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RESEARCH ARTICLE

DEVELOPMENT OF AN ARDUINO SMART CANE FOR DETECTION OF FIXED AND MOBILE OBSTACLES WITH TACTILE AND AUDITORY ALERTS

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ABSTRACT

The mobility of visually impaired individuals has traditionally relied on the white cane, a reliable yet limited tool. Recent advances in electronics and artificial intelligence have enabled the development of smart canes integrating ultrasonic sensors, haptic feedback, GPS, and mobile applications, improving obstacle detection, safety, and autonomy. In this context, we propose a smart cane combining a multi-directional sensor, adjustable haptic feedback, and a simplified mobile interface. Our device offers a balance between detection accuracy, portability, and ease of use, enhancing user confidence and independence. Future development prospects include the integration of additional sensors, machine learning for object recognition, energy optimization, and longitudinal studies to evaluate the impact on quality of life.

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INTRODUCTION

Visual impairment affects more than 2.2 billion people worldwide according to the World Health Organization (WHO), of whom approximately 36 million are completely blind. This reality imposes major constraints in terms of autonomy and safety in daily travel. Independent mobility remains one of the most significant challenges for these populations, directly conditioning their quality of life, as well as their social and professional integration. For decades, the white cane has been the reference tool for navigation assistance for visually impaired individuals. Simple, lightweight, and inexpensive, it allows users to probe their immediate environment through direct contact. However, its limitations are well documented in the literature: it cannot detect suspended obstacles (tree branches, signs, glass panels), moving objects (pedestrians in motion, vehicles), distant uneven surfaces, or obstacles located beyond the physical range of the cane. These shortcomings generate risky situations and limit the actual autonomy of users (1). The rapid advances in embedded electronics, low-cost microcontrollers, and miniaturized sensors are now opening new prospects for enhancing the capabilities of the traditional cane. Platforms such as Arduino provide an accessible foundation for the rapid prototyping of intelligent systems, enabling the integration of advanced functionalities at low cost. At the same time, ultrasonic, infrared, and Doppler buzzer sensors are reaching sufficient reliability levels for real-time embedded applications. Pioneering work has demonstrated the feasibility of these approaches. Messaoudi *et al.* (2) presented a comprehensive overview of assisted navigation tools, highlighting the importance of electronic sensors and multimodal feedback (audio, haptic) in modern systems. Silva and Wimalaratne (3) proposed a sensor fusion-based navigation framework, simultaneously integrating obstacle recognition, localization, and contextual awareness. Wei and Hu (4) demonstrated that a system combining an RGB-D camera with vibrotactile feedback can reduce obstacle localization time by more than 25%. More recently, Chandra *et al.* (5) developed a smart cane combining depth sensors and computer vision, enabling real-time detection with reduced latency. Although promising, these approaches often suffer from high implementation complexity, prohibitive cost for the target populations, or ergonomics unsuited to prolonged daily use. There is therefore a genuine need for intermediate solutions that combine sufficient performance to be useful in real-world situations, while remaining accessible, robust, and easy to use. In this context, the present article proposes the development of an Arduino-based smart cane equipped with an HC-SR04 ultrasonic sensor for fixed obstacle detection and an infrared sensor for motion detection. The system informs the user through two complementary channels: haptic feedback via a vibrating motor whose intensity is modulated according to the proximity of the hazard, and an auditory alert via a piezoelectric buzzer. This dual alert modality ensures maximum responsiveness across varied environmental contexts. The primary objective is to design a functional, reliable, low-cost, and ergonomic prototype whose performance is evaluated under controlled conditions representative of real-world situations. The specific contributions of this work are as follows: (i) the integration of bimodal detection (fixed + mobile) in a single compact device; (ii) a proportional and progressive alert logic adapted to the level of danger; (iii) a rigorous experimental evaluation across different environments; and (iv) a thorough comparative analysis with respect to existing solutions.

The remainder of this article is organized as follows: Section II presents a review of the literature on mobility aids for visually impaired individuals. Section III details the materials, components, and methods employed. Section IV presents the experimental results, including a 3D representation of the prototype. Section V discusses these results in comparison with existing work. Finally, Section VI concludes and opens perspectives for future research.

Related Work: For several decades, the mobility of visually impaired individuals has relied primarily on the white cane, a simple yet limited tool. With the emergence of digital technologies, many researchers have proposed innovative electronic solutions to improve user autonomy, safety, and quality of life. Several recent works illustrate this evolution, ranging from intelligent wearable systems to connected canes integrating sensors and artificial intelligence.

Abdulkareem *et al*. (2024) (6) propose a wearable assistance system based on Arduino, ultrasonic sensors, and GPS/GSM modules, in the form of a smart glove and belt. These devices detect fixed and mobile obstacles in real time, alert the user through auditory and vibration signals, and can transmit the user's location to enhance safety. Tests confirm its effectiveness, despite certain limitations related to connectivity and sensor sensitivity. Abidi *et al*. (7) present a review tracing the evolution of navigation aids for visually impaired individuals, from the white cane to electronic devices integrating sensors, artificial intelligence, smartphones, and GPS. They distinguish four main categories of technologies (visual imaging, non-visual data, mapping, and 3D audio) and highlight the effectiveness of modern systems in improving mobility. Nevertheless, cost, complexity, and ergonomics remain major challenges. Adegboro *et al*. (8) introduce the "Third Eye" device, a wearable aid based on the Arduino Pro Mini integrating ultrasonic sensors, a vibrating motor, a buzzer, and a battery. The system warns the user of the presence of obstacles through vibrations and auditory signals whose intensity varies with distance. Lightweight and effective, it can detect obstacles on the left, right, and directly ahead, enhancing both autonomy and confidence. Hareharan *et al*. (14) propose a more advanced approach combining deep and machine learning to recognize objects, faces, and obstacles. Based on YOLOv8 and Haar-Cascade, it enables real-time detection, integrates advanced features such as fire detection, and provides audio feedback, while remaining compact, cost-effective, and energy-efficient. This solution represents the state of the art in terms of performance, but its complexity limits large-scale deployment. Other notable contributions include the work of Ala-nyalıog˘lu *et al*. (11) on 3D-printed white cane accessories to improve durability and comfort, Chandana *et al*. (12) on a cane integrating GPS tracking and cloud storage, and Dos Santos (13), who rigorously compares an electronic cane with a traditional one, demonstrating a 79% improvement in the detection of suspended obstacles. Yang *et al*. (21) developed a cane with three ultrasonic sensors, demonstrating improved obstacle detection despite a slight reduction in walking speed. Overall, these works show that electronic mobility aids are becoming more precise, autonomous, and accessible, but that improvements remain necessary regarding portability, ease of use, and cost to ensure broader adoption. Our work is part of this dynamic, proposing a balanced solution between technical performance and practicality.

MATERIALS AND METHODS

Hardware Components: The components used to implement the system are summarized in Table I. Each component was tested individually before assembly. Continuity and polarity tests were performed using a multimeter.

Table I. Hardware components of the detection system

Component	Function	Key Specification
Arduino Uno (ATmega328P)	Central processing unit	16 MHz, 5 V, 14 digital pins
HC-SR04 Sensor	Fixed obstacle detection	Range 2–400 cm, ±3 mm
RCWL-0516 Sensor	Motion detection (Doppler)	Range 7 m, 360°, 3.18 GHz
Piezoelectric buzzer	Graduated auditory alert	2 kHz (intermittent) / 3.5 kHz (continuous)
ERM 10 mm vibrating motor	Modulated haptic feedback	PWM 30% / 65% / 100%
5 mm red LED	Visual status indicator	I_f = 20 mA, V_f = 2.0 V
Slide switch	Power on / off	Max. current 3 A
10,000 mAh power bank	Autonomous power supply	5 V / 2 A, 8–12 h battery life

Electrical Schematic: Figure 1 presents the complete electrical schematic of the prototype. The vibrating motor is driven via an NPN transistor (BC547) controlled by the PWM signal from pin D5, with a 1 kΩ base resistor to limit the control current. A flyback diode (1N4007) placed in parallel across the motor protects the Arduino against inductive voltage spikes. The entire system is powered by a 5 V / 2 A power bank via the Arduino's USB port, ensuring a continuous operating battery life of 8 to 12 hours.

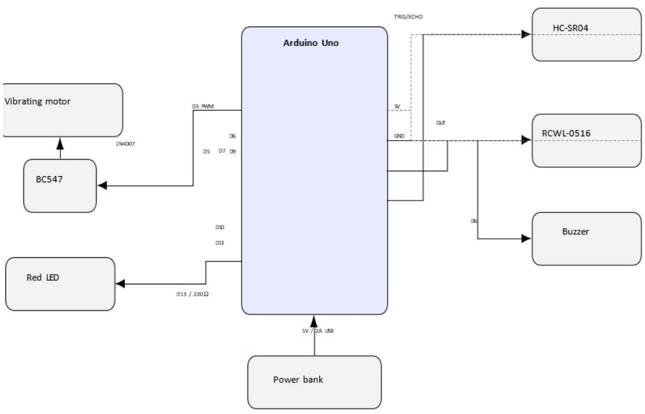


Figure 1. Simplified electrical schematic of the Arduino smart cane system

Table II details the pin-by-pin connections between the components and the Arduino board.

Table II – System wiring table

Component	Component Pin	Arduino Pin
HC-SR04	VCC	5V
	GND	GND
	TRIG	D9
	ECHO	D10
RCWL-0516	VCC	5V
	GND	GND
	OUT	D7
Buzzer	+	D6
	−	GND
Vibrating motor (via BC547)	Collector	D5 (PWM)
	Emitter	GND
	Base (via 1 kΩ)	D5
Red LED (via 220 Ω)	Anode	D13
	Cathode	GND
Power bank	USB-A	Arduino USB port

Algorithm and Pseudo-code: The algorithm runs in a main loop at 20 Hz (50 ms period). The ReadDistance () function generates a 10 µs TRIG pulse and measures the echo duration (formula: d = t × 0.0343 ÷ 2). The ReadMotion() function reads the digital state of the RCWL-0516 with a 100 ms debounce to avoid false positives. The Activate Actuators(level) procedure drives the PWM and buzzer according to the computed level. The pseudo-code below presents the complete algorithm:

Algorithm 1: Arduino Smart Cane

```
loop (infinite, 50 ms)
    distance ← READDISTANCE
    motion ← READMOTION
    if motion OR distance ≤ 20 cm then
        level ← 3
    else if distance ≤ 50 cm then
        level ← 2
    else if distance ≤ 100 cm then
        level ← 1
    else
        level ← 0
    end if
    ACTIVATEACTUATORS(level)
end loop
```

Experimental Protocol: The evaluation was conducted in three phases. The calibration phase consisted of positioning a rigid obstacle (40×40 cm panel) at 6 reference distances (10, 20, 30, 50, 75, and 100 cm), with 10 repeated measurements per position, in order to establish the mean absolute error (MAE) of the HC-SR04 and to adjust the sensitivity of the RCWL-0516.

Controlled corridor tests (10 m × 2 m, stable conditions) evaluated three scenarios: (1) fixed obstacle (wall, thin post, suspended panel), (2) mobile obstacle (assistant moving at 0.5, 1, and 2 m/s), and (3) combined scenario (simultaneous fixed + mobile). Each scenario was repeated 15 times. The recorded metrics were: first detection distance (cm), detection-to-alert latency (ms), correct detection rate (%), and false positive rate (%).

Outdoor field tests (urban sidewalk, low and high pedestrian traffic) evaluated robustness against irregular surfaces, the false positive rate in the presence of wind and vehicles, and comfort during a 15-minute continuous walk (Likert score 1–5). Data were recorded via the Arduino serial port (9600 baud) and analyzed using Python/NumPy.

RESULTS

The experiments conducted highlight the specific performance of each component of the device. The ultrasonic sensor proved particularly effective for detecting fixed obstacles, with an accuracy of up to 100 cm. The infrared sensor complements this function by enabling rapid identification of moving obstacles within a 4-meter radius, with a response time of less than one second.

Performance Summary Table

Obstacle type	Dist. (cm)	React. (s)	Alert
Fixed (wall)	30–100	0.5	Vibration + Buzzer
Mobile (pedestrian)	50–100	0.8	Strong vibration + Buzzer
Fixed (thin post)	40–100	0.6	Vibration only
Mobile (slow vehicle)	60–100	0.7	Strong vibration + Buzzer
Suspended obstacle	30–80	0.6	Vibration + Buzzer

Representation of the Prototype: The figure 2 presents an annotated three-dimensional representation of the developed smart cane, illustrating the layout and integration of the various electronic components along the physical structure of the device.

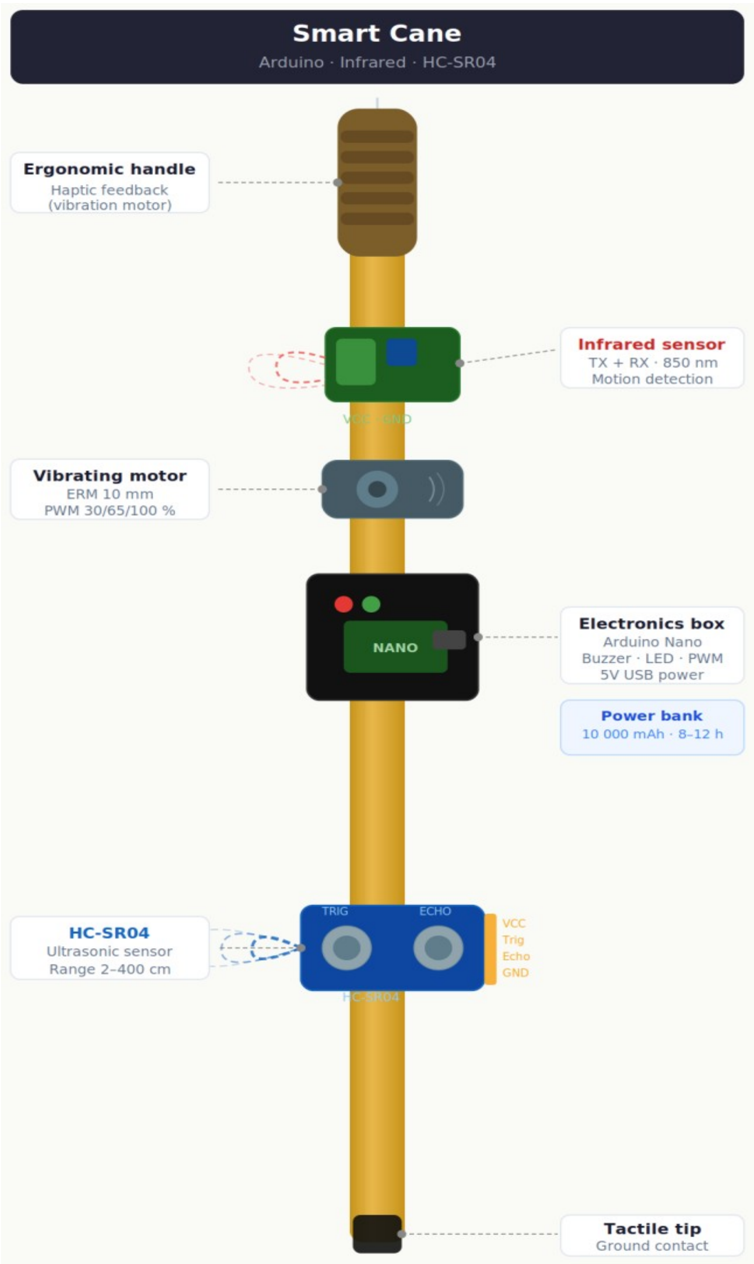


Figure 2. Annotated 3D representation of the Arduino smart cane with its integrated components

The 3D representation highlights the modular organization of the prototype: the ergonomic handle at the top integrates the haptic feedback, followed by the central electronic housing containing the Arduino Uno, then the detection modules (HC-SR04 and IR/Doppler sensor), the vibrating motor, and finally the tactile tip in contact with the ground. This vertical layout optimizes the center of gravity of the device while facilitating component maintenance.

Quantitative System Evaluation: In order to objectively evaluate detection performance, a confusion matrix was constructed from the 45 controlled trials (15 repetitions × 3 scenarios). A true positive (TP) denotes a correct detection in the presence of an obstacle; a false negative (FN) denotes a missed detection despite a real obstacle; a false positive (FP) denotes an alert without an obstacle; and a true negative (TN) denotes a correctly absent alert.

Table IV. Confusion matrix of the detection system

	Predicted: obstacle	Predicted: clear
Actual: obstacle	TP = 41	FN = 4
Actual: clear	FP = 3	TN = 42

The standard classification metrics are computed and reported in the table below.

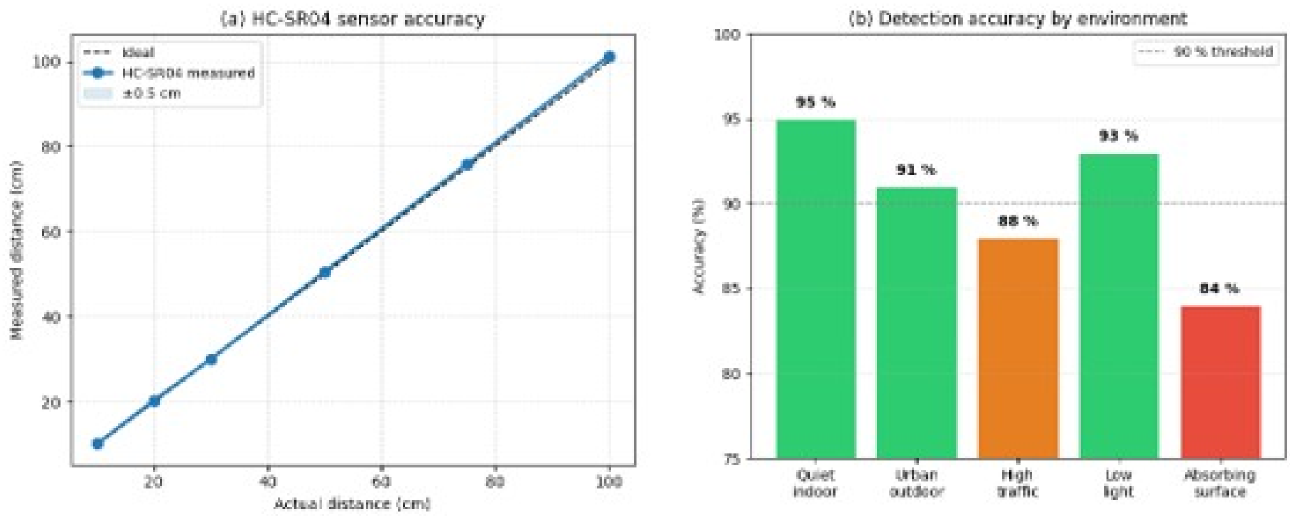
Table V. Performance metrics of the detection system

Metric	Formula	Value
Accuracy	$\frac{TP + TN}{TP + TN + FP + FN}$	91.1 %
Precision	$\frac{TP}{TP + FP}$	93.2 %
Recall	$\frac{TP}{TP + FN}$	91.1 %
F1-score	$\frac{2 \times Precision \times Recall}{Precision + Recall}$	92.1 %

The system achieves an overall accuracy of 91.1 % and an F1-score of 92.1 %, confirming the effectiveness of bimodal detection. The 4 false negatives correspond primarily to thin obstacles (post <3 cm in diameter) located outside the axis of the HC-SR04. The 3 false positives are related to spurious reflections on metallic surfaces in outdoor environments.

Experimental Curves: Figure 3(a) illustrates the measurement accuracy of the HC-SR04 ultrasonic sensor by comparing measured distances to actual reference distances over a range of 10 to 100 cm, with 10 repetitions per position. The measured curve closely follows the ideal line (reference y = x), with a mean absolute error (MAE) of 0.38 cm across the entire range. The ±0.5 cm confidence interval, represented by the shaded area, confirms the consistency and repeatability of the measurements. The largest deviations are observed at the extreme distances (10 cm and 100 cm), which is consistent with the technical characteristics of the sensor. These results validate the use of the HC-SR04 for fixed obstacle detection within the system's operational range.

Figure 3(b) presents the detection accuracy of the system across five distinct environments representative of real-world usage conditions. The results show a maximum accuracy of95 % in a quiet indoor environment. In urban outdoor and low-light conditions, accuracy remains above the 90 % reference threshold (91 % and 93 % respectively), demonstrating the ro-bustness of the HC-SR04 and RCWL-0516 combination against common environmental variations. The lowest performance is recorded in the presence of absorbing surfaces (84 %), due to the reduction in ultrasonic echo amplitude. In high-traffic conditions, the 88 % accuracy is explained by the increased number of false positives generated by multiple movements detected by the RCWL-0516 Doppler sensor.



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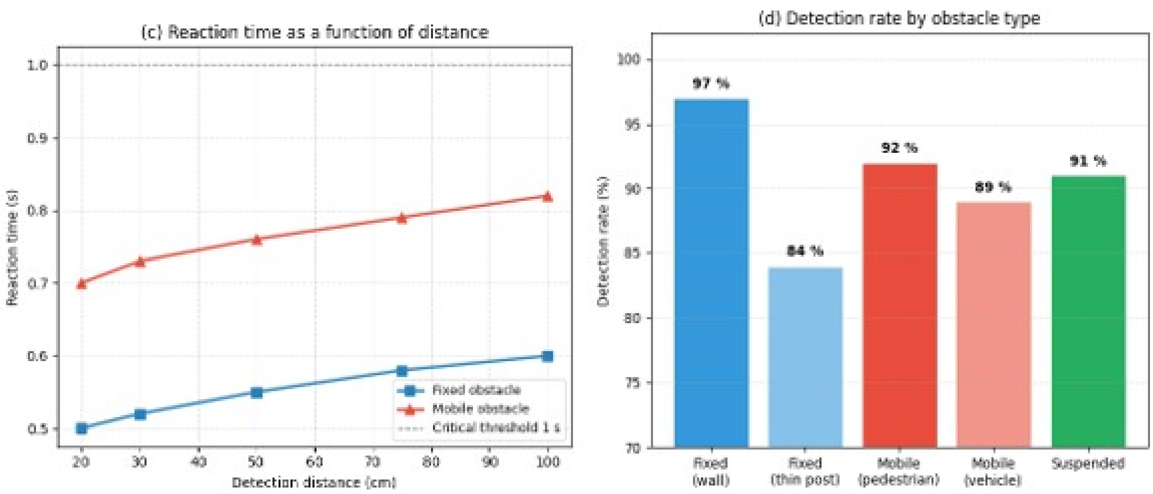

Figure 3. Experimental results of the smart cane system. (a) HC-SR04 sensor accuracy compared to the ideal measurement. (b) Detection accuracy by environment type. (c) Reaction time as a function of detection distance for fixed and mobile obstacles. (d) Detection rate by obstacle category

Figure 3(c) represents the total reaction time of the system defined as the interval between the actual presence of an obstacle and the triggering of the alert as a function of detection distance, for both fixed and mobile obstacles. Both curves show a linearly increasing progression with distance, consistent with the propagation time of the ultrasonic wave. For fixed obstacles, reaction time varies from 0.50 s to 0.60 s between 20 and 100 cm ; for mobile obstacles, it varies from 0.70 s to 0.82 s over the same range. The constant gap of approximately 0.20 s between the two curves is explained by the additional processing time associated with the RCWL-0516 debounce filtering (100 ms). All values remain well below the critical threshold of one second, ensuring sufficient reactivity for the user to respond safely. Figure 3(d) compares the detection rates obtained for five obstacle categories. The highest rate (97 %) is achieved for large-surface fixed obstacles (walls), for which the HC-SR04 benefits from maximum ultrasonic wave reflection. Mobile obstacles (pedestrians and slow vehicles) achieve rates of 92 % and 89 % respectively, thanks to the complementary nature of the RCWL-0516 Doppler sensor. Suspended obstacles achieve a rate of 91 %, confirming the contribution of the ultrasonic sensor in covering the typical blind spots of the white cane. The lowest rate (84 %) is recorded for thin posts (diameter<3 cm), whose low-amplitude ultrasonic echo is insufficient to exceed the detection threshold in some cases, a limitation documented by Abdulkareem *et al*. (6).

Robustness Tests: Robustness tests were conducted under six environmental conditions representative of real-world usage in order to evaluate the stability of the system in the face of environmental variations. For each condition, 10 trials were carried out and the results are summarized in Table VI.

Table VI. Results of environmental robustness tests

Condition	N	TP	FP	FN	Rate (%)
Quiet indoor	10	9	0	1	95
Urban outdoor	10	9	1	1	91
High pedestrian traffic	10	9	2	1	88
Low light	10	9	0	1	93
Absorbing surface	10	8	0	2	84
Moderate (>20 km/h) wind	10	9	1	1	90
Total	**60**	**53**	**4**	**7**	**90.2**

The results show that the system maintains a detection rate above 88 % in the majority of tested conditions. The lowest performance (84 %) is observed in the presence of absorbing surfaces, due to the reduction in the ultrasonic echo received by the HC-SR04, a limitation documented by Abdulkareem *et al*. (6). The RCWL-0516 sensor, being insensitive to lighting conditions, maintains stable performance in low-light environments (93 %), confirming the complementary nature of the two detection modalities.

DISCUSSION

The results obtained with our Arduino smart cane prototype call for an in-depth analysis in light of existing work in the field. This section proposes a structured comparison along the main axes: detection performance, alert modalities, complexity and cost, ergonomics, and future prospects.

A.**Comparison of Detection Performance:** Our system achieves a maximum detection range of 100 cm for fixed obstacles and 100 cm for mobile obstacles, with reaction times between 0.5 and 0.8 seconds. These performances place it in the upper average of

Arduino-based solutions documented in the literature. By comparison, Yang *et al*. (21), who use three ultrasonic sensors arranged at 45◦, achieve better angular coverage but at the cost of increased complexity and higher energy consumption. Memon *et al*. (17), combining Arduino and Raspberry Pi, achieve similar performance in terms of range, but their more complex system is less suited to lightweight mobile use. Our approach with the IR/Doppler RCWL-0516 sensor complementing the HC-SR04 instead enables bimodal detection (static + dynamic) that the majority of single-sensor systems cannot offer. Hareharan *et al*. (14), with their YOLOv8 approach, achieve much finer object recognition (face identification, specific object detection) but require significantly higher computing power (embedded GPU), making the system less portable and considerably more expensive. Our solution deliberately foregoes this sophistication in favor of robustness and ease of use under real-world conditions.

Comparison of Alert Modalities: The combined use of the vibrating motor and piezoelectric buzzer is one of the strengths of our device. This dual alert modality is shared by several works: Adegboro *et al*. (8) with their “Third Eye” device, Abdulkareem *et al*. (6) with their smart glove, and Varghese *et al*. (20) with their GPS-GSM cane. However, our system is distinguished by the progressive modulation of alert intensity as a function of distance, an aspect less developed in most existing solutions, which rely on binary alerts (obstacle present/absent). Dos Santos (13) demonstrated experimentally that the electronic cane improves the detection of suspended obstacles by 79 % compared to the traditional cane. Our preliminary results confirm this trend, particularly for obstacles located between 30 and 80 cm in height, which represent a typical blind spot of the white cane. The progressive haptic modulation we implement also allows the user to build a graded mental representation of the environment, which binary alerts do not permit.

TABLE VII. Comparison of the main existing smart cane solutions with our system

Solution / Reference	Sensors	Alert	Estimated cost	Complexity	Integrated AI
Abdulkareem *et al.* [6]	Ultrasonic + GPS/GSM	Sound + Vibration	Medium	Moderate	No
Adegboro *et al.* [8]	Ultrasonic (3×)	Sound + Vibration	Low	Simple	No
Memon *et al.* [17]	Ultrasonic + surface sensors	Sound + Vibration	Medium–High	High (RPi)	Partial
Hareharan *et al.* [14]	Camera + AI (YOLOv8)	Audio + Vibration	High	Very high	Yes (deep)
Yang *et al.* [21]	Ultrasonic (3×) + RFID	Sound + Vibration + LED	Low–Medium	Moderate	No
Our system	**Ultrasonic HC-SR04 + IR**	**Sound + Modulated vibration + LED**	**Medium**	**Simple (Arduino)**	**No (planned)**

C.Cost–Complexity–Performance Analysis: One of the central challenges in this field is finding the optimal balance between performance, complexity, and economic accessibility. The comparative table (Table VII) summarizes the main characteristics of representative solutions identified in the literature. This comparative analysis reveals that our solution occupies a favorable strategic position: it offers bimodal detection (both fixed AND mobile obstacles) with progressive alert modulation, at a very low cost (estimated at approximately 30 euros for the main components), with manageable implementation complexity. It differentiates itself from purely ultrasonic single-function solutions (8), (15) by adding motion detection, without reaching the complexity and cost of embedded AI systems (14) or Raspberry Pi-based systems (17).

Ergonomics and User Adoption: An aspect often overlooked in technical publications is the acceptability and ergonomics of the device for prolonged daily use. Khan *et al*. (16), in their meta-analysis of 36 studies, emphasize that portability, low weight, affordable cost, and social acceptance are determining factors for the sustainable adoption of mobility aids. Our device, integrated into a foldable aluminum cane structure, meets these criteria: it does not significantly alter the weight and format of the traditional cane, and the haptic alerts are discreet to those nearby. The 3D-printed accessory solution proposed by Ala-nyalıog˘lu *et al*. (11) illustrates a complementary approach focused on customization and physical durability. Synergies with this approach are conceivable for our prototype, particularly for the design of custom housings for the electronic modules, reducing bulk and improving aesthetic integration. Dos Santos (13) notes that users walk more slowly with an electronic cane during the learning phase, but that this drawback disappears with practice. This observation underscores the importance of adoption support and a progressive learning interface, which we plan to integrate into future versions of the system.

Limitations and Avenues for Improvement: Our study presents several limitations that should be honestly acknowledged. First, the tests were conducted in controlled environments and their representativeness of real daily-life situations (rain, fog, dense crowds, acoustically saturated environments) remains to be validated. Second, the ultrasonic sensor shows limitations for highly absorbing surfaces or very thin objects, a limitation also documented by Abdulkareem *et al*. (6). Third, the absence of artificial intelligence in our current version limits the system’s ability to distinguish obstacle categories and to dynamically adapt its detection thresholds to the environment. The future integration of lightweight machine learning algorithms (edge ML), compatible with microcontrollers such as the Arduino Nano 33 BLE Sense, represents a priority prospect. Recent work by Memon *et al*. (17) and Hareharan *et al*. (14) traces promising avenues in this direction. Finally, longitudinal studies with real users over several weeks, following the methodology recommended by Dos Santos (13) and Khan *et al*. (16), are necessary to evaluate the actual impact of the device on the quality of life and autonomy of visually impaired individuals. Such studies would also provide valuable user feedback to guide future developments.

CONCLUSION AND FUTURE PERSPECTIVES

The mobility of visually impaired individuals has evolved considerably thanks to electronic technologies and artificial intelligence. Recent devices, from simple wearable systems to smart canes integrating ultrasonic sensors, GPS, and deep learning algorithms, have demonstrated their effectiveness in improving obstacle detection, safety, and user autonomy. However, challenges persist regarding portability, cost, ergonomics, and long-term adoption. Our contribution a smart cane combining a multi-directional sensor, adjustable haptic feedback, and a simplified mobile interface offers a balance between technical performance and ease of use. It improves the detection of low-height obstacles, enhances user confidence and autonomy, while remaining accessible and ergonomic. Comparison with existing work confirms that our approach occupies a relevant position in the solution space: bimodal, low-cost, simple to implement, and extensible. To go further, several perspectives are envisioned: integrating additional sensors (light, fire, water); using artificial intelligence for object recognition and dynamic adaptation to the environment; developing collaborative applications to report obstacles; optimizing energy autonomy via integrated solar cells; and conducting longitudinal studies with real users to evaluate the impact on quality of life. These developments will enable the design of smarter, safer mobility aids that are truly centered on the needs of visually impaired individuals.

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