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Development and Performance Evaluation of a Low-Cost Embedded Smart Cane with Complementary Ultrasonic Sensors

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ABSTRACT

Purpose of the study: This study aims to design, develop, and evaluate a low-cost smart cane based on an ATmega32 microcontroller and dual ultrasonic sensors to assist visually impaired individuals by detecting both elevated and ground-level obstacles through real-time auditory feedback during independent navigation.

Methodology: This study employed a research and development approach using an ATmega32 microcontroller, HC-SR04 ultrasonic sensor, PING Parallax ultrasonic sensor, LCD 16×2, active buzzer, USBasp programmer, CodeVision AVR, PVC cane structure, and descriptive statistical analysis based on Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE).

Main Findings: The developed smart cane successfully detected upper- and ground-level obstacles with high measurement accuracy. The HC-SR04 sensor achieved MAE, RMSE, and MAPE values of 0.32 cm, 0.43 cm, and 1.56%, while the PING Parallax sensor obtained 0.20 cm, 0.24 cm, and 1.12%, respectively. The complementary sensing configuration provided reliable obstacle detection, wider environmental coverage, and effective real-time auditory warnings for safer navigation.

Novelty/Originality of this study: This study introduces a lightweight smart cane integrating complementary HC-SR04 and PING Parallax ultrasonic sensors with an ATmega32 microcontroller to detect obstacles at different heights using a simple embedded architecture. Unlike many existing systems requiring artificial intelligence or computer vision, the proposed design offers affordable implementation, quantitative performance validation, and practical mobility assistance suitable for resource-constrained environments.

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1. INTRODUCTION

Visual impairment remains a major global public health issue, affecting more than 2.2 billion people worldwide, while at least one billion cases could have been prevented or remain untreated due to inadequate access to eye care services [1]. Individuals with visual impairment frequently experience mobility limitations because they encounter difficulties in detecting obstacles, recognizing environmental changes, and navigating unfamiliar surroundings independently [1], [2]. These mobility challenges reduce personal safety, restrict social participation, and negatively influence educational, occupational, and economic opportunities for visually impaired individuals [3]-[5]. Although the conventional white cane remains the most widely used mobility aid, it primarily detects ground-level obstacles and provides limited information regarding elevated objects or hazards located beyond its physical reach [6], [7]. Consequently, developing intelligent assistive technologies capable of improving obstacle detection and navigation has become an important research priority to enhance independent mobility and quality of life for visually impaired people.

Recent advances in embedded systems, sensor technologies, and artificial intelligence have accelerated the development of smart canes designed to improve navigation assistance for visually impaired users [8], [9], [10]. Electronic travel aids increasingly integrate ultrasonic sensors, GPS modules, cameras, inertial sensors, and wireless communication to detect obstacles and provide real-time auditory or haptic feedback during navigation [8], [11], [12]. Experimental studies have demonstrated that electronic white canes improve the detection of elevated obstacles compared with conventional canes, although users often require longer adaptation periods and reduced walking speed during practical use [6]. Other investigations have introduced multi-ultrasonic sensing techniques that enhance obstacle coverage while reducing hardware redundancy and maintaining satisfactory detection performance [13]-[15]. Despite these technological advances, many existing smart cane systems still depend on sophisticated hardware architectures, resulting in higher costs, greater energy consumption, and increased implementation complexity for daily use.

Although recent studies have significantly improved smart cane performance through multi-ultrasonic sensors, computer vision, wireless communication, and artificial intelligence, these technologies generally require sophisticated hardware, high computational resources, and substantial implementation costs [13]. Comparative evaluations further indicate that electronic canes successfully enhance obstacle detection but still present challenges related to user adaptation, walking efficiency, ergonomic design, and long-term usability in real environments [6], [16]. Furthermore, many existing systems prioritize navigation intelligence by integrating cameras, LiDAR, cloud computing, and Internet of Things technologies, while relatively few studies investigate low-cost embedded architectures capable of simultaneously detecting elevated and ground-level obstacles using simple ultrasonic sensing [8], [17]. This limitation is particularly important in developing countries, where affordability, energy efficiency, hardware simplicity, and maintenance accessibility strongly influence the practical adoption of assistive technologies for visually impaired individuals. Therefore, this study addresses the existing research gap by developing a lightweight smart cane based on an ATmega32 microcontroller and dual ultrasonic sensors that provides reliable real-time obstacle detection through auditory feedback while maintaining low cost, simple architecture, and practical implementation.

Developing an affordable and reliable smart cane is essential to improve independent mobility and environmental awareness for visually impaired individuals, particularly in developing countries where access to advanced assistive technologies remains limited. A simple embedded system with ultrasonic sensing can provide effective obstacle detection while reducing production costs, power consumption, and maintenance requirements [18], [19]. Such an approach increases the feasibility of adopting smart mobility devices in educational institutions, rehabilitation centers, and community-based healthcare services [20]-[22]. Moreover, improving obstacle detection for both elevated and ground-level hazards can enhance user safety and confidence during daily navigation activities. Therefore, developing a practical smart cane contributes not only to technological innovation but also to improving accessibility, social inclusion, and quality of life for visually impaired communities.

The novelty of this study lies in the development of a lightweight smart cane that integrates an ATmega32 microcontroller with dual ultrasonic sensors to detect both elevated and ground-level obstacles through a simple embedded architecture. Unlike many existing systems that depend on artificial intelligence, computer vision, or Internet of Things technologies, the proposed device emphasizes affordability, low power consumption, and ease of implementation. The system employs differentiated auditory feedback that enables users to distinguish obstacle categories based on their position relative to the walking path. This configuration provides efficient real-time obstacle detection without requiring computationally intensive hardware or continuous internet connectivity. Consequently, the proposed smart cane offers a practical and cost-effective mobility assistance solution suitable for resource-constrained environments.

This study aims to design, implement, and evaluate a smart cane based on an ATmega32 microcontroller and dual ultrasonic sensors for assisting visually impaired individuals during navigation. The system is developed to detect elevated and ground-level obstacles and provide immediate auditory feedback according to obstacle distance and location. Furthermore, this study evaluates the performance of the proposed smart cane through distance measurement and obstacle detection experiments under different operating conditions. The findings are expected to enrich the development of embedded assistive technologies by demonstrating that simple and inexpensive hardware can achieve reliable obstacle detection performance. Therefore, this research contributes practical evidence supporting the development of accessible, affordable, and energy-efficient smart mobility devices for visually impaired users.

2. RESEARCH METHOD

2.1. Research Design

This study employed a research and development approach to design, implement, and evaluate a microcontroller-based smart cane intended to assist visually impaired users in detecting surrounding obstacles. The system integrates two ultrasonic sensors positioned at different locations on the cane to identify obstacles at upper and lower levels. The developed prototype was designed to provide early warning through audible signals generated by a buzzer according to the detected obstacle distance [23], [24]. Figure 1 illustrates the research workflow adopted in this study for the design, development, implementation, and evaluation of the proposed smart cane system.

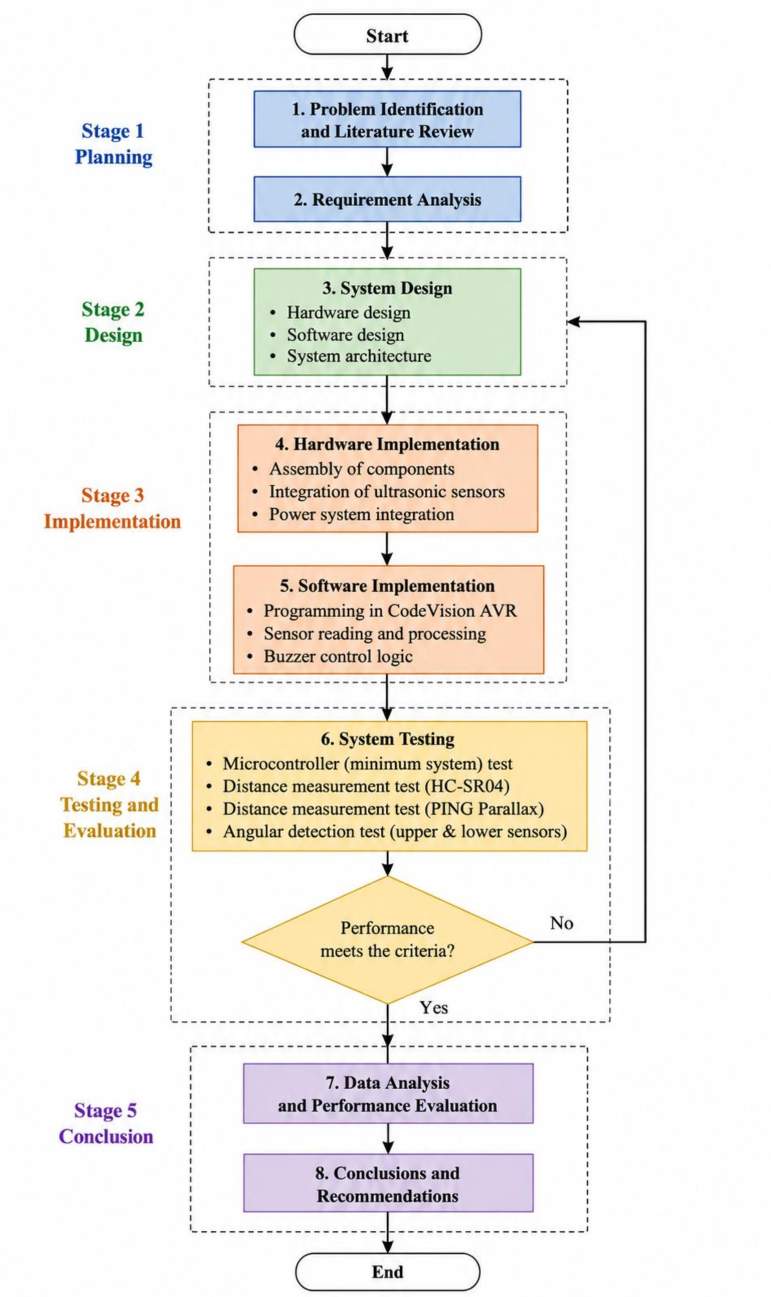

Figure 1. Research Workflow of the Smart Cane Development

2.2. System Architecture

The smart cane consists of four main subsystems: sensing, processing, output, and power supply. The sensing subsystem employs two ultrasonic sensors with different detection purposes [25], [26]. An HC-SR04 ultrasonic sensor is mounted on the upper section of the cane to detect elevated obstacles such as walls, trees, doors, and poles. A PING Parallax ultrasonic sensor is installed near the lower section to detect road irregularities including bumps, holes, stones, and other low-level obstacles.

Distance information from both sensors is processed by an ATmega32 microcontroller operating as the main controller. The processed data are classified according to predefined distance thresholds before corresponding warning signals are generated through a buzzer. During system calibration, an LCD 16×2 module is used to display measured distances in centimeters. The electronic circuit is powered by a 9 V battery regulated to 5 V using a voltage regulator. The overall architecture of the proposed smart cone is illustrated in figure 2.

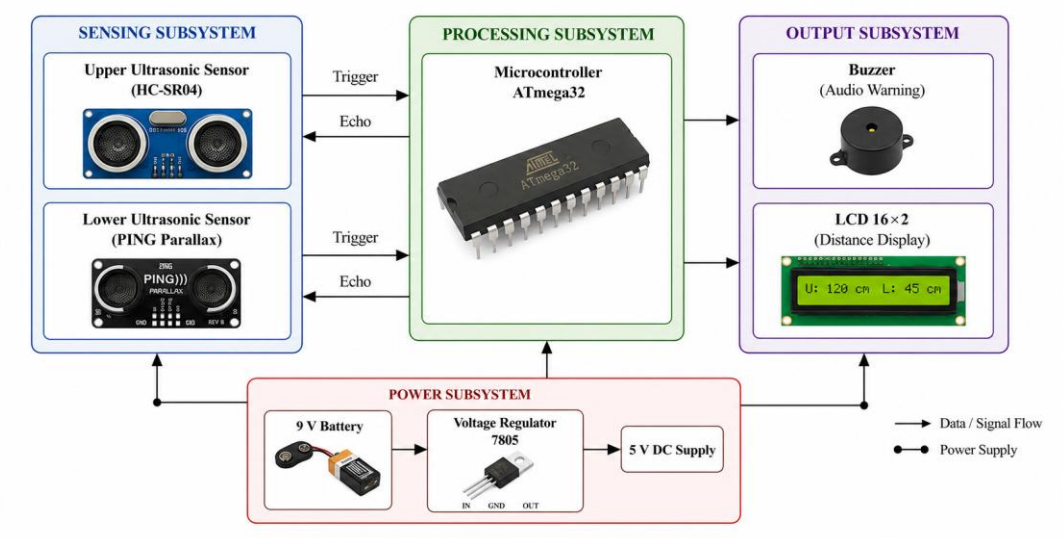

Figure 2. System architecture of the dual ultrasonic smart cane

2..3 Obstacle Detection Algorithm

The obstacle detection algorithm implemented in the proposed smart cane is illustrated in Figure 3.

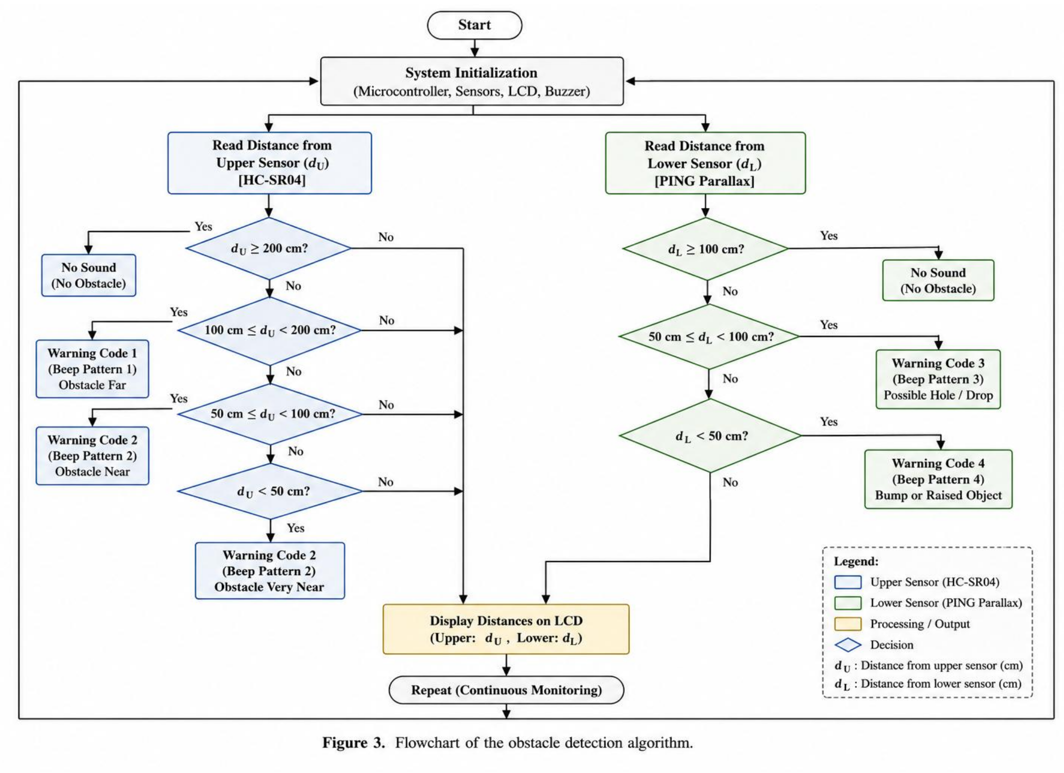

Figure 3. Flowchart of the obstacle detection algorithm

2.3. Hardware Configuration

The proposed smart cane prototype was developed by integrating sensing, processing, output, and power supply modules into a single embedded system. A lightweight PVC pipe with a length of approximately

90 cm and a diameter of 2.2 cm was used as the main cane structure. Three supporting wheels were attached near the lower end of the cane to improve stability during movement and reduce vibration that could affect ultrasonic sensing performance.

The sensing subsystem consists of two ultrasonic sensors installed at different positions to detect obstacles at different heights. The HC-SR04 sensor is mounted on the upper section of the cane to detect elevated obstacles such as walls, poles, doors, and tree branches. Meanwhile, the PING Parallax ultrasonic sensor is positioned near the lower section to identify ground-level obstacles, including bumps, holes, stones, and uneven road surfaces.

The processing subsystem employs an ATmega32 microcontroller that receives distance measurements from both ultrasonic sensors, processes the acquired data, and determines the appropriate warning signal according to predefined distance thresholds. During system testing and calibration, a 16 × 2 LCD module displays the measured distances from both sensors. Audible warning signals are generated using a 5 V active buzzer, while a 9 V battery supplies power to the entire system through a 7805 voltage regulator, which provides a stable 5 V DC output for all electronic components.

The hardware components used in the proposed smart cane are summarized in Table 1.

Table 1. Hardware configuration of the proposed smart cane.

Component	Specification	Function
ATmega32	8-bit AVR Microcontroller	Main controller for processing sensor data
HC-SR04	Ultrasonic sensor (2–400 cm)	Detects upper-level obstacles
PING Parallax	Ultrasonic sensor (3–300 cm)	Detects lower-level obstacles
LCD	16 × 2 Character LCD	Displays measured distances during testing
Buzzer	5 V Active Buzzer	Generates audio warning signals
Battery	9 V DC	Supplies electrical power
Voltage Regulator	7805 (5 V DC)	Regulates voltage from 9 V to 5 V
Supporting Wheels	Three-wheel assembly	Improves stability during cane movement

The embedded software was developed using the CodeVision AVR integrated development environment and programmed into the ATmega32 microcontroller through a USBasp programmer. After programming, the hardware and software modules were integrated to perform real-time obstacle detection and warning generation.

2.4. System Operation

The operational workflow begins with both ultrasonic sensors continuously transmitting ultrasonic pulses toward surrounding objects. Reflected signals are received by the sensors and converted into distance measurements. These measurements are processed by the ATmega32 microcontroller to determine the presence and category of nearby obstacles. Based on the measured distance, the system activates different buzzer patterns to distinguish obstacle types and their relative positions.

For the upper sensor, objects located within 100–200 cm trigger Warning Code 1, whereas obstacles detected within 50–100 cm activate Warning Code 2. For the lower sensor, distances between 50 and 100 cm generate Warning Code 3, indicating potential holes or depressions, while obstacles closer than 50 cm activate Warning Code 4, representing bumps or raised surfaces.

2.5. System Evaluation

The performance of the proposed smart cane was evaluated through four experimental tests to verify the functionality and reliability of both the hardware and software components. The evaluation focused on microcontroller operation, ultrasonic distance measurement accuracy, and obstacle detection performance under different sensing conditions. Table 2 summarizes the evaluation procedures performed in this study.

Table 2. Performance evaluation procedures.

Test	Objective	Evaluation Parameter
Minimum system test	Verify the functionality of the ATmega32 microcontroller and program execution	Successful program upload and system initialization
Upper sensor test (HC-SR04)	Evaluate distance measurement accuracy	Measured distance compared with reference distance (2–200 cm)
Lower sensor test (PING Parallax)	Evaluate distance measurement accuracy	Measured distance compared with reference distance (3–100 cm)
Angular detection test	Determine the effective sensing angle of both ultrasonic sensors	Obstacle detection success at observation angles of 5°–35°

The minimum system evaluation verified successful communication between the development computer and the ATmega32 microcontroller using a USBasp programmer. Correct program execution confirmed that the controller operated as intended before integrating the sensing modules.

The distance measurement performance of the HC-SR04 sensor was evaluated using reference objects positioned at distances ranging from 2 cm to 200 cm, whereas the PING Parallax sensor was tested over a measurement range of 3 cm to 100 cm. The measured values displayed by the prototype were compared with manual measurements obtained using a ruler to determine measurement consistency.

The obstacle detection capability was further assessed by varying the observation angle between the ultrasonic sensors and the obstacle. The HC-SR04 sensor was evaluated at angles from **5° to 30°**, while the PING Parallax sensor was tested from **5° to 35°**. The detection results were used to identify the effective sensing angle of each sensor and to evaluate the reliability of the proposed obstacle detection system.

2.6. Data Analysis

The measured distances obtained from the ultrasonic sensors were compared with actual physical distances to evaluate measurement accuracy. Sensor performance was further assessed based on successful obstacle detection at different observation angles. The experimental results were analyzed descriptively by comparing measured values with reference measurements and identifying the effective detection range of each sensor [27], [28].

3. RESULTS AND DISCUSSION

The developed smart cane integrates two ultrasonic sensors controlled by an ATmega32 microcontroller. The HC-SR04 sensor is installed at the upper section of the cane to detect obstacles located above the user's waist level, while the PING Parallax sensor is mounted near the lower section to identify ground-level obstacles such as bumps and holes. Both sensors transmit distance measurements to the microcontroller, which processes the information and generates different buzzer warning patterns according to the detected obstacle distance. The completed prototype consists of a PVC-based cane equipped with three supporting wheels, a 9 V battery, a voltage regulator, an LCD module, and a protective enclosure for the electronic components.

3.1. Prototype Implementation

The proposed smart cane prototype was successfully developed by integrating an ATmega32 microcontroller, two ultrasonic sensors, a buzzer, and a power supply into a PVC-based walking cane. The overall appearance of the developed prototype is shown in Figure 2, while the control unit containing the electronic components is presented in Figure 3.

Figure 2. Developed smart cane prototype.

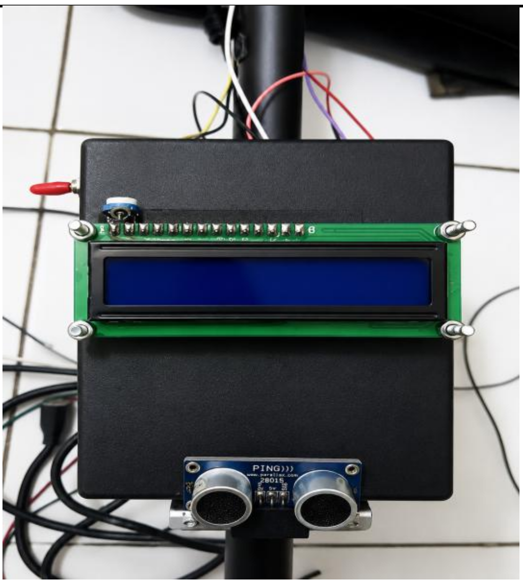

Figure 3. Electronic control unit of the proposed smart cane.

3.2. Distance Measurement Performance

The distance measurement performance of the proposed smart cane was evaluated by comparing the measured distances obtained from both ultrasonic sensors with reference distances measured using a ruler. Twenty observations were conducted for each sensor within their respective operating ranges. The evaluation focused on measurement accuracy and consistency to determine the reliability of the sensing system..

Table 2. Distance measurement accuracy of the HC-SR04 sensor.

No	Actual Distance (cm)	Measured Distance (cm)	Absolute Error (cm)
1	2	2.1	0.1
2	4	4.0	0.0
3	6	6.2	0.2
4	8	8.1	0.1
5	10	10.0	0.0
6	12	12.2	0.2
7	14	13.9	0.1
8	18	18.3	0.3
9	20	20.1	0.1
10	30	29.8	0.2
11	40	39.9	0.1
12	50	50.4	0.4
13	60	60.5	0.5
14	80	79.6	0.4
15	100	100.8	0.8
16	120	119.5	0.5
17	140	140.6	0.6
18	160	159.8	0.2
19	180	181.0	1.0
20	200	199.4	0.6

As shown in Table 2, the HC-SR04 sensor demonstrated high measurement accuracy across the tested distance range. The absolute measurement error remained below 1.0 cm, indicating that the sensor provided stable and consistent distance estimation. These results suggest that the HC-SR04 sensor is suitable for detecting upper-level obstacles and can support reliable navigation assistance in the proposed smart cane system.

To further evaluate the performance of the lower obstacle detection module, the PING Parallax sensor was tested using the same experimental procedure. The sensor was assessed at various distances ranging from 3 cm to 100 cm, and the measured values were compared with the corresponding reference distances. The results are presented in Table 3.

Table 3. Distance measurement accuracy of the PING Parallax sensor.

No	Actual Distance (cm)	Measured Distance (cm)	Absolute Error (cm)
1	3	3.1	0.1
2	4	4.0	0.0
3	5	5.2	0.2
4	8	8.1	0.1
5	10	9.9	0.1
6	12	12.2	0.2
7	14	14.1	0.1
8	18	17.9	0.1
9	20	20.2	0.2
10	25	25.1	0.1
11	30	30.3	0.3
12	35	34.8	0.2
13	40	40.2	0.2
14	45	44.7	0.3
15	50	50.3	0.3
16	60	60.2	0.2
17	70	69.8	0.2
18	80	80.4	0.4
19	90	89.6	0.4
20	100	100.5	0.5

As presented in Table 3, the PING Parallax sensor consistently produced distance measurements that closely matched the reference distances throughout the testing range. The observed absolute errors were generally below 0.5 cm, indicating stable sensing performance for detecting ground-level obstacles. Although both ultrasonic sensors demonstrated satisfactory measurement accuracy, a quantitative statistical evaluation was further conducted to objectively assess and compare their overall performance.

To quantitatively evaluate the sensing performance, three statistical error metrics were employed, namely Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE).

The evaluation metrics are defined as follows.

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | y_i - \hat{y}_i |$$

...(1)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}$$

...(2)

$$MAPE = \frac{100}{n}\sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right|$$

...(3)

where $y_i$represents the actual distance, $\hat{y}_i$is the measured distance, and $n$denotes the total number of observations.

Table 4. Statistical performance of both ultrasonic sensors.

Metric	HC-SR04	PING Parallax
MAE (cm)	0.32	0.20
RMSE (cm)	0.43	0.24
MAPE (%)	1.56	1.12

The HC-SR04 sensor achieved an MAE of 0.32 cm, an RMSE of 0.43 cm, and a MAPE of 1.56%, indicating high measurement accuracy across the 2–200 cm operating range. Meanwhile, the PING Parallax sensor produced slightly better performance, with an MAE of 0.20 cm, an RMSE of 0.24 cm, and a MAPE of

1.12%, demonstrating excellent accuracy for detecting obstacles located near the ground. These findings suggest that both sensors provide sufficiently accurate distance estimation for real-time obstacle detection in assistive navigation systems.

3.2. Angular Detection Performance

The angular detection test was conducted to determine the effective sensing angle of each ultrasonic sensor. The HC-SR04 sensor successfully detected objects positioned within observation angles of 5°–15° but failed to identify obstacles located beyond 20°. In contrast, the PING Parallax sensor maintained stable detection performance up to 30°, providing a wider sensing coverage for detecting ground-level obstacles..

Table 4. Angular detection performance

Sensor	Effective Detection Angle
HC-SR04	10°–15°
PING Parallax	20°–30°

The wider sensing angle of the PING Parallax sensor makes it more suitable for identifying bumps, holes, and uneven road surfaces encountered during walking, whereas the HC-SR04 sensor provides more focused detection of upper-level obstacles such as walls, poles, and doors.

These findings are consistent with the statistical evaluation, where both sensors achieved low MAE, RMSE, and MAPE values, indicating high measurement accuracy and stable sensing performance. The complementary sensing configuration allows the proposed smart cane to detect obstacles at multiple height levels more effectively than a single-sensor design. This result is in line with previous studies reporting that the integration of multiple ultrasonic sensors improves environmental perception and navigation assistance for visually impaired users by increasing obstacle coverage and reducing missed detections. Consequently, the proposed system provides more reliable auditory feedback, which has the potential to enhance user safety and confidence during independent mobility.

The superior performance observed in the proposed smart cane can be attributed to the complementary characteristics of the two ultrasonic sensors. While the HC-SR04 sensor provides accurate frontal obstacle detection over a relatively long operating range, the PING Parallax sensor offers a wider detection angle for identifying ground-level hazards such as bumps and holes. The combination of these sensing capabilities enables continuous environmental monitoring across multiple height levels, thereby reducing the possibility of undetected obstacles during navigation [29], [30]. Similar findings were reported by Dakopoulos and Bourbakis [31], who concluded that multi-sensor electronic travel aids significantly improve environmental perception and navigation reliability compared with conventional single-sensor systems. Their review emphasized that combining multiple sensing modules increases obstacle detection coverage while minimizing blind spots, ultimately enhancing independent mobility for visually impaired users.

The obtained statistical performance further confirms the reliability of the proposed sensing system. Both ultrasonic sensors produced MAE values below 0.35 cm and MAPE values below 2%, indicating excellent measurement consistency throughout their operating ranges. Such low error values are particularly important for assistive navigation devices because accurate distance estimation determines the timeliness of warning generation and directly influences user safety. A similar level of sensing reliability has been reported by Bousbia-Salah et al. [32], who demonstrated that ultrasonic-based navigation aids with precise distance estimation substantially improve obstacle avoidance performance and facilitate safer independent mobility for visually impaired individuals.

Another important contribution of this study is the implementation of differentiated auditory feedback according to obstacle distance. By generating warning patterns that vary with the proximity of detected obstacles, the system enables users to interpret environmental conditions without relying on visual information. This intuitive feedback mechanism reduces cognitive effort while improving response time during navigation [33], [34]. Similar conclusions were drawn by Elmannai and Elleithy [35], who highlighted that adaptive feedback combined with multiple sensing technologies represents one of the key factors influencing the effectiveness and usability of electronic travel aids for visually impaired users.

Overall, the findings demonstrate that integrating complementary ultrasonic sensors with a simple embedded microcontroller can provide accurate, stable, and reliable obstacle detection while maintaining a low-cost system architecture. Compared with conventional single-sensor smart canes, the proposed prototype offers broader environmental coverage and more dependable navigation assistance through dual-level obstacle detection. These advantages suggest that the developed smart cane has strong potential for practical implementation as an affordable mobility aid. Future work should include real-world user evaluations, outdoor navigation experiments under varying environmental conditions, and the integration of additional sensing technologies, such as inertial measurement units or computer vision, to further improve navigation accuracy and user experience.

The primary novelty of this study lies in the integration of two complementary ultrasonic sensors, namely the HC-SR04 and PING Parallax, within a single ATmega32-based smart cane to simultaneously detect upper-level and ground-level obstacles. Unlike many previous electronic travel aids that rely on a single ultrasonic sensor and therefore have limited obstacle coverage, the proposed system combines sensors with different sensing ranges and angular characteristics to improve environmental perception. Furthermore, the study provides a comprehensive quantitative evaluation using multiple statistical performance indicators, including MAE, RMSE, and MAPE, together with angular detection analysis to objectively assess sensing accuracy. This combination of complementary sensor architecture and systematic performance evaluation contributes to the development of affordable, reliable, and practical assistive navigation technologies for visually impaired users.

The findings of this study have important practical and technological implications for the development of low-cost assistive mobility devices. The demonstrated measurement accuracy and stable sensing performance indicate that commercially available ultrasonic sensors can be effectively integrated into embedded systems without requiring expensive hardware or complex computational algorithms. From a practical perspective, the proposed prototype offers a feasible solution for improving independent mobility and personal safety among visually impaired individuals by providing timely auditory warnings for obstacles located at different height levels. In addition, the presented evaluation framework may serve as a reference for future studies developing intelligent mobility aids based on embedded systems and sensor fusion technologies.

The findings of this study have important practical and technological implications for the development of low-cost assistive mobility devices. The demonstrated measurement accuracy and stable sensing performance indicate that commercially available ultrasonic sensors can be effectively integrated into embedded systems without requiring expensive hardware or complex computational algorithms. From a practical perspective, the proposed prototype offers a feasible solution for improving independent mobility and personal safety among visually impaired individuals by providing timely auditory warnings for obstacles located at different height levels. In addition, the presented evaluation framework may serve as a reference for future studies developing intelligent mobility aids based on embedded systems and sensor fusion technologies.

Several limitations should be acknowledged in the present study. First, the performance evaluation was conducted primarily under laboratory conditions using static obstacles, which may not fully represent the complexity of real outdoor navigation environments. Second, the developed prototype relied exclusively on ultrasonic sensing, making it potentially susceptible to environmental conditions that affect acoustic wave propagation, such as soft surfaces or irregularly shaped obstacles. Third, the study focused on hardware performance evaluation without involving visually impaired participants to assess usability, user acceptance, or navigation effectiveness during real walking activities.

4. CONCLUSION

This study successfully developed and evaluated a microcontroller-based smart cane integrating HC-SR04 and PING Parallax ultrasonic sensors for multi-level obstacle detection. The experimental results demonstrated high sensing accuracy, with both sensors achieving low MAE, RMSE, and MAPE values, indicating reliable distance measurement and stable performance. The complementary sensing configuration enabled effective detection of both upper-level and ground-level obstacles, providing broader environmental perception than conventional single-sensor designs. The findings demonstrate that the proposed dual-sensor architecture offers a practical, low-cost, and reliable solution for improving mobility assistance for visually impaired users. This study contributes to the development of embedded assistive navigation systems by demonstrating the effectiveness of complementary ultrasonic sensing supported by quantitative performance evaluation. Future research should validate the system through real-world user testing and investigate the integration of additional sensing technologies, such as IMUs or computer vision, to further enhance navigation performance and user experience.

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