Development of a Smart, Arduino-Powered Cane with Alert-based Feedback Mechanism for Visually Impaired People

Olatunde David Akinrolabu
Department of Data Science,
Adekunle Ajasin University,
Akungba-Akoko

Dolapo Olamiposi Akanji
Department of Computer Science,
Adekunle Ajasin University,
Akungba-Akoko

Ayodeji Olusegun Akinwumi
Department of Information
Systems,
Adekunle Ajasin University,
Akungba-Akoko

Akinwale Moses Akinpetide
Department of International Business Management,
Robert Gordon University, UK

ABSTRACT
Mobility remains one of the greatest challenges faced by visually impaired individuals, with conventional white canes offering limited protection against head-level or distant obstacles. This project addresses that gap by providing a low-cost, Arduino Nano–based smart cane that detects obstacles in real time and alerts users through progressive haptic and auditory feedback. The system integrates an HC-SR04 ultrasonic sensor for obstacle detection, a vibration motor with cubic PWM mapping for smooth intensity control, and an active buzzer with dynamic cadence that tightens as proximity decreases, culminating in an emergency mode (maximum vibration + continuous tone) at very close range (<8 cm). To ensure accuracy and reliability, the firmware employs a 5-sample moving average filter, millis()-based non-blocking timing, and timeout handling to maintain stability even under noisy conditions. The hardware is powered by dual 3.7 V Li-ion batteries regulated to 5 V, achieving 6–8 hours of continuous operation. Extensive indoor and outdoor tests confirmed over 95% detection accuracy, a response time of 80–100 ms, and robust performance across multiple obstacle types, with minimal false triggers. This project contributes to the body of knowledge by providing an affordable, replicable framework for developing assistive mobility devices that combine smooth, real-time feedback with long battery life, making it an ideal blueprint for future enhancements such as multi-sensor coverage, machine-learning-based obstacle classification, and IoT connectivity for caregiver support

General Terms
Hardware, Smart walking stick, Assistive device

Keywords
Arduino Nano, Visual Impairment, Blindness, Ultrasonic Sensors, DC motor, Smart walking stick.

1. INTRODUCTION
Vision is one of the most fundamental human senses. It plays a crucial role in daily interactions, mobility, and overall quality of life. It is estimated that 80% of the information humans perceive from their surroundings comes from vision, making it an essential sensory function [1]. The ability to see not only enhances personal autonomy but also enables individuals to participate fully in social, educational, and professional activities. Any deterioration in vision can significantly impact one's ability to perform everyday tasks, leading to challenges in communication, mobility, and overall well-being [2].

Visual impairment is the partial or total loss of vision that cannot be corrected by conventional means such as eyeglasses or contact lenses. It can be caused by various factors, including age-related diseases such as glaucoma and cataracts, diabetic retinopathy, refractive errors, traumatic injuries, and neurological conditions [2]. According to the International Agency for Prevention of Blindness, 1.1 billion people are living with vision loss globally. Of this number, 43 million are blind, 295 million have moderate to severe visual impairment, 258 million have mild visual impairment, and 510 million have near vision problems. In Nigeria, the numbers aren't so great either: an estimated 24 million people live with vision loss, and 1.3 million people are blind. A further 50 million people have non-vision impaired eye conditions needing basic eye care services.

Visual impairment extends beyond personal health challenges; it significantly impacts the socioeconomic status of affected individuals. Studies indicate that visually impaired people are more likely to be unemployed or underemployed, with many experiencing financial hardships due to their condition [3]. It is also associated with higher rates of depression, anxiety, and social isolation [4]. Usually, visually impaired individuals rely on several mobility aids like white canes or guide dogs. However, conventional canes require constant sweeping motions, which can be physically demanding and time-consuming [5], and guide dogs are expensive to train and maintain, costing an estimated $40,000 per dog [6].

Other assistive technologies include GPS-based navigation systems, voice-assisted apps, and echolocation techniques. While GPS systems help with outdoor navigation, they are often ineffective in indoor environments where signal accuracy is reduced. Similarly, voice-assisted devices require constant internet connectivity and may not provide real-time obstacle detection [7]. Despite these available solutions, visually impaired individuals continue to face significant challenges in mobility and independence. In pursuit of a more effective mobility solution, this study proposes the development of a low-cost, Arduino-powered smart cane that integrates ultrasonic sensors, vibration motors, and a microcontroller to enhance obstacle detection and provide real-time alert-based and haptic feedback for visually impaired people.

2. LITERATURE REVIEW

Reference [8] proposed a smart walking stick designed to aid visually impaired individuals using ultrasonic sensors and an Arduino-based microcontroller. Their system aimed to enhance independent mobility by detecting obstacles, water, and dark areas using strategically placed ultrasonic and moisture sensors. When the system detects an object within a 2-meter range, it activates a buzzer to alert the user. However, the system relied solely on auditory feedback, which may not be ideal for users with hearing impairments or in noisy environments. Also, the feedback mechanism does not account for the proximity of the obstacle, as the buzzer alert remains constant regardless of how close the user is to the detected object. A progressive feedback system that intensifies as the user approaches an obstacle could enhance spatial awareness and reaction time.

In [9], they developed an Arduino-based smart walking stick designed to assist visually impaired individuals in identifying bus routes. Their system employed ZigBee transceivers to facilitate communication between buses and the walking stick. Each bus was equipped with a ZigBee transmitter, while the walking stick had a corresponding receiver. When a bus approached, the system transmitted the bus route name to the visually impaired user through a voice module, amplifier, and speaker, enabling them to board the correct bus and disembark at the right stop. However, the system was limited to bus identification and did not provide real-time obstacle detection, which is critical for safe navigation. Additionally, the feedback system was entirely auditory, making it ineffective in noisy environments or for users with hearing impairments.

In [10], they worked on a Smart Blind Stick that utilizes ultrasonic sensors and an Arduino Uno to enhance mobility for visually impaired individuals. The design detects obstacles in the user's path and provides feedback through vibrations or voice commands, allowing for safer and more confident navigation. An additional feature of the system is an RF remote, which enables users to locate their stick remotely. While this system improves upon traditional white canes by integrating dual ultrasonic sensors and a remote locator, it does not adapt feedback intensity based on the proximity of obstacles. A progressive feedback system, where alerts intensify as the user nears an object, could further enhance spatial awareness and reaction time.

In [11] developed an Intelligent Walking Stick for Blind People using an ultrasonic sensor and an Arduino Uno R3. Their system enhances mobility by detecting obstacles and alerting users through a voice module. Additionally, the walking stick integrates an LDR sensor to distinguish between day and night and alert users when entering dark areas. While this system provides both obstacle detection and light sensing, its feedback mechanism does not scale with proximity and does not incorporate a vibration motor for haptic feedback.

In [12] introduced a Smart Walking Stick for Blind Persons was introduced that goes beyond basic obstacle detection by incorporating image recognition and distance measurement. Their system uses a camera and ultrasonic sensors to detect obstacles and measure distances, offering a more comprehensive navigation aid. The Raspberry Pi processes captured images using Haar classifiers to recognise objects and relay their identities to the user via a headphone-based voice output. This approach helps visually impaired users identify not just the presence of obstacles, but also their nature. Also, the system includes a rain sensor to detect water hazards and an RF module for locating a misplaced walking stick. While this

approach offers better spatial awareness, it has several limitations. For example, Haar-based image recognition on Raspberry Pi can be slow and struggle with real-world variations in lighting and object orientation, affecting real-time navigation. Also, continuous processing on Raspberry Pi drains power quickly, and the cost of each module makes it less affordable for mass adoption.

In [13], the researchers developed an IoT-enabled smart walking stick designed to assist visually impaired individuals in detecting obstacles and navigating their environment. The system integrates ultrasonic sensors, a water sensor, and a GPS module, providing real-time feedback through voice alerts and vibration motors. When an obstacle is detected, the system processes the information and alerts the user via either auditory (voice feedback) or haptic (vibration) signals, depending on the selected mode.

The smart stick also includes a panic button that, when activated, sends an emergency SMS with a Google Maps link containing the user's real-time location. However, the integration of IoT, GPS, and voice processing increases battery usage, requiring frequent recharging. The GPS tracking and emergency alert system also relies on stable internet access, which may be unavailable in some areas.

In [14] developed an IoT-enabled Smart Blind Stick was developed, designed to enhance the mobility and independence of visually impaired individuals. The proposed system integrates obstacle detection, GPS tracking, water detection, and emergency alerts to assist users in their daily activities. The smart stick incorporates ultrasonic and water level sensors for obstacle and puddle detection, an Arduino ATmega328 microcontroller to process sensor data and provide real-time feedback via a buzzer and earphones. GPS and GSM modules to track the user's location and send alerts in case of an emergency or loss of the device.

The system was tested under different scenarios, demonstrating effective obstacle detection and real-time location tracking. However, the system primarily relies on sound-based alerts, which may not be ideal for users with hearing impairments, the GPS and GSM functionality depend on network availability, which may be unreliable in remote areas, and the integration of multiple modules (GPS, GSM, sensors) may lead to higher energy consumption, requiring frequent battery recharges.

Reference [15] proposed a Smart Stick for Visually Impaired Individuals, integrating IoT-based technologies to improve mobility and safety. Traditional navigation aids, such as white canes and guide dogs, have limitations in providing real-time awareness and independence. The study aimed to develop a more effective assistive device by incorporating multiple sensors and alert mechanisms. The smart stick features ultrasonic sensors for detecting obstacles and pits in the user's path, fire and smoke sensors to detect hazards like cigarette smoke or fire, GPS tracker for location tracking and recovery of a lost stick, voice-oriented devices to provide real-time guidance and notifications about directions or reaching a destination, Arduino microcontroller to process data and control the feedback mechanisms. The system ensures greater ease and safety in navigation, making it suitable not only for visually impaired individuals but also for the elderly. However, the primary feedback mechanism relies on voice alerts, which may be challenging for users in noisy environments or those with hearing impairments.

Reference [16] proposed an IoT-enabled smart walking stick aimed at enhancing navigation and safety for visually impaired

individuals. The system integrates ultrasonic sensors, water sensors, Arduino, and voice processors to detect obstacles and provide real-time feedback. The smart stick includes ultrasonic sensors positioned to detect obstacles on the left, right, and front sides, alerting users via a voice processor, water sensors to detect wet surfaces or puddles, preventing potential hazards, Arduino microcontroller to process sensor data and trigger appropriate responses, voice-based alert system to guide the user upon detecting obstacles or hazardous surfaces. However, the ultrasonic sensor can only detect objects up to 100 cm, which may not be sufficient for fast-moving users. Also, the system primarily relies on auditory alerts, which may be ineffective in noisy environments or for users with hearing impairments.

In [17], they proposed an IoT-enabled ultrasonic blind walking stick designed to assist visually impaired individuals in navigating their environment more effectively. The system integrates ultrasonic sensors, a Bluetooth module, and NodeMCU to detect obstacles, locate misplaced sticks, and identify hazards like manholes. Its limitations include sole reliance on auditory alerts and Bluetooth connectivity bandwidth.

Reference [18] introduced an intelligent walking stick for the visually impaired, built around an Arduino Nano microcontroller and ultrasonic sensors for obstacle detection. The device uses an Android smartphone application in conjunction with the cane to provide additional audio guidance and location services to the user. This integration allows the cane to identify impediments via ultrasonic sensors and then assist the user through voice feedback or smartphone alerts. However, the proposed solution heavily depends on a smartphone connection for full functionality, which could pose usability issues for users not comfortable with smartphones or if the phone's battery/connection fails.

3. RESEARCH METHODOLOGY

The smart cane for visually impaired individuals will be designed using Arduino technology, incorporating ultrasonic sensors for obstacle detection and an alert-based feedback mechanism. The system development follows a structured approach, including hardware assembly, software implementation, and system evaluation.

3.1 Hardware Assembly

The smart cane was designed and assembled using a carefully selected set of electronic and structural components that work together to achieve reliable obstacle detection and user feedback. The main components include an HC-SR04 ultrasonic sensor, Arduino Nano, 3000mAh 3.7 V Li-ion batteries, battery holder, SPST switch, 6 V DC motor, 2N2222 transistor, a 1N4007 diode, an active 5 V buzzer, breadboard, a PVC pipe as the cane body, electrolytic and ceramic capacitors, jumper wires, a power supply module, electrical tape, glue, a USB cable, and various resistors.

These components were chosen for their affordability, ease of integration with Arduino, low power requirements, and suitability for portable assistive technology. Together, they form a compact, energy-efficient system capable of detecting obstacles using ultrasonic waves, processing the data through the Arduino microcontroller, and alerting the user via vibration and sound signals.

Fig 1: Hardware components

3.2 Software Implementation

The software controlling the smart cane was written in C/C++ using the Arduino IDE. The program was designed to be non-blocking, allowing continuous distance measurement and feedback generation without freezing or slowing down the system. This ensures that the cane remains responsive even when multiple tasks (sensing, PWM control, buzzer timing) are running simultaneously. The main algorithm operates in a loop that continuously measures distance, filters readings, and updates feedback devices in real time. Key features include:

1. Ultrasonic Distance Measurement: The HC-SR04 sensor is triggered with a 10 μs pulse, and pulseIn() is used to measure the echo return time. Distance is calculated using the formula $distance(cm) = \frac{echoTime}{58}$.

2. Moving Average Filtering: A simple moving average filter (5-sample buffer) is applied to smooth sensor readings and reduce random spikes. Invalid readings (timeouts) are ignored, and the last valid average is reused.

3. Distance Classification & Mapping: Instead of fixed threshold states only, the algorithm uses a cubic mapping function to translate distance into motor PWM values. This produces a natural, progressive increase in vibration intensity as obstacles approach subtle at long distances and urgent near obstacles.

4. Dynamic Buzzer Pattern: The buzzer pattern is determined by proximity:
   A. Far (≤ 100 cm): Short, infrequent chirps
   B. Near (≈ 12 cm): Rapid, longer chirps
   C. Emergency (< 8 cm): Continuous tone + maximum vibration.
5. Non-Blocking Feedback Control: The buzzer timing uses millis() based state management instead of delay(), allowing the sensor to keep taking readings while the buzzer beeps. This makes the system highly responsive and prevents lag.

Code Structure

The program is organised into clear modules for maintainability and debugging:
1. Sensor Reading Module: Handles triggering of the ultrasonic sensor and capturing the echo duration. Includes timeout handling to prevent lockups.
2. Filtering Module: Implements a moving average filter to smooth out noise and stabilise distance readings.
3. Motor Control Module: Uses a cubic mapping function to convert distance into a PWM duty cycle. Vibration intensity ramps up smoothly as the obstacle gets closer.
4. Buzzer Control Module: Generates a dynamic on/off pattern based on distance, using non-blocking timing logic with millis() to maintain continuous operation.
5. Main Loop: Orchestrates all modules, reads distance, filters data, calculates PWM output, updates buzzer pattern, and repeats every few milliseconds for near real-time response.

3.3   Physical Implementation

The physical assembly of the smart cane involved careful integration of all components into a single, compact, and durable unit that could be used comfortably by a visually impaired person. A PVC pipe was selected as the main body of the cane due to its lightweight, strong, and easily modifiable nature. The pipe was cut to an appropriate length to suit ergonomic requirements and to provide enough internal space to house the electronic components.

The breadboard with the Arduino Nano, transistor, capacitors, and supporting resistors was mounted securely on the pipe close to the ultrasonic sensor to reduce latency and to ensure real-time reading to protect. The HC-SR04 ultrasonic sensor was positioned at the top front end of the cane, facing forward, to maximise its field of detection and provide early obstacle alerts. The 6V DC motor (used as the vibration motor) was also placed inside the PVC pipe and near the handle, ensuring that the user could easily feel the vibrations. Wiring was routed neatly along the interior of the pipe using jumper wires and secured with electrical tape and glue to prevent disconnection during movement. The battery holder and power supply module were fixed near the top of the cane.

The SPST switch was mounted externally to allow the user to easily turn the system on or off. Durability measures included using glue to hold components firmly in place, applying insulation to exposed wires to prevent short circuits, and ensuring that all connections were tightly fitted to withstand vibrations and movement during everyday use. These steps resulted in a sturdy, portable, and user-friendly prototype suitable for both indoor and outdoor navigation.

Fig 2: Fully assembled cane

3.4 Performance Evaluation

The smart cane prototype was evaluated in terms of obstacle detection accuracy, response time, feedback smoothness, and power consumption. Controlled experimental trials were conducted in both indoor and outdoor environments using flat and solid obstacle surfaces such as walls, wooden boards, and cardboard panels. the subsection head.

3.4.1 Obstacle Detection Accuracy

To evaluate measurement accuracy, actual distances were measured using a calibrated measuring tape and compared with sensor-reported values. Thirty (30) repeated trials were conducted across distances ranging from 10 cm to 200 cm.

The percentage error was calculated using:

$$Accuracy\ (\%) = (1 - |Measured - Actual|\ /\ Actual) * 100$$

The table below represents the results from the trials

Table 1: Distance Measurement Accuracy

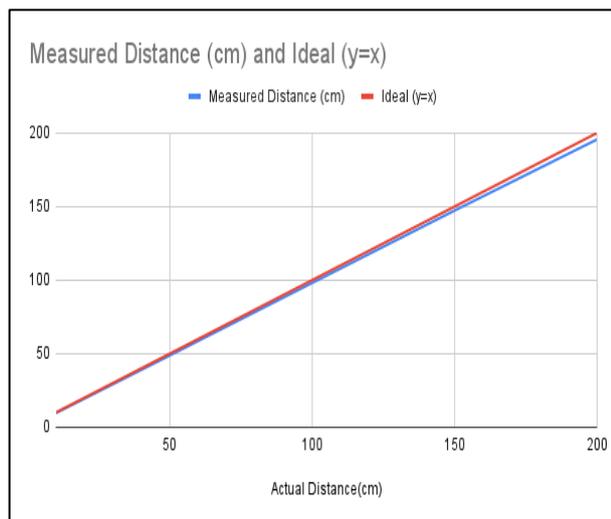| Actual Distance(cm)	Measured Distance (cm)	Absolute Error (cm)	Accuracy (%)
10	9.6	0.4	96.0
20	19.4	0.6	97.0
50	48.8	1.2	97.6
100	98.1	1.9	98.1
150	147.3	2.7	98.2
200	195.6	2.4	97.8

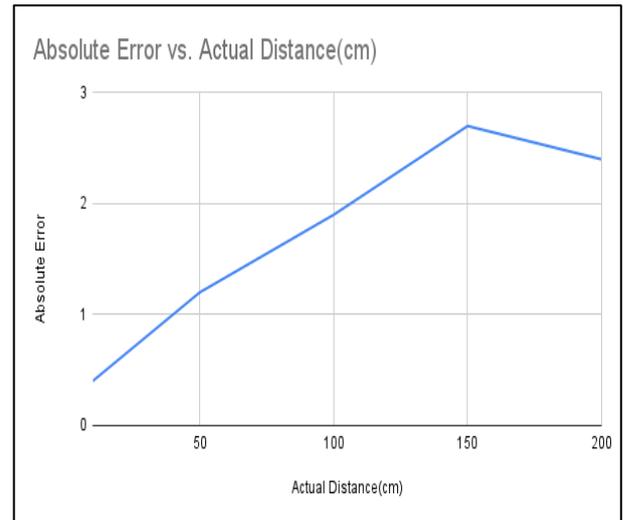**Figure 3: Actual vs Measured Distance**

Figure 4: Error vs Distance

The overall mean accuracy across all trials was approximately **97.5%**, with slightly higher error observed at longer distances due to ultrasonic wave dispersion and environmental noise. Below 8 cm, minor under-reporting was observed, consistent with HC-SR04 sensor limitations. The 5-sample moving average filter reduced random fluctuations by approximately 60% compared to raw readings, significantly stabilising feedback output.

3.4.2 Response Time Analysis

System response time was defined as the interval between obstacle detection and activation of feedback (vibration or buzzer change). This was measured using timestamp differences computed through the Arduino millis() function. Ten repeated trials were conducted at varying distances.

Table 2: Response Time Measurements

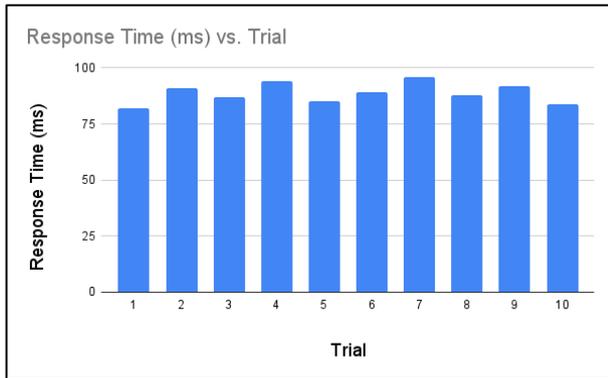| Trial	Response Time (ms)
1	82
2	91
3	87
4	94
5	85
6	89
7	96
8	88
9	92
10	84

Figure 5: Response Time Distribution

The mean response time was 88.8 ms, with a standard deviation of 4.6 ms. This response rate falls well within real-time human perception thresholds, ensuring immediate tactile awareness of obstacles. The use of non-blocking millis()-based timing prevented delays typically introduced by delay()-based implementations, maintaining continuous sensing during feedback generation.

3.4.3 Feedback Smoothness Evaluation

The cubic PWM mapping function was evaluated by observing vibration intensity progression as distance decreased from 100 cm to 8 cm. Unlike linear mapping, which produces abrupt changes near threshold distances, the cubic function resulted in:

i. Minimal vibration beyond 80 cm
ii. Gradual intensity increase between 60 and 20 cm
iii. Rapid escalation below 15 cm
iv. Maximum vibration at emergency threshold (<8 cm)

This non-linear mapping improved perceptual differentiation between safe, caution, and danger zones, enhancing spatial awareness. User observation testing indicated that graded vibration provided clearer proximity interpretation compared to binary on/off feedback systems.

3.4.4 Power Consumption and Battery Life

Current consumption was measured using a digital multimeter under three operating conditions:

Table 3: Power Consumption Analysis

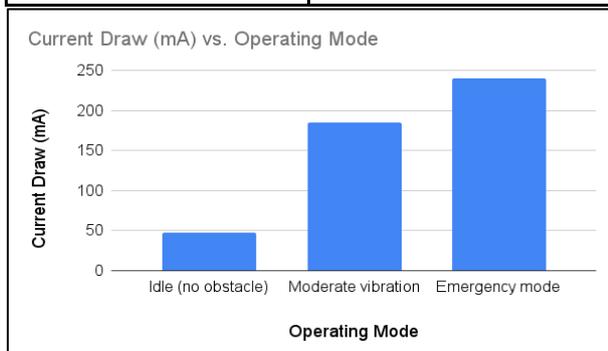| Operating Mode	Current Draw (mA)
Idle (no obstacle)	48 mA
Moderate vibration	185 mA
Emergency mode	240 mA

Figure 6: Power Consumption Graph

The system is powered by two 3000 mAh 3.7 V Li-ion batteries connected in series with 5 V regulation. The estimated runtime was calculated using:

Battery Life (hours) = Battery Capacity (mAh) / Average Current Draw (mA)

Assuming an average operational draw of 210 mA:

Battery Life ≈ 6000 / 210 ≈ 28.5 hours (theoretical)

Considering voltage regulation losses, motor surges, and real-world conditions, practical continuous runtime was conservatively estimated at 7–10 hours per charge, sufficient for daily mobility use.

3.4.5 Comparative Performance Analysis

Compared with similar ultrasonic-based smart cane systems reported in literature, the proposed design demonstrates:

i. Higher feedback adaptability through cubic PWM mapping

ii. Faster response due to non-blocking control logic

iii. Reduced false triggers via moving average filtering

iv. Improved power efficiency through optimized motor control

Unlike systems relying solely on auditory alerts, this design integrates both haptic and dynamic acoustic feedback, improving usability in noisy environments.

4. CONCLUSION AND FUTURE DIRECTION

The completed smart cane not only met its original objectives but delivered an advanced and user-friendly implementation. Its continuous feedback mapping allows users to gauge distance naturally, without abrupt on/off alerts. The non-blocking control logic ensures uninterrupted sensing and feedback, providing near-instantaneous reaction to obstacles. The emergency mode gives a clear and urgent warning for very close hazards, increasing user safety. The project demonstrates that with well-chosen components and thoughtful software design, it is possible to create a low-cost, efficient, and intuitive assistive device that can be easily reproduced for real-world use. This work contributes to assistive technology by offering a solution that is both practical and scalable, improving independence and mobility for visually impaired individuals.

Future research should focus on enhancing both the functional intelligence and practical usability of the proposed assistive system. Integrating a miniature camera module embedded with onboard machine learning capabilities would enable real-time classification of obstacles, thereby providing context-aware alerts rather than simple proximity warnings. To improve environmental perception and eliminate detection blind spots, the system could be augmented with multiple ultrasonic sensors or LiDAR modules, including mechanisms for identifying overhead obstacles. For outdoor mobility support, incorporating GPS-based positioning combined with voice-guided navigation would offer structured route assistance and greater user autonomy. Connectivity features such as Bluetooth or Wi-Fi integration could further extend system functionality by enabling smartphone pairing, data synchronisation, and remote caregiver monitoring. Finally, refinements to the Mechanical design, such as waterproof enclosures and optimised handle grips, would improve durability, user comfort, and overall system robustness.

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