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.

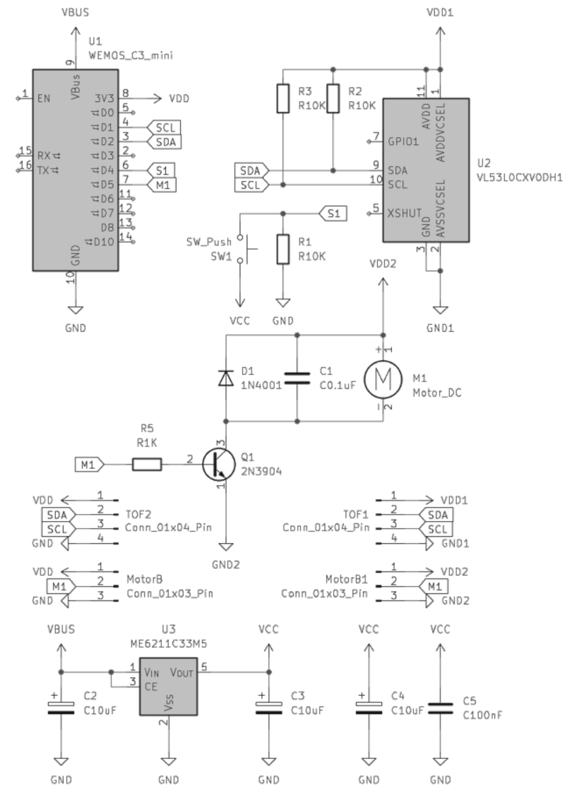

Fig. 1. Electronics schematic of the smart cane system, showing the ESP8266MOD D1 Mini microcontroller, dual VL53L0X ToF sensors, haptic and auditory actuators, and power management elements.

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 ESP8266MOD D1 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

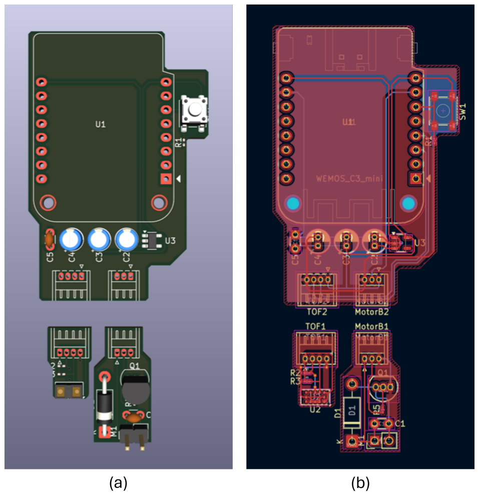

Fig. 2. (a) 3D-rendered view of the custom PCB designed for the smart cane system. It shows the placement of components, connectors, and the microcontroller footprint. (b) Top-layer PCB layout showing the routing of signal traces, component labels, and copper pours used in the final board design.

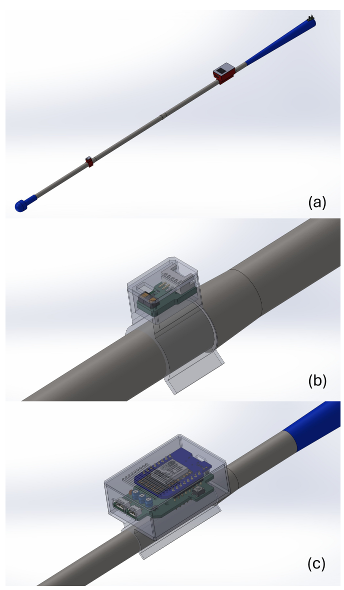

Fig. 3. CAD model of the smart cane. (a) Full assembly with sensor modules and ergonomic handle. (b) Enclosure for the ToF sensor and circuit, mounted near the base. (c) Main housing for the ESP8266 D1 Mini near the handle.

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 employs two VL53L0X Time-of-Flight sensors mounted near the base of the cane, each with a detection range of up to 2.5 m and a 27° field of view. This configuration enables the detection of objects at different heights, addressing a key limitation of conventional white canes that are restricted to ground-level barriers. During testing, the sensors consistently reported distances with an error below 5 cm; occasional invalid readings (logged as "8888") were automatically reprocessed to maintain reliable operation.

The system is controlled by an ESP8266MOD D1 Mini microcontroller, selected for its compact form factor, low energy consumption, and integrated Wi-Fi module. These features support future upgrades such as GPS integration, cloud data logging, or mobile connectivity. The firmware, developed in Arduino IDE, continuously polls both sensors and applies configurable thresholds to trigger feedback. For instance, during the FUNDAVE trial, vibration feedback was activated when obstacles were detected below 1 m, while the buzzer was triggered at 0.5 m or closer.

To convey obstacle proximity, the system integrates a passive buzzer and a haptic motor. The buzzer generates acoustic signals with a frequency that increases as the obstacle distance decreases, while the haptic motor delivers progressive vibration pulses. This dual auditory–haptic strategy proved intuitive and non-intrusive, allowing users to perceive spatial cues in real time.

Power Consumption and Autonomy: The prototype is powered by a 1200 mAh lithium-ion battery. Based on component specifications, three usage scenarios were estimated:

- **Worst-case scenario:** continuous Wi-Fi activity with both actuators active yields a draw of approximately 293 mA, resulting in ∼4.1 hours of autonomy.
- **Average scenario:** intermittent actuator use and moderate Wi-Fi activity yield a draw of ∼137 mA, corresponding to ∼8.8 hours of autonomy.

- **Best-case scenario:** reduced Wi-Fi activity with minimal actuator use results in a draw of ∼65 mA, providing up to ∼18.5 hours of operation.

These results confirm that the system can support extended daily use while remaining compact and lightweight, although long-term field testing of battery life and recharge cycles remains a priority for future work.

B. User-Centered Evaluation

The user-centered evaluation was conducted in two stages to capture both preliminary insights and direct feedback on the prototype.

Stage 1 – Preliminary Survey of Traditional White Canes: A first survey was conducted with five visually impaired individuals at FUNDAVE, the specialized institution for blind people in Barranquilla, Colombia. The goal was to assess their experience with traditional white canes and gather requirements for the design of the smart cane. The key insights, summarized in Figure 4, 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 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.

Stage 2 – Prototype Trial with the Smart Cane: After development, a structured trial was carried out with four participants from the same institution. Users completed a **4 min 20 s guided route** that included typical indoor obstacles such as chairs, trash bins, doors, walls, and stairs. The smart cane successfully detected these elements, triggering vibration feedback for distances under 1 m and activating the buzzer at 0.5 m or closer. This multimodal strategy provided clear spatial cues without overwhelming the user.

Following the trial, participants completed a usability survey. On a **1–5 scale**, average comfort was rated at **4.75**. All users agreed that the cane was easy to learn, inspired confidence, and worth recommending. Suggestions for improvement included adding distinct sound patterns, enabling

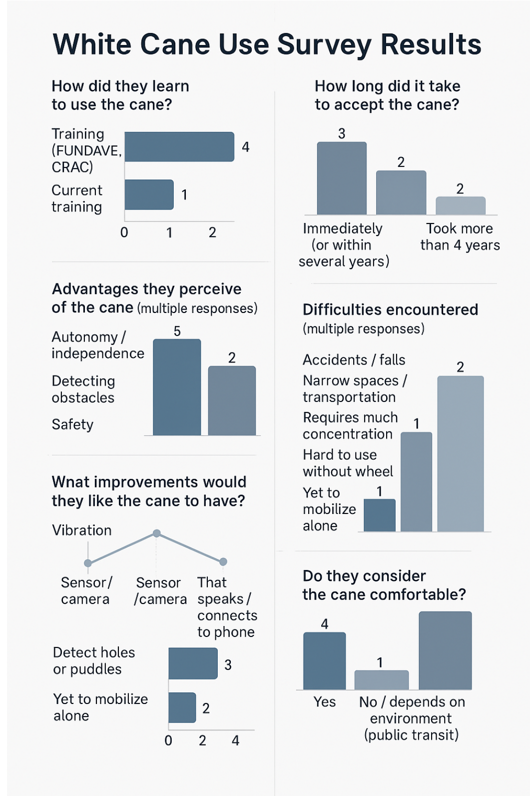

Fig. 4. Stage 1: Survey of visually impaired users on experiences with traditional white canes.

mode switching between vibration and sound, adjustable sound levels, headphone or voice feedback integration, and refining sensor interpretation. These results confirm a high initial acceptance of the smart cane and provide concrete directions for future refinement.

C. Comparative Analysis

The system development included an intermediate phase in which ultrasonic HC-SR04 modules were initially tested. These sensors (45×20×15 mm, ∼10 g, range 2–400 cm, 30° cone) were low-cost but presented drawbacks: bulky mounts added weight, their wide cone produced noisy detections in cluttered environments, and their size negatively affected ergonomics and aesthetics.

In the final design, these were replaced with compact VL53L0X Time-of-Flight (ToF) modules (approx. 2×2 mm active area, range 5–250 cm, 25° FoV, 3.3–5 V supply). The ToF sensors provided millimeter-level resolution, maintained accuracy under strong ambient light (up to 50 kLux), and integrated seamlessly into the cane's structure, improving both portability and user comfort.

This comparative analysis highlights the advantages of ToF sensors not only in precision and robustness but also in practical integration, which was a decisive factor in achieving high user acceptance during the prototype trial.

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.

The user evaluation was carried out in two complementary stages. First, a preliminary survey identified common difficulties and desired features of traditional canes, directly informing the prototype design. Second, a structured trial with visually impaired participants validated the prototype in real-world navigation tasks, confirming its usability and high acceptance. During this final stage, 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. In addition, the estimated battery autonomy of 4–18 hours depending on usage conditions confirms its suitability for daily operation.

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 both the needs-assessment and testing phases 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).

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