB-D cameras, IMU, GPS and embedded computing for navigation and obstacle recognition. While such approaches demonstrate considerable technical potential, they also highlight a contrast with the need for affordable and relatively simple assistive devices.

Therefore, a gap remains in understanding how a low-cost smart cane using relatively simple ultrasonic sensing and haptic feedback can be designed and evaluated through a human-centered approach. The present study addresses this gap by combining technical evaluation of obstacle detection with user-oriented evaluation of usability, feedback interpretation, comfort and perceived usefulness.

4. Research Aim & Objectives

Aim : To design and evaluate a low-cost smart cane using ultrasonic obstacle detection and haptic feedback to support independent mobility among visually impaired users through a human-centered design approach.

Objective

RO1 :- To examine the mobility-related challenges faced by visually impaired users and identify the requirements for technology-assisted obstacle awareness.

RO2 :- To design and develop a low-cost smart cane integrating ultrasonic sensing and haptic feedback for early obstacle detection.

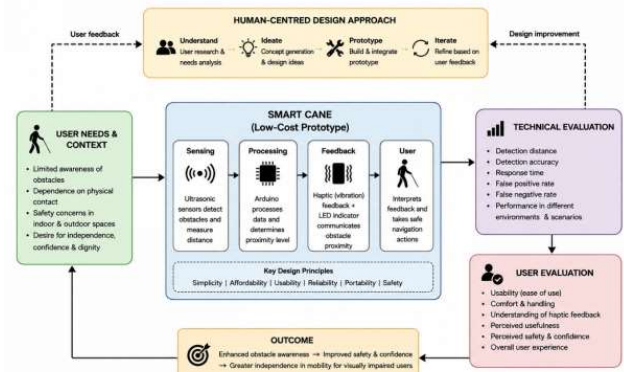
RO3 :- To evaluate the technical performance of the proposed smart cane in detecting obstacles under different distances and environmental conditions.

RO4 :- To evaluate the usability, perceived usefulness, comfort and user experience of the smart cane and identify design improvements for supporting independent mobility.

5. Conceptual Framework

The conceptual framework illustrates the relationship between user needs, human-centered design, smart cane development, technical evaluation, and user evaluation. The framework begins with the mobility needs and challenges of visually impaired users, which guide the human-centred design process of understanding, ideation, prototyping, and iteration. These requirements are translated into a low-cost smart cane using ultrasonic sensing, Arduino-based processing, and haptic feedback. The developed prototype is evaluated through both technical measures, such as detection distance, accuracy and response time, and user-centred measures, including usability, comfort, understanding of feedback, perceived usefulness, safety and confidence. The findings from these evaluations are intended to guide further design improvements. The overall outcome is enhanced obstacle awareness, which can contribute to improved safety, confidence and greater independence in mobility.

Fig 1 : Conceptual Framework

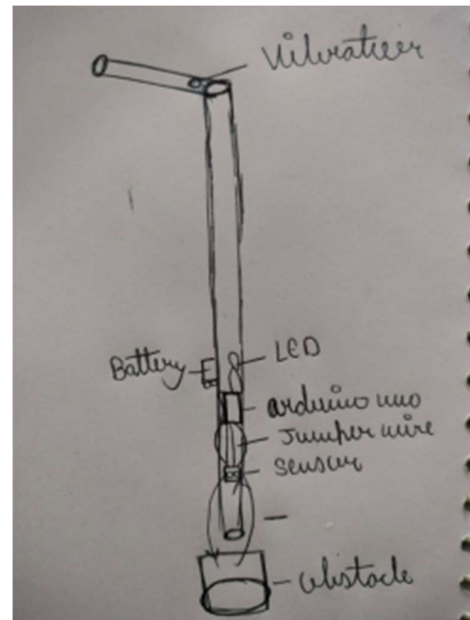


6. Proposed Methodology/Prototype Development

Phase 1: Brainstorming and Conceptualization

The first phase involved identifying a suitable solution to the mobility challenges faced by visually impaired users. During the brainstorming process, different possible concepts were discussed, particularly a wearable vest and a smart cane. The smart cane was selected because it is based on a familiar mobility aid already used by visually impaired people. The proposed concept focused on extending the functionality of the conventional cane by adding ultrasonic obstacle detection and alert mechanisms. The initial design included ultrasonic sensing for detecting obstacles, an LED indicator, and a vibration-based alert to provide information before the user physically reached an obstacle.

Fig 2 : Brainstorming and Conceptualization [Source : Self]

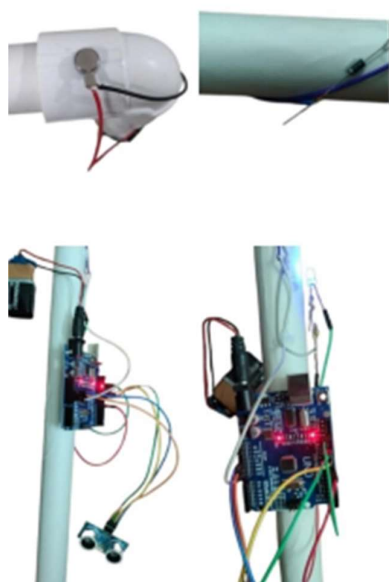


Phase 2: Hardware Selection

The second phase focused on identifying and selecting the hardware components required to develop the prototype. The components were selected with consideration for cost-

efficiency and reliability. An Arduino Uno was selected as the main processing unit, while HC-SR04 ultrasonic sensors were used for distance measurement and obstacle detection. An active buzzer and 9V battery were also identified as components of the system. The selection of these components provided the basic electronic infrastructure required to develop a portable obstacle-detection system within the familiar structure of a cane.

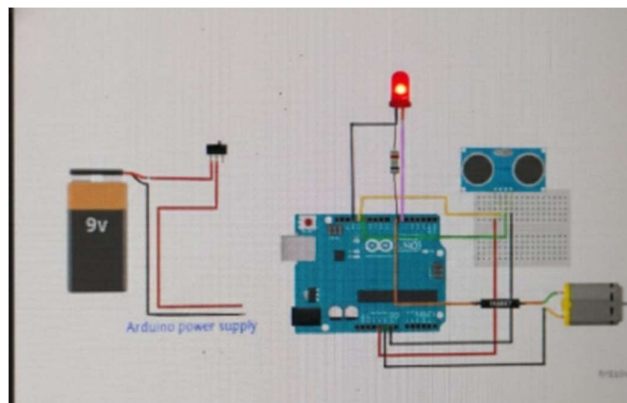
Fig 3 : Hardware Selection [Source : Self]



Phase 3: Circuit Blueprint and System Design

In the third phase, the electronic circuit was planned before physical assembly. A circuit schematic was developed to establish the connections between the Arduino Uno and the ultrasonic sensors. The blueprint mapped the 5V logic of the Arduino with the trigger and echo pins of the sensors and also planned the connections for the vibration and LED feedback. PWM pins were considered for controlling the feedback mechanism. This stage helped establish the electronic structure of the prototype and provided a reference for connecting the different components during the subsequent prototyping stage.

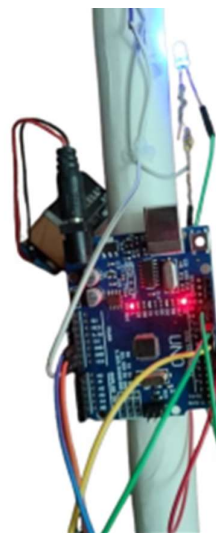
Fig 4 : Circuit Blueprint and System Design



Phase 4: Prototyping

The fourth phase involved constructing a temporary version of the electronic circuit to verify the functioning of the proposed system before permanent assembly. The prototype was developed using a temporary circuit so that individual connections could be checked and modified without permanently fixing the components. At this stage, the ultrasonic sensors were tested to determine whether they were correctly reading distance information, while the overall circuit was checked to ensure that the programmed logic was functioning as expected. This iterative prototyping stage allowed technical problems to be identified before moving towards the permanent physical construction of the smart cane.

Fig 5 : Prototyping [Source : Self]



Phase 5: Programming and System Logic

The fifth phase focused on developing the software logic required to operate the smart cane. C++ code was written for the Arduino to process the distance information received from the ultrasonic sensors and activate the alert mechanism when an obstacle was detected within the programmed range. The basic logic described in the project was based on a distance threshold, where detection of an obstacle below the specified distance activated the vibrator and LED light. This phase established the relationship between sensor input and user feedback, allowing

the electronic system to respond automatically to detected obstacles.

Fig 6: Programming and System Logic



Phase 6: Structural Design and Sensor Mounting

Once the electronic components were functioning, the sixth phase focused on integrating them into the physical structure of the cane. A lightweight PVC pipe was used to simulate the cane structure and provide a suitable mounting surface for the electronic components. One of the main challenges during this stage was determining the appropriate angle for mounting the sensors. If the sensors were positioned too low, they could incorrectly identify the ground as an obstacle. Therefore, the sensor position was adjusted so that it faced forward and could detect objects in the user's path.

Fig 7 : Structural Design and Sensor Mounting



Phase 7: Assembly, Soldering and Finishing

The seventh phase involved converting the temporary prototype into a more permanent and durable assembly. The electronic connections were transferred from the breadboard to a permanent printed circuit board (PCB), which was attached to the PVC cane structure. The components were soldered to provide more secure connections and reduce the possibility of wires becoming disconnected during movement. The wires were subsequently insulated, and the battery was securely mounted on the structure. This phase focused on improving the physical stability and durability of the prototype so that it could be used for subsequent real-world testing.

Fig 8 : Assembly, Soldering and Finishing

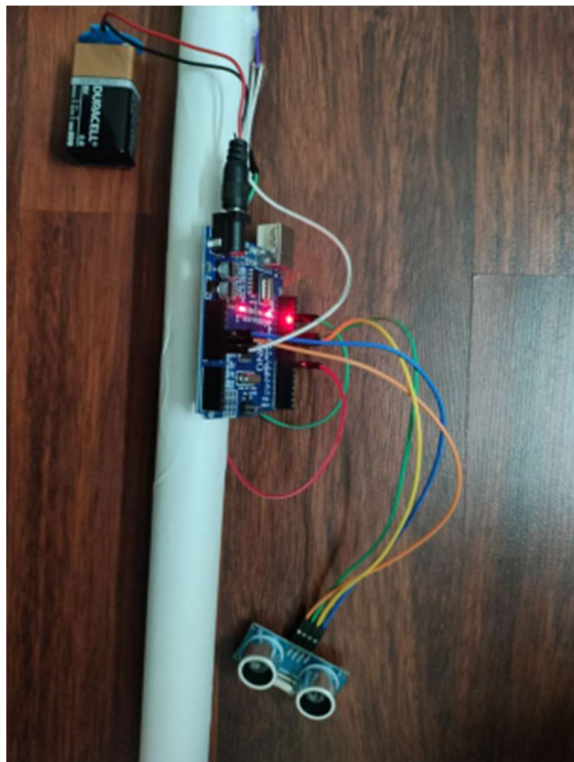


Phase 8: Real-World Testing

The final phase involved testing the completed smart cane in practical conditions using different types of obstacles. The project reports testing the device with walls, suitcases and moving objects to examine its ability to identify obstacles outside the initial laboratory setup. The testing was also used to calibrate the sensitivity of the ultrasonic sensors and reduce false-positive alerts. The system was adjusted to ignore objects beyond one metre so that unnecessary alerts would not overwhelm the user. This phase provided an initial assessment of the prototype's performance in situations resembling everyday mobility and formed the basis for further evaluation and refinement of the smart cane.

The eight phases demonstrate a progressive development process beginning with problem-oriented concept generation and continuing through hardware selection, system design, prototyping, programming, structural integration, assembly and real-world testing. The project therefore provides a strong foundation for the proposed research study. For the research paper, these existing development phases can be presented as the prototype development stage, while the proposed technical measurements and user evaluation can subsequently be presented as the two formal research evaluation phases.

Fig 9 : Real-World Testing



7. Practical Implications

The proposed smart cane has several practical implications for the development of affordable assistive mobility technologies. First, the prototype demonstrates how commonly available and relatively low-cost electronic components, such as ultrasonic sensors, an Arduino-based processing unit and vibration feedback, can be integrated into a familiar mobility

aid. The use of a conventional cane as the physical basis may reduce the need for users to learn an entirely new mobility device. The existing project also demonstrates that sensor positioning, physical mounting and calibration are important practical considerations, particularly because incorrect sensor orientation can result in the ground being detected as an obstacle.

From a human-centered design perspective, the study highlights the importance of considering usability alongside technical performance. A smart cane should not only detect an obstacle but should communicate the information in a form that is easily understood without creating unnecessary alerts. The use of vibration as feedback may be particularly useful in situations where users need to remain aware of surrounding sounds. However, the effectiveness of the feedback, its intensity, timing and interpretation need to be evaluated with actual users. The proposed evaluation can therefore provide practical guidance for improving sensor placement, alert thresholds, cane weight, component arrangement and overall handling. The findings may be useful for students, designers, researchers and developers working on affordable assistive technologies, particularly in contexts where highly sophisticated navigation systems may not be practical because of cost or complexity. The prototype should, however, be considered an additional mobility aid rather than a replacement for the conventional cane until its safety and effectiveness are established through systematic user testing.

8. Conclusion

This study presents a human-centered approach to the design and proposed evaluation of a low-cost smart cane intended to support independent mobility among visually impaired users. The project extends the familiar function of the conventional cane by incorporating ultrasonic sensing and electronic feedback to provide information about obstacles before physical contact. The development process covered brainstorming and conceptualization, hardware selection, circuit design, prototyping, programming, structural development, assembly and preliminary real-world testing. The existing prototype was tested with walls, suitcases and moving objects, and adjustments were made to reduce false-positive alerts.

The study argues that the value of an assistive mobility device should not be assessed only through its technical functioning. Detection accuracy, response time and sensing range are important, but the device must also be comfortable, understandable, usable and appropriate for everyday mobility. Therefore, the proposed methodology combines technical evaluation with user-centered evaluation focusing on usability, haptic feedback, comfort, perceived usefulness, safety and confidence. This approach can help identify the relationship between the technical capabilities of the smart cane and the actual experience of its intended users.

The main contribution of the study is therefore positioned not as the invention of a new smart cane, but as an exploration of how simple, low-cost sensing and haptic feedback can be incorporated into a familiar mobility aid through a human-centered design process. The findings from systematic technical

testing and user evaluation can provide design recommendations for future iterations of the prototype. Further development should focus on larger-scale testing, more diverse environmental conditions, involvement of visually impaired users, refinement of haptic feedback patterns, improved physical integration of components and longer-term evaluation of usability. With these developments, low-cost smart mobility aids may offer an accessible means of providing additional environmental awareness while retaining the familiarity and simplicity of the conventional cane.

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