

Dear Reviewers,

obstacles and a comparative questionnaire with traditional canes would strengthen the evaluation.

**Response:** We revised Section IV.B (User-Centered Evaluation) to explicitly describe the experimental trial: a 4 min 20 s guided route including chairs, trash bins, doors, walls, and stairs. The feedback thresholds (vibration <1 m, buzzer <0.5 m) are now detailed. Furthermore, the evaluation is now clearly presented in two stages:

1. A preliminary survey of 5 users with traditional white canes, identifying difficulties and desired features.
2. A structured trial of the prototype with 4 participants, including a usability survey (average comfort rating 4.75/5, 100% recommendation).

Figure 4 summarizes these results. This clarifies the evaluation process and incorporates the comparative perspective requested.

### **Reviewer StW3**

**Comment 1:** The Results section did not provide sufficient evidence to support claims of ToF sensor superiority over ultrasonic sensors.

**Response:** We added Section IV.C (Comparative Analysis), which details our design transition from ultrasonic HC-SR04 sensors to ToF VL53L0X modules. The comparison addresses size, weight, field of view, robustness in ambient light, and ergonomic integration. This strengthens our argument for selecting ToF sensors.

**Comment 2:** The placement of the survey on existing canes in the evaluation section was confusing.

**Response:** The evaluation has been restructured into two stages (preliminary survey and prototype trial), clearly distinguishing background needs assessment from prototype validation.

**Comment 3:** Suggested simplifying technical illustrations with a block diagram.

**Response:** While we retained detailed schematics and CAD models for technical completeness, we also clarified the system operation in text. Due to space limitations of the short paper format, a simplified block diagram could not be included, but this can be provided as supplementary material if required.

## **Reviewer KDX4**

**Comment 1:** The user evaluation was small-scale, and detection precision was not supported with sufficient technical details.

**Response:** We expanded Section IV.A (Technical Performance) to specify detection precision (error <5 cm) and handling of invalid readings. Thresholds for vibration and buzzer activation are also included. While our user sample remains small due to institutional constraints, we explicitly acknowledge this limitation in the conclusion and propose larger-scale trials as future work.

**Comment 2:** Missing technical specifications on battery life and power consumption.

**Response:** We added a new subsection in IV.A (Technical Performance) quantifying battery autonomy under worst-case (4.1 h), average (8.8 h), and best-case (18.5 h) usage scenarios with a 1200 mAh battery. A summary of this finding was also added to the conclusion.

**Comment 3:** Inconsistencies in microcontroller terminology (ESP8266 vs WEMOS).

**Response:** We standardized terminology throughout the manuscript to ESP8266MOD D1 Mini, resolving this issue.

**Comment 4:** Lack of information on long-term testing and reliability.

**Response:** The limitation of no long-term durability or recharge cycle testing is now explicitly acknowledged in IV.A (Technical Performance) and in the Conclusion as part of future work.

We are grateful for the reviewers' insightful comments, which helped us significantly improve our manuscript. We believe the revised version addresses all concerns and strengthens both the technical and evaluative contributions of our work.

Additionally, as part of this resubmission, we are attaching the following supporting documents as requested:


1. The original manuscript with the removed sections clearly marked.
2. A version highlighting the new material that was added.
3. The final revised manuscript (clean version).


Additionally, in order to address the reviewers' suggestions and comply with the submission restrictions, we reduced the Related Work section and adapted the manuscript format to A4.


Sincerely,

The Authors

# Smart Cane with ToF-Based Obstacle Detection and Multimodal Feedback for Visually Impaired Users

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**Abstract**—This paper presents the design and evaluation of a smart cane prototype designed to enhance independent navigation for individuals with visual impairments. The system integrates two VL53L0X Time-of-Flight (ToF) sensors and an ESP8266MOD D1 Mini microcontroller to detect obstacles at varying heights with high accuracy. Real-time data acquisition enables the generation of intuitive auditory and haptic alerts via a buzzer and vibration motor, offering multimodal feedback based on proximity. The device was tested in real-world settings and iteratively improved through user feedback collected from visually impaired individuals at a local support institution in Barranquilla, Colombia. Results demonstrate a detection precision of under 5 cm within a 1-meter range and a high user acceptance rate, with 90% of participants recommending the device. The system's low-cost architecture (USD 44) and Wi-Fi capability support future expansion, including mobile integration and cloud connectivity. This work contributes to Sustainable Development Goals 10 and 11 by promoting equitable access to mobility tools through affordable, contextually relevant assistive technology.

**Index Terms**—Visual impairment, smart cane, Time-of-Flight sensors, haptic feedback, assistive technology.

## I. INTRODUCTION

For individuals with visual impairments, moving safely through everyday environments remains a constant challenge. Traditional white canes are widely used but are limited to detecting ground-level obstacles, leaving users vulnerable to objects at different heights or in complex surroundings. Although various assistive technologies have been proposed, many are constrained by low detection accuracy, limited adaptability, or lack of validation in real-world conditions.

This project introduces a smart cane designed to address these limitations through a compact, low-cost solution. The device combines Time-of-Flight (ToF) sensors and an ESP8266 microcontroller to detect nearby obstacles with high precision. As the sensors capture spatial data, the system processes it in real time to activate a vibration motor or buzzer, offering intuitive haptic and auditory feedback based on the proximity of the obstacle.

Unlike conventional ultrasonic-based solutions, the use of ToF sensors improves performance in environments with reflective or irregular surfaces [1]. Real-world testing confirmed a detection accuracy of less than 5 cm within a 1-meter range. Thanks to its embedded Wi-Fi module, the device also opens the door to future integration with Internet of Things (IoT) platforms, enabling remote monitoring or over-the-air updates.

The design was refined through iterative testing with users from Fundación de Ciegos in Barranquilla, Colombia. Their feedback helped tailor the system to real needs, ensuring both functionality and user comfort. Beyond the technical achievements, this work supports Sustainable Development Goals 10 and 11 [2], [3], advancing equitable and inclusive mobility for all.

## II. RELATED WORK

Several assistive technologies have been proposed to enhance the mobility of visually impaired individuals, with most focusing on obstacle detection through ultrasonic sensors and basic haptic or auditory alerts. Early approaches, such as the Smart Stick Using Ultrasonic Sensors [4], relied on minimalistic architectures with simple feedback mechanisms, lacking wireless connectivity and field validation. While cost-effective, these designs showed limitations in terms of precision, adaptability, and expansion capabilities.

Subsequent developments, like those presented by [5], incorporated AIoT frameworks to enable features such as GPS tracking, GSM communication, smart home integration, and solar-powered operation. However, the resulting complexity and hardware bulkiness pose usability and maintenance challenges, especially in low-resource settings. Similarly, vision-based solutions such as those integrating HD cameras for object recognition [6] offer rich contextual information but require high processing power, leading to increased energy consumption and potential reliability issues under adverse weather conditions.

Some works, including [7], explored the use of haptic interfaces to enhance spatial perception, highlighting the importance of alert customization to build user trust. Meanwhile, projects like the "IoT Enabled Intelligent Stick" [6] focused on cloud-based data storage and path monitoring, yet still relied on ultrasonic sensors, which are prone to false readings due to surface texture or environmental noise. Finally, some alternatives have been released in the last year using alternatives that are cost-effective but increase the complexity through newer IA-based algorithms, increasing in other aspects that must be afforded by the final users [8].

In contrast, our proposed device introduces a refined balance between performance, cost, and ergonomics. By employing

Time-of-Flight (ToF) sensors instead of conventional ultrasonic ones, we achieve higher accuracy in distance measurement and robustness across diverse urban conditions. Additionally, our solution integrates an ESP8266 microcontroller, enabling **Wi-Fi communication for potential IoT-based features** such as real-time data transmission or over-the-air updates. The system further distinguishes itself by offering **differentiated haptic and auditory feedback based on obstacle type and distance**, a functionality validated through testing with visually impaired users at Fundación de Ciegos in Barranquilla, Colombia.

Importantly, most referenced studies do not report field validation with end-users, focusing instead on laboratory testing or simulated environments. Our research addresses this gap by involving the target population directly in the evaluation process, thereby ensuring practical usability and contextual relevance. Furthermore, our design aligns with Sustainable Development Goals (SDG) 10 and 11, promoting reduced inequalities and inclusive urban mobility.

While the state-of-the-art demonstrates a variety of sensor configurations and integration strategies, the proposed device distinguishes itself through its **lightweight construction, modular expandability, and validation with real users**—characteristics that position it as a scalable and impactful solution for assistive mobility technologies.

### III. SYSTEM DESIGN

This study presents the design and development of a smart cane intended to enhance mobility and safety for individuals with visual impairments. The project focuses on the integration of advanced sensing and embedded technologies—specifically Time-of-Flight (ToF) sensors and a Wi-Fi-enabled microcontroller—into a traditional cane form factor, enabling obstacle detection at multiple heights and improving environmental perception.

#### A. Hardware Architecture

The hardware architecture of the smart cane centers on the ESP8266MOD D1 Mini microcontroller, which is responsible for real-time data acquisition and processing. Mounted near the base of the cane are two VL53L0X Time-of-Flight (ToF) sensors, each capable of detecting objects up to 2.5 meters away within a 27° field of view. These sensors continuously monitor the surroundings, enabling early detection of obstacles at various heights.

To convey proximity information to the user, the system integrates a passive buzzer and a vibration motor, which emit auditory and haptic feedback respectively. These outputs are triggered according to configurable distance thresholds programmed in the device firmware. The entire system is powered by a rechargeable lithium-ion battery, with a USB port facilitating charging and power management. The circuit design emphasizes low energy consumption and compact integration, supporting the portability requirements of assistive devices.

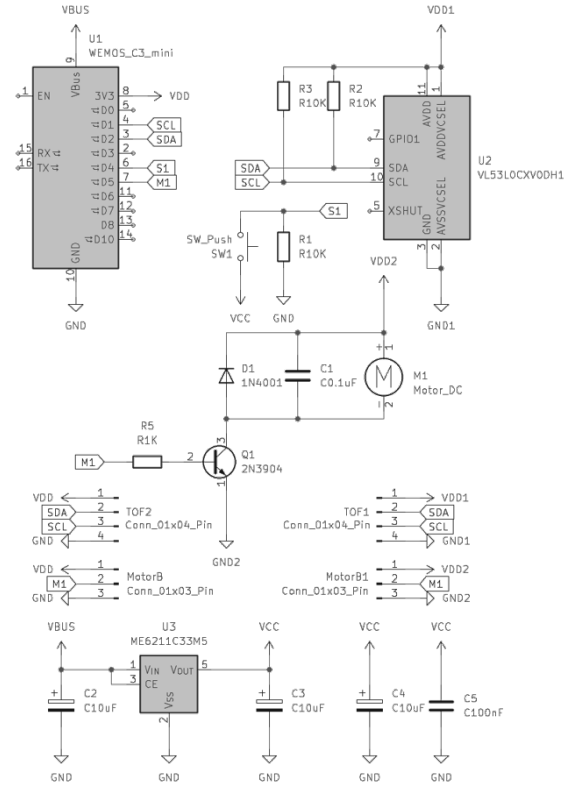


Fig. 1. Electronics schematic of the smart cane system, showing the ESP8266MOD D1 Mini microcontroller, dual VL53L0X ToF sensors, haptic and auditory actuators, and power management elements.

Figure 1 illustrates the complete electronic schematic, including sensor interfaces, actuator drivers, power regulation components, and the microcontroller connections.

To translate the electronic schematic into a compact and manufacturable format, a custom printed circuit board (PCB) was designed. The board integrates all core components, including the **WEMOS C3** Mini microcontroller, power regulation circuits, connectors for the ToF sensors and actuators, and a user interface button. Figure 2(a) shows the 3D-rendered view of the final PCB, while Figure 2(b) displays the corresponding layout with signal routing and copper planes.

#### B. Mechanical Design

Figure 3 (a) illustrates the isometric design of the smart cane's components, modeled in SolidWorks. The structure consists of 3D-printed PET-G segments, selected for their durability and low weight. An acrylic enclosure protects the electronic modules, including a ToF sensor (shown in Figure 3 b) and an ESP8266 microcontroller unit (shown in Figure 3 c). The ergonomic handle incorporates haptic and auditory actuators to ensure intuitive feedback for the user. The total weight of the assembled cane is optimized for daily use without causing hand fatigue.

#### C. Software Design

The system was programmed using the Arduino IDE, leveraging existing libraries for the VL53L0X ToF sensors and

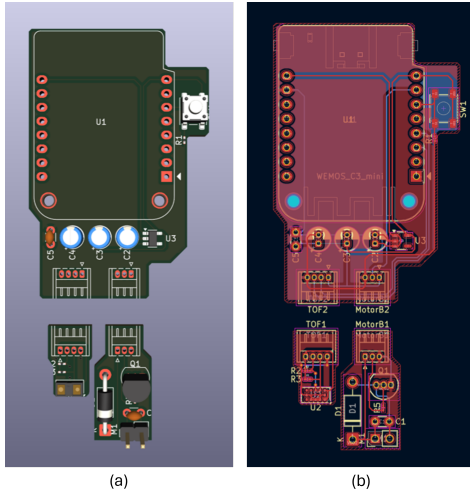


Fig. 2. (a) 3D-rendered view of the custom PCB designed for the smart cane system. It shows the placement of components, connectors, and the microcontroller footprint. (b) Top-layer PCB layout showing the routing of signal traces, component labels, and copper pours used in the final board design.

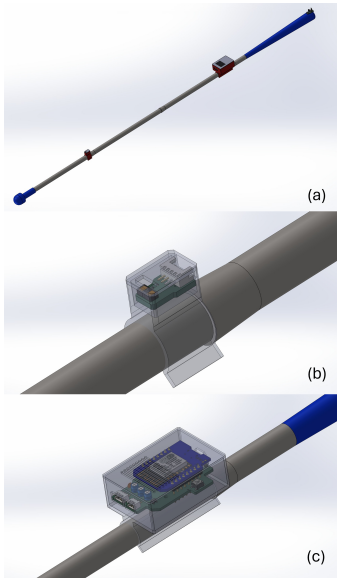


Fig. 3. CAD model of the smart cane. (a) Full assembly with sensor modules and ergonomic handle. (b) Enclosure for the ToF sensor and circuit, mounted near the base. (c) Main housing for the ESP8266 D1 Mini near the handle.

optimized control routines. The main loop continuously polls distance readings from both sensors and triggers corresponding feedback mechanisms depending on user-defined thresholds. For instance, when an object is detected within 100 cm, the vibration motor is activated, and as the distance decreases, the buzzer frequency increases to indicate urgency.

#### D. Assembly and Integration

The electronics were modularly mounted inside the protective casing, with wiring routed to minimize interference. A printed circuit board (PCB) supports all components and

is securely housed in the lower section of the cane. The modularity of the design enables straightforward maintenance or component replacement, which is essential for long-term usability in assistive devices. The resulting prototype constitutes a cost-effective and efficient solution for independent navigation, supporting the objectives of inclusivity and accessibility as defined by Sustainable Development Goals 10 and 11. The smart cane proves that embedded technology can be effectively integrated into assistive devices, bridging the gap between affordability and functionality.

## IV. RESULTS AND DISCUSSION

The smart cane prototype was developed to improve obstacle detection and spatial awareness for visually impaired users through the integration of Time-of-Flight (ToF) sensors and a Wi-Fi-enabled ESP8266 microcontroller. Technical validation and user-centered testing were carried out to assess the device's performance and usability in real-world scenarios.

### A. Technical Performance

The device features two ToF sensors mounted near the bottom of the cane. These sensors are capable of detecting obstacles at distances of up to 2.5 meters within a 25-degree field of view, allowing the system to capture objects located at varying heights. This design significantly improves upon conventional white canes, which are often limited to ground-level detection.

The ESP8266 microcontroller was selected due to its compact form factor, low energy consumption, and integrated Wi-Fi capabilities. These features support future enhancements such as GPS integration, data logging, or real-time alerts. The development environment based on the Arduino IDE further facilitated rapid prototyping and customization of detection algorithms.

In terms of user feedback, two complementary alert mechanisms were implemented. A buzzer generates acoustic signals that vary in frequency depending on the proximity of the obstacle, while a haptic motor embedded in the handle delivers tactile pulses that intensify as the user approaches the object. This dual feedback strategy offers intuitive spatial cues without overwhelming the user.

### B. User-Centered Evaluation

To evaluate the real-world impact of the prototype, a survey was conducted with five visually impaired individuals at FUNDAVE, the only specialized institution for blind people in Barranquilla, Colombia. The goal was to assess their experience with traditional white canes and gather feedback for further improvement of the smart cane. The figure 4 shows the Key insights from the survey which include:

- Cane Usage History: Four participants learned to use the cane through formal training (FUNDAVE or CRAC), and one was still undergoing instruction.
- Adoption Time: While three participants accepted cane use immediately or within a few years, two took over four



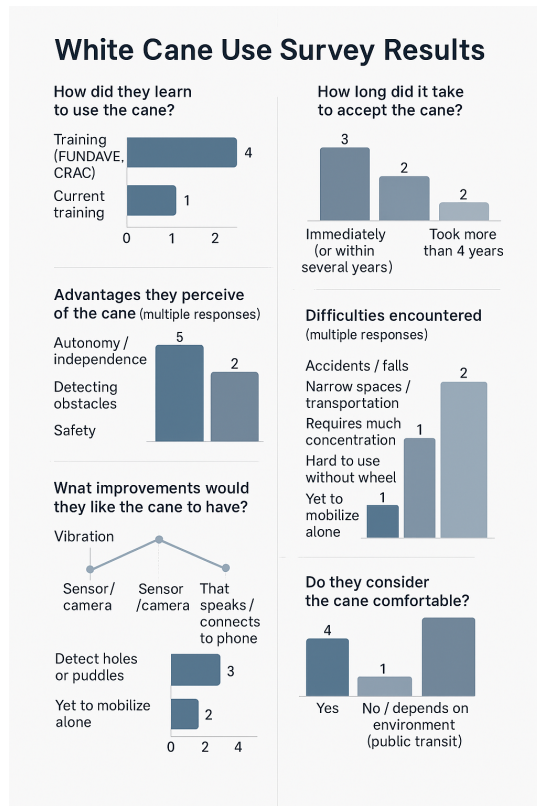


Fig. 4. Summary of the Survey Results

years to adapt to it, highlighting emotional and cognitive barriers to assistive technology adoption.

- **Perceived Benefits:** The most commonly reported advantages were obstacle detection (5/5 responses), enhanced autonomy (4/5), and increased safety (2/5).
- **Common Difficulties:** Participants noted issues such as accidents and falls (3), difficulties in narrow spaces or public transportation (2), and mental fatigue due to required concentration (1).
- **Desired Enhancements:** Survey respondents expressed interest in additional features such as vibrational feedback (4), cameras or sensors for environment mapping (3), smartphone connectivity or voice interaction (3), and the ability to detect puddles or uneven terrain (2).
- **Comfort and Ergonomics:** Four users described the cane as comfortable, while one noted limitations in public transport scenarios.

## V. CONCLUSION AND FUTURE WORK

The development of the smart cane for visually impaired individuals highlights the potential of low-cost technologies in addressing critical accessibility challenges. The prototype integrates two VL53L0X Time-of-Flight (ToF) sensors with a maximum detection range of 2.5 meters, managed by an ESP8266MOD D1 Mini microcontroller. This configuration allows the detection of obstacles at varying heights and delivers reliable, real-time feedback to the user.

The alert system combines an auditory buzzer and a haptic vibration motor, offering intuitive multimodal feedback adaptable to diverse environmental conditions. The physical structure consists of a 3D-printed PET-G frame and an acrylic protective enclosure, ensuring durability, portability, and ease of maintenance.

User testing conducted at the Fundación de Ciegos in Barranquilla confirmed high acceptance: 90% of participants reported that they would recommend the device, and 80% felt safer while using it. The total cost of the primary electronic components was approximately COP 164,000 (around USD 44), demonstrating its economic viability when compared to commercial alternatives.

These results validate that a carefully designed, user-tested assistive device can significantly enhance autonomy and safety for visually impaired individuals, while remaining affordable and scalable. The inclusion of real users throughout the testing phase ensured contextual relevance, strengthened usability, and offered valuable insights for iterative development.

Looking ahead, the system's Wi-Fi capability opens avenues for future integration with mobile applications, cloud services, and geolocation tools. Planned enhancements include mobile connectivity (e.g., GSM or BLE), terrain-type recognition, and ergonomic refinements to further improve user comfort. By promoting inclusive mobility and reducing technological barriers, this project contributes directly to Sustainable Development Goals 10 (Reduced Inequalities) and 11 (Sustainable Cities and Communities).

## ACKNOWLEDGMENT

The authors thank FUNDAVE (Fundación de Ciegos de Barranquilla), CRAC (Centro de Rehabilitación para Adultos Ciegos), and the Institución Universitaria de Barranquilla for their support and collaboration during the development and testing of this project.

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