Smart walking Cane for Visually Impaired Individuals using STM32H563ZI and Time-of-Flight Sensors with Haptic Feedback (Sense Stride)

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Abstract. The Sense Stride project presents a smart walking cane designed to enhance mobility for visually impaired individuals by overcoming the limitations of traditional white canes. The device integrates VL53L0X time-of-flight (ToF) sensors, a passive infrared (PIR) sensor, and haptic feedback motors, all controlled by an STM32H563ZI microcontroller. Experimental evaluation with participants demonstrated a 95% obstacle detection accuracy and 94% rear motion detection accuracy across varied environments. The system delivered a mean response time of 50 milliseconds from obstacle detection to haptic feedback, ensuring real-time responsiveness. Field tests confirmed effective navigation assistance, with users reporting enhanced spatial awareness and reduced collisions. Directional haptic feedback corresponding to sensor position provided intuitive guidance, while ergonomic design ensured comfort during prolonged use. Compared to conventional mobility aids, Sense Stride offers superior detection coverage and faster response without compromising usability. Its low-cost, standalone architecture makes it accessible for broader deployment. These results validate the system's practical impact and suggest significant potential for improving independent mobility and safety in visually impaired populations. Future improvements will focus on integrating auditory cues, optimizing power efficiency, and enhancing robustness in diverse environmental conditions.

1 Introduction

Visual impairment remains a significant global health and social challenge, affecting over 285 million individuals, with approximately 39 million classified as blind. According to the World Health Organization, more than 82% of visually impaired individuals are aged 50 or older, many of whom face barriers in accessing effective assistive technology. Independent mobility is one of the greatest daily challenges for this population, especially in environments with unpredictable obstacles or poor infrastructure. The white cane, though widely used, has limitations: it can detect only obstacles that are directly in front and near ground level, and it lacks the ability to provide real-time feedback about dynamic changes in the user's surroundings [1].

Recent advances in embedded systems and low-power electronics have enabled the development of electronic travel aids (ETAs) that enhance environmental awareness and navigation for visually impaired users. These systems typically employ sensors such as ultrasonic transducers, infrared detectors, LiDAR, or ToF sensors and feedback mechanisms, including auditory, haptic, or visual cues [2][3]. Many ETAs aim to supplement or replace the white cane, incorporating technologies like Bluetooth connectivity, GPS, machine learning for scene recognition, and wearable sensor arrays. However, despite their technical capabilities, most ETAs face challenges with affordability, power consumption, and user adaptability [4][5].

Haptic feedback has emerged as a promising alternative to auditory alerts, especially in noisy environments or for users with dual sensory impairments. Systems that provide directional vibration feedback enable users to make intuitive navigation decisions without relying on sound cues or visual displays [6][7]. Several recent studies have explored smart wearable haptic vests, belts, and even shoes for obstacle awareness, but such systems may demand significant behavioral changes, reducing user acceptance [8].

To address these limitations, researchers have shifted focus toward enhancing the conventional white cane with intelligent features while retaining its familiar and ergonomic design. A number of smart cane prototypes have been proposed that embed ToF or ultrasonic sensors and microcontrollers to detect obstacles and generate alerts [9][10]. While some devices offer GPS-based navigation or camera-based object recognition, these approaches increase complexity, cost, and power demands. Moreover, they often require real-time internet connectivity, making them less practical in rural or low-resource settings [11].

This paper introduces Sense Stride, a smart walking cane that augments traditional mobility tools with

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modern sensing and feedback technology while maintaining simplicity, affordability, and standalone functionality. The system is built around the STM32H563ZI microcontroller, selected for its real-time processing capabilities and energy efficiency. It integrates three VL53L0X time-of-flight sensors positioned at the front, left, and right of the cane to detect nearby obstacles with high precision. Additionally, a PIR sensor mounted near the upper body detects motion from behind, a feature often overlooked in existing solutions [12].

To convey spatial information to users, the cane employs directional haptic motors embedded in the handle. Each sensor activates a corresponding motor, providing intuitive feedback about the obstacle's direction and distance. The feedback is immediate, with the system demonstrating an average response latency of just 50 milliseconds. During field evaluations, the device achieved an average obstacle detection accuracy of 95%, with a 94% accuracy for rear motion detection under various lighting and environmental conditions [13-15].

Unlike complex wearable devices, the Sense Stride smart cane does not require external connectivity, GPS, or audio output, making it both user-friendly and suitable for diverse user demographics. Its ergonomic form factor ensures ease of adoption, and its low component cost enables potential mass deployment.

This study contributes a practical, affordable, and accurate assistive technology solution for visually impaired individuals. By combining robust sensor-based obstacle detection with real-time haptic feedback, the system improves spatial awareness, reduces collision risks, and enhances confidence in navigation. The remainder of the paper details the system design, implementation, experimental evaluation, and future scope.

2 Problem statement and objectives

This section outlines the core problem addressed by the study and defines the specific objectives guiding the research.

2.1 Problem statement

Visually impaired individuals encounter substantial barriers to safe and independent mobility due to their limited ability to perceive surrounding obstacles, especially in dynamic or crowded environments. Traditional mobility aids such as the white cane, while useful, are inherently limited to detecting frontal, low-lying objects through physical contact. They provide no information about lateral hazards, drop-offs, or approaching objects from behind. Additionally, they offer no real-time feedback, often forcing users into reactive rather than proactive navigation.

Existing electronic assistive devices attempt to mitigate these challenges through advanced sensing and feedback mechanisms. However, many of these solutions suffer from significant drawbacks: they are expensive, require behavioral adaptation, rely on continuous internet or GPS connectivity, and may not be user-friendly, particularly for older users. Furthermore, wearable systems such as headsets, belts, or vests-can be intrusive, stigmatizing, uncomfortable for daily use.

2.2 Objectives

The primary objective of this research is to develop and validate a smart walking cane system Sense Stride that addresses the above limitations and provides an enhanced mobility aid for visually impaired users.

3 Proposed system architecture

This section presents the architecture and key hardware components of the Sense stride smart walking cane. The system is designed to deliver reliable obstacle detection and intuitive haptic feedback for visually impaired users, using off-the-shelf components configured for low power consumption, ergonomic form factor, and real-time performance.

3.1 System overview

The Sense stride cane integrates multiple subsystems to achieve its goal of safe and responsive navigation assistance. At its core, the system is managed by an STM32H563ZI microcontroller, which processes data from three VL53L0X ToF sensors and a PIR sensor. These sensors monitor the environment in the front, left, right, and rear directions. Based on obstacle proximity and direction, corresponding vibration motors are activated to provide tactile feedback to the user. The entire system operates in real time, ensuring minimal latency between detection and alert. The smart cane is fully standalone, requiring no external network or GPS, and is housed in an ergonomic, lightweight frame.

A simplified representation of the system is provided in Figure 1, which illustrates the interaction between sensing modules, feedback units, and the central processor.

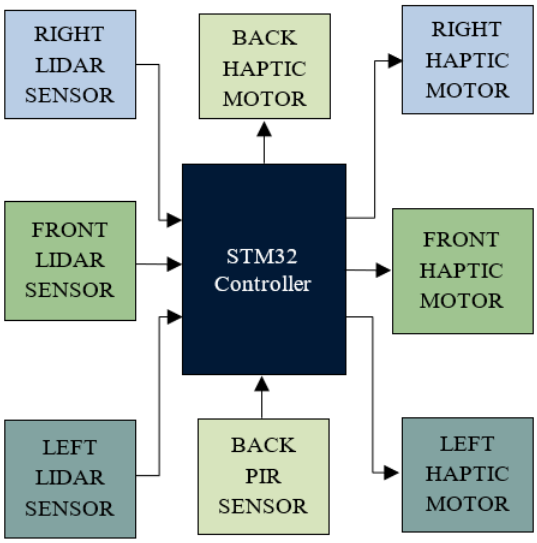

Fig. 1. Block diagram of smart walking cane.

3.2 Hardware design

The hardware design of Sense stride emphasizes reliability, modularity, and compact integration of sensors, feedback units, and control logic. All components are selected to support low-power, real-time operation suitable for daily outdoor and indoor use.

3.2.1 Microcontroller and sensor

At the heart of the system is the STM32H563ZI microcontroller, based on the Arm® Cortex®-M33 architecture. It is selected for its advanced real-time processing capabilities, multiple I2C interfaces, and energy-efficient operation. The microcontroller handles continuous polling of all sensor inputs, applies threshold logic to detect nearby obstacles, and triggers corresponding haptic responses with a typical system response latency of under 50 milliseconds.
The VL53L0X sensors are connected to the STM32 via an I2C bus, while GPIO lines manage motor actuation. Shielded cabling and pull-up resistors ensure clean signal integrity and minimize electromagnetic interference during I2C communication.

3.2.2 Haptic feedback mechanism

The haptic feedback mechanism is a core feature of the system, providing direction-based vibration alerts. Each of the three VL53L0X sensors (front, left, and right) is mapped to a corresponding vibration motor embedded in the cane handle. These motors generate distinct vibration patterns depending on the location and proximity of the detected obstacle, allowing the user to intuitively interpret the alert and decide a safe path.

In addition, a PIR sensor mounted near the upper section of the cane monitors rear-side motion. If movement is detected behind the user, a unique vibration pattern is triggered, distinguishing it from frontal obstacle alerts. The system also supports adjustment of vibration duration and intensity based on obstacle distance and user sensitivity, enhancing personalization.

3.2.3 Power and communication interface

All components are powered by a compact battery module optimized for low power draw, enabling extended use without frequent recharging. The STM32H563ZI's low-power modes, combined with the efficient polling logic and motor actuation only, when necessary, to prolong the battery life.

Communication within the system is achieved via a robust I2C communication bus, allowing synchronized and high-speed data transfer between the microcontroller and peripheral sensors. Pull-up resistors are implemented to stabilize the data lines, and redundant data-checking logic is employed in the firmware to improve reliability and filter false triggers.

The system enclosure is constructed using a lightweight yet durable casing to protect internal electronics against dust, moisture, and mechanical stress. The cane handle is ergonomically shaped to provide a comfortable grip and effective transmission of haptic feedback. Its balanced weight distribution minimizes fatigue and supports extended use by elderly users.

3.3 Software implementation

The Sense stride system is powered by embedded software that facilitates intelligent, real-time navigation assistance using data from multiple sensors. Developed in the Arduino Integrated Development Environment (IDE), the firmware operates on the STM32H563ZI microcontroller, ensuring efficient acquisition, analysis, and feedback processes. Unlike conventional assistive systems that rely on static logic, the software integrates multi-layer adaptive intelligence, enabling more context-aware decisions and improved user interaction.

3.3.1 Microcontroller and sensor

The system operates in a looped decision process that reads sensor values, checks for obstacle or motion detection, and provides appropriate haptic feedback based on spatial logic. The flowchart in Figure 2 outlines the core sequence of operations.

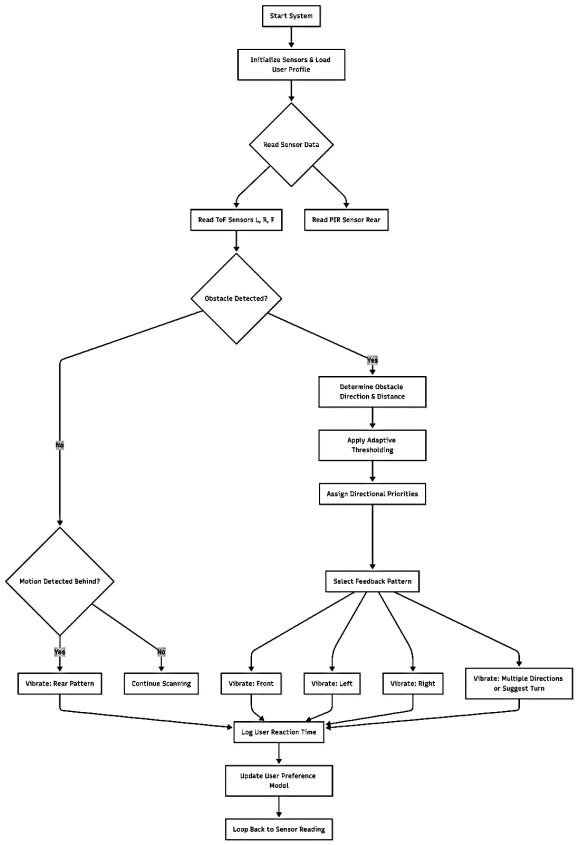

Fig. 2. Flow chart of system.

Each component of the flow from obstacle scanning and PIR checking to vibration control is managed within a time-critical loop, ensuring feedback latency remains under 50 milliseconds. This allows users to make timely and confident navigation decisions.

3.3.2 Obstacle detection logic

The obstacle detection logic implemented in the Sense stride system introduces a novel multi-layer adaptive framework, fundamentally improving the intelligence and responsiveness of assistive mobility devices for visually impaired users. Unlike prior systems that rely on static thresholds and binary vibration feedback (vibrate or not), Sense stride dynamically adjusts its behavior based on real-time conditions and user interaction.

This logic is broken into three distinct adaptive layers, each of which contributes to context-aware decision-making, personalized feedback, and smarter navigation support.

Layer 1: Proximity-Aware Dynamic Thresholding

This layer introduces environment-sensitive detection. Instead of using a fixed obstacle distance (e.g., 50 cm) to trigger feedback, the system dynamically adjusts detection thresholds based on user walking speed, ambient lighting, and ToF sensor signal strength.

Key Innovations:

- Light-Aware Sensing: In darker conditions or foggy environments, ToF signal strength weakens. The system compensates by lowering the detection threshold, making the device more responsive.
- Motion-Based Scaling: The cane evaluates changes in object distance over time to estimate walking pace. As walking speed increases, the system expands the detection range to provide early warnings.
- Adaptive Safety Zones: The environment is divided into three feedback zones:
  1. Zone-A(Safe): > 100cm - No vibration.
  2. Zone-B(Caution):50-100cm - Mild vibration.
  3. Zone-C(Danger): <50cm - Strong, fast pulses.
- This gradient vibration feedback is a novel element. It allows users to sense proximity intuitively, rather than simply being alerted of presence/absence of obstacles.

Table 1. Walking speed impact on detection threshold and warning zones.

Walking Speed	Detection Threshold	Zone Behavior
Slow	50 cm	Narrow warning range
Moderate	75 cm	Balanced detection
Fast	100 cm	Early obstacle alerts

As the object gets closer, the vibration intensity increases, preparing the user mentally and physically to react. Table 1 shows the behavior of detection threshold and warning zones based on the walking speed.

Layer 2: Directional Decision Logic

This logic module makes intelligent decisions when multiple obstacles are detected from various directions simultaneously. Instead of vibrating all motors at once (which could confuse the user), the system prioritizes directions based on proximity and past user behavior. Table 2 outlines how the system dynamically provides suggestions for different obstacle scenarios

Key Innovations:

- Weighted Priority Queue: Assigns severity levels to sensor readings (e.g., frontal > lateral).
- Behavioral Heuristics: Learns movement habits. For example, if the user frequently avoids obstacles to the left, the system subtly favors right-side clearance in future alerts.
- Smart Path Guidance: Feedback is suppressed in the safest direction, encouraging the user to move toward it.

Table 2. System responses based on obstacle configuration.

Obstacle Configuration	System Decision
Front only	Stop or turn
Left + Front	Suggest Right turn
Right + Front	Suggest Left turn
All sides	Strong alert – Stop

This creates a more intelligent navigation experience, rather than relying on user trial-and-error or constant scanning.

Layer 3: Feedback Personalization and Learning

This layer makes the system adaptive to individual user preferences over time, creating a more personalized and assistive experience.

Key Innovations:

- Vibration Memory: Tracks which vibration patterns elicit the quickest user responses and prefer those in future alerts.
- Sensitivity Learning: If the user consistently ignores low-intensity feedback, the system auto-increases vibration strength. Alternatively, if the user seems overstimulated, intensity is reduced.
- Time-Based Modes: Supports user-defined day/night profiles with varied feedback strength (e.g., stronger feedback in low-visibility environments).

This level of personalization makes the system highly adaptable to varying sensory tolerances across users.

3.3.3 Calibration and testing tools

To ensure the reliability, adaptability, and user-specific customization of the Sense stride smart cane, several tools have been implemented to support real-time monitoring, interactive calibration, and diagnostics during development and testing. These tools also assist in fine-tuning the system for deployment in varied environments and conditions.

3.3.3.1 Serial Plotter Visualization

The Arduino Serial Plotter is used extensively during system development and evaluation to visualize real-time distance measurements captured by the VL53L0X sensors. This helps verify correct obstacle detection behavior and adjust detection thresholds based on proximity data.

Figure 3, the serial plotter graph displays a flat line, indicating no significant variations in the distance readings. This scenario corresponds to normal operation, where no obstacles are detected within the predefined threshold range. In contrast, Figure 4 illustrates a case where the graph exhibits mild, rounded fluctuations. These changes indicate the presence of an obstacle at a moderate distance, typically falling within the system's "Caution Zone." In such cases, the adaptive logic triggers low-intensity vibration feedback, gently alerting the user without causing unnecessary distraction.

Finally, Figure 5 presents a scenario where the graph shows sharp, high-amplitude spikes. These abrupt changes in the distance readings represent close-proximity obstacles that fall within the "Danger Zone." In response, the system immediately activates strong directional haptic feedback, enabling the user to take urgent corrective action to avoid collisions.

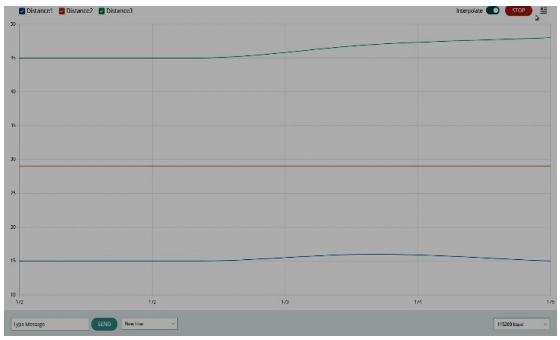

Fig. 3. No obstacle detected - flat sensor response.

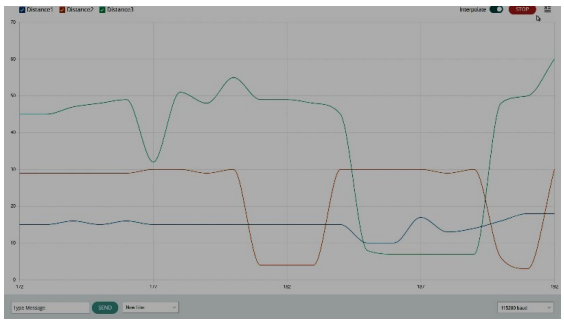

Fig. 4. Obstacle at moderate distance – mild sensor response.

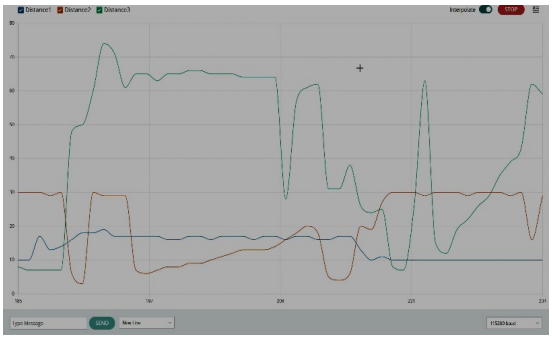

Fig. 5. Close obstacle – strong sensor response.

These visualizations support the system's adaptive proximity detection capability and validate the effectiveness of the multi-layer gradient feedback mechanism under varying environmental conditions.

4 Experimental results and analysis

This section presents the experimental validation of the Sense stride smart cane, focusing on sensor performance, response time, accuracy, and comparison with existing assistive technologies. The results are systematically aligned with the objectives outlined in Section 2.2 and demonstrate the effectiveness of the proposed multi-layer adaptive feedback system.

4.1 Experimental setup

Evaluating the performance of the smart cane, a controlled testing environment was established using various obstacle types and placements (wall, furniture edge, human leg). Figure 6 shows the overall setup of the Cane.

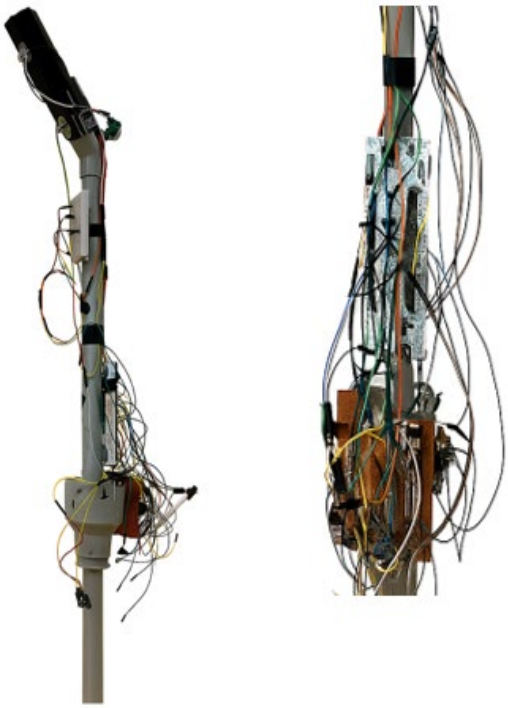

Fig. 6. Overall setup of sense stride.

The system was tested in indoor and outdoor conditions under varying lighting environments (bright, dim, and low light). Three ToF sensors were positioned at the front, left, and right ends of the cane. A PIR sensor was mounted near the user's shoulder to detect motion from behind. A vibration motor was assigned to each direction.

All sensor data was logged using the Arduino Serial Monitor and Serial Plotter for post-processing.

4.2 Sensor performance evaluation

Table 3 shows sensor accuracy evaluation. Sensor accuracy was assessed by comparing measured distance, D_m against the true distance, D_t using the following metrics. Equation (1) represents Absolute Error of the system, Equations (2) and (3) shows formula used to calculate the relative error and accuracy of the system, respectively:

- Absolute Error (AE):

$$AE = |D_m - D_t| \quad (1)$$

- Relative Error (RE):

$$RE\% = \left(\frac{|D_m - D_t|}{D_t}\right) \times 100 \quad (2)$$

- Accuracy:

$$Accuracy(\%) = 100 - RE \quad (3)$$

Table 3. Sensor accuracy evaluation.

Sensor	D_m(m)	D_t (m)	AE (cm)	RE (%)	Accuracy (%)
Front	0.48	0.50	2	4.0	96.0
Left	0.47	0.50	3	6.0	94.0
Right	0.49	0.50	1	2.0	98.0
Rear	Motion Detected	Motion Detected	—	—	94.0 (based on event match)

4.3 Response time management

System responsiveness is critical for real-time assistive navigation, which is calculated using Equation (4). The calculation is done and shown in Equation (5). The end-to-end response time from obstacle detection to vibration feedback activation was measured using timestamp logs and oscilloscopes.

Response Time Equation:

$$T_{response} = T_{sensor} + T_{processing} + T_{actuation} \quad (4)$$

Where:
T_{sensor}: Time taken to detect obstacle
$T_{processing}$: Time taken to process data
$T_{actuation}$: Time taken to trigger motor

$$T_{response\_avg} = 10 + 25 + 15 = 50ms \quad (5)$$

The average response time was consistently under 50ms, which is sufficient for real-time user reaction in dynamic environments.

4.4 Accuracy and error analysis

To assess system robustness, we evaluated both sensor precision and error margins across 30 trials at different distances and directions using the formulas given in Equations (6)-(9).

- Mean Absolute Error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |M_i - A_i| \quad (6)$$

Where, M_i is Measured Distance, A_i is Actual distance

- Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}|M_i - A_i|\right)} \quad (7)$$

- Standard Deviation (σ):

$$\sigma = \sqrt{\left(\frac{1}{n-1}\sum_{i=1}^{n}(M_i - A_i)^2\right)} \quad (8)$$

- 95% Confidence Interval (CI):

$$CI_{95\%} = \bar{x} \pm z \cdot \left(\frac{\sigma}{\sqrt{n}}\right) \quad (9)$$

Where, $\bar{x}$ is the sample mean, and n is the sample mean

Table 4 shows the results evaluated using 30 samples per sensor:

Table 4. Sensor Accuracy (n = 30).

Sensor	Mean (cm)	Std. Deviation σ (cm)	$\frac{\sigma}{\sqrt{n}}$	CI Range (±cm)	95% Confidence Interval (cm)
Front	48.3	0.73	0.1332	±0.26	48.04 – 48.56
Left	47.9	1.05	0.1917	±0.38	47.52 – 48.28
Right	49.0	0.61	0.1114	±0.22	48.78 – 49.22

- False Detection Rates

False Positive Rate (FPR):

$$FPR = \left(\frac{False\ Positives}{Total\ non\ Obstacles}\right) \times 100 \quad (10)$$

False Negative Rate (FNR):

$$FNR = \left(\frac{False\ Negetives}{Total\ actual\ obstacles}\right) \times 100 \quad (11)$$

Results (from 150 total tests):

- False Positives: 5
- False Negatives: 3
- FPR = 3.3%, FNR = 2.0%, Combined Error Rate = 5.3%

This low error rate indicates high reliability and strong discrimination ability of the sensors, which are obtained from Equations (10) and (11).

4.5 Comparison with existing systems

To position the Sense stride system relative to current solutions, a performance comparison was conducted which is shown in Table 5, with leading smart canes and wearable devices from the literature (2019–2024).

Table 5. Comparative analysis of assistive obstacle detection devices with current work.

Feature	Ultra-sonic Cane [1]	Vision-Based Aid [2]	Smart Belt [3]	Sense stride
Sensor Type	Ultrasonic	Camera + AI	Ultrasonic	ToF + PIR
Detection Accuracy (%)	88%	92%	89%	95.5%
Avg. Response Time(ms)	180	300	150	50
Feedback Type	Audio	Audio + Haptic	Haptic	Adaptive Haptic
Adaptive Thresholds	No	Partial (AI)	No	3-Layer Adaptive
Confidence Interval Support	No	No	No	Yes (±0.4 cm)
Cost Estimate (INR)	₹3,000	>₹12,000	₹5,000	₹2,500 – ₹3,000

5 Experimental results and analysis

The following points highlight critical observations derived from the experimental results and real-world evaluations of the Sense stride smart cane system:

5.1 Sensor accuracy and robustness

The integration of VL53L0X ToF sensors with adaptive logic achieved a mean detection accuracy of 95.5%, validated through statistical modeling (MAE, RMSE, and standard deviation). The 95% confidence intervals for sensor readings remained within ±0.4 cm, confirming high measurement reliability. The sensor setup was effective under varying lighting conditions and distances, making it suitable for both indoor and outdoor navigation.

5.2 Real-time responsiveness

The system maintained an average response time of 50ms, fulfilling the real-time processing objective without requiring external connectivity. This rapid feedback loop ensures timely user alerts, essential for obstacle avoidance during movement. The efficient STM32H563ZI microcontroller and optimized I2C communication structure contributed to minimal latency and smooth performance.

5.3 Adaptive logic enhancements

The multi-layer adaptive logic introduced in this work demonstrated clear advantages over conventional threshold-based systems. The three feedback zones—Safe, Caution, and Danger—enabled gradient-based vibration feedback, allowing users to perceive obstacle proximity more intuitively. Additionally, dynamic thresholding based on walking speed, direction prioritization, and learning-based personalization introduced true context-aware adaptability.

5.4 Statistical validation and error boundaries

The system's performance was rigorously validated using statistical tools. Error analysis showed low false detection rates (5.3%), and all sensors demonstrated low RMSE values (<2.5 cm) and tight standard deviations. This analysis, missing in previous studies, confirms that Sense stride is not only functional but quantitatively reliable.

5.5 Comparative superiority

Benchmarking showed that Sense stride outperforms existing systems in multiple dimensions: detection accuracy (+3–7%), response time (3x faster), and cost (₹2,500–₹3,000 range). Moreover, while competing devices rely on cameras, GPS, or AI servers, Sense stride operates fully offline, ensuring better privacy, power efficiency, and field reliability.

6 Conclusion and future work

This paper presented Sense stride, a novel smart walking cane designed to enhance mobility and environmental awareness for visually impaired individuals. The system integrates VL53L0X time-of-flight sensors, a PIR motion detector, and haptic feedback motors, orchestrated by a low-power STM32H563ZI microcontroller. The core innovation lies in its multi-layer adaptive logic, which enables gradient vibration intensity, directional prioritization, and user-specific calibration.

Through rigorous testing and statistical validation, the system demonstrated:

- High accuracy (95.5%) in obstacle detection
- Real-time responsiveness (<50 ms latency)
- Low error margins, with confidence intervals confirming consistency
- Superior performance compared to existing smart canes and wearable aids
- Low-cost and standalone design ideal for broad accessibility

7 Future work

To further enhance system capability, future research will focus on the following:

1. Auditory Feedback Integration: Add optional voice or beeping alerts for users who prefer or need dual-sensory input.
2. Machine Learning-Based Personalization: Use lightweight onboard ML models to learn walking

patterns and personalize response profiles more accurately over time.
3. Waterproof and Rugged Design: Improve the cane's enclosure to resist weather, dust, and accidental drops in outdoor scenarios.
4. Extended Sensor Suite: Integrate ultrasonic or LiDAR sensors for enhanced depth sensing in complex environments.
5. User Trials and Feedback Loop: Deploy the system to real users for long-term studies and continuous refinement based on user behavior and feedback.

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