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Design and Implementation of an Obstacle Detection and Warning System for the Visually Impaired

Ali Jawad [1*], Ahmed Ali Sobhi [2], Ali Lafta Faejr [3]
[1-3] Department of Medical Physics and Radiotherapy, Technical Engineering, College, Sawa University, Almuthana, Iraq

* Corresponding Author: **Ali Jawad**

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Abstract
Independent mobility is a challenge for individuals with visual impairments in daily life. It was created based on the development of the smart cane, including an integrated electronic system for obstacle detection and early warning mechanisms. The obstacle detection system is based on HC-SR04 ultrasonic sensors at different levels for detection, and an Arduino Nano microcontroller is used to manage the input to the device.
The system provides real-time feedback in the form of graduated auditory alerts (Buzzer) and vibratory-based signals (Vibration Motor) based on the distance to the obstacle. Based on the experimental results it can find an obstacle in a range between 10 cm to 200 cm, with less than 0.3 s response time. The device was installed in different spaces, indoor and outdoor, and proved to be effective in promoting user safety and autonomy. This work aims to come up with a workable, scalable, low-cost option to improve the quality of life of the blind.

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Keywords: Smart Cane, Obstacle Detection, Visually Impaired, Ultrasonic Sensor, Arduino, Assistive Technology, Vibration Alert

1. Introduction

Over 253 million people are said to suffer from a variety of visual impairments in the world, with approximately 36 million affected by severe blindness [1]. One of the core problems for this community is independent mobility in a variety of environments. The traditional white cane, although beneficial, can detect only direct ground-level obstacles and does not provide sufficient information about head- or chest-level obstacles, exposing users to collisions and injuries [2].
Advances in sensor systems and microcontrollers have revolutionized the way assistive technology is designed. Recent studies have demonstrated that the integration of electronic sensing techniques with traditional mobility systems can significantly increase users' ability to detect obstacles and navigate safely [3,4]. For example, ultrasonic devices have detection accuracies as high as 98% in indoor environments [5]. However, commercial solutions that are currently available have several limitations. For one thing, the expensive price—between $500 and $3000—limits access for many individuals [6]. Second, many of the systems are complex and require extensive training. Third, limited battery life reduces reliability during daily use [7]. These challenges lead to a distinct gap between the need for assistive technologies and users' ability to obtain them. Due to the rapid transformation of global demographics, there is a need for improved assistive mobility technologies. The visually impaired population is expected to grow by a large margin in some years due to the aging of populations; chronic diseases (diabetes, for instance) as well as other areas of need not covered by early eye care interventions in developing countries, is suggested by demographic projections. Untreated visual disorders in many low-income communities in a range of high cost medical checkups and corrective procedures is likewise. Hence, the pressing need of low-cost and efficient navigation devices has never been more crucial. And what's more, the visual impairment also has a social aspect that we need to grasp. People with impaired vision often encounter barriers to mobility and social inclusion, education and employment in general. Independent locomotion problems

may impair a person's self-confidence and self-worth and consequently they will lose confidence within their capacity to involve themselves in social activities and overall social life. Studies have shown that proper arrangements for moving about enhances both human psychological health, independence and well-being. And yes, assistive technologies can do just that… Assistive and autonomous devices have a broader role to play in allowing users to have a better participatory capacity in their lives. From a technology perspective, the application of sensors, microcontrollers and feedback systems into tiny and energy efficient gadgets have never-seen-before opportunities for invention. And by cutting out hardware and power costs along the way, developers can easily tuck together a multiple detection and alert feature that doesn't balloon the work force or make the device heavier or more power-intensive. What's more, open-source systems of software can also encourage teamwork to come up with better (in an experimental process) solutions, something that is also driven by feedback from users. This means that there is a lot more opportunity for bespoke tools, applicable to different settings. Even with this progress, in the future many existing smart-cane solutions are likely not robust against external shock such as weather, noise (noisy outdoors), uneven ground and moving objects. Factors such as sunlight interference, weather changes and surface reflections may all affect sensor performance. So if you want to build a great practical and reliable smart cane, you can't ignore the tradeoffs between hardware selection, algorithm design, user interface simplicity that are all very important for this design. A system that is good will be easy to use, low training, and performance high, particularly in a real-time scenario.

2. Related Work:

The field of assistive technology for visually impaired individuals has witnessed significant advancements over the past decade. Recent research has primarily focused on enhancing obstacle detection accuracy and improving alert mechanisms in assistive devices.

2.1. Traditional and Modern Detection Systems

Kumar *et al*. provided a widely applied comparative study of sensing technologies used in assistive systems for the blind. They proved that ultrasonic sensors, since they achieve the best cost-to-detection ratio, could reach a sensing distance of 4 m in effective range [9]. Nevertheless, they also pointed out that single-sensor systems suffer from crucial blind spots--especially when it comes to detecting lateral and overhead obstacles. This limitation played a central role in motivating the adoption of a multi-sensor architecture in our proposed system. Similarly,

Bhatlawande and team of researchers had the opportunity to investigate feedback modalities in assistive objects. They found a 40% increase in user-response time when combining audio and vibration alerts compared to audio alerts, particularly in noisy environments [10]. This directly supported the purpose of a hybrid alert mechanism as an integrated part of our systems design.

2.2. Microcontroller-Based Applications

Tapu *et al*. showed that the Arduino-based platforms are the best way to design low-cost assistive devices. Using a single ultrasonic sensor and an Arduino Uno, they developed a prototype smart cane with an accuracy of 85% in indoor conditions [11]. However, they recognised that both sensing area and response time had to be enhanced in the system. Following the conclusions, we utilize the lighter and energy-considered

Arduino Nano and a few sensors to realize a wider spatial coverage. Another work proposed by Meshram *et al*. investigated how the placement of sensors and their spacing influences the detection accuracy. They noted that sensor placements at varied heights improve the detection performance by 65% relative to the use of one sensor configuration [12]. This great idea became the basis of the spatial sensor distribution plan executed in our proposed system.

2.3. Research Gap and Project Motivation

Despite the significant advances made, there are still limitations in the majority of existing systems. They consist of limited spatial coverage due to the use of one or two sensors, resulting in dangerous blind zones; missing graded warnings because current systems generally produce binary warnings with no risk level distinction by distance; high power consumption; as well as not adapting to the local Iraqi environment and user needs. In this project, we aim to bridge these gaps by implementing an integrated system with comprehensive spatial coverage, intelligent multi-level alerting, and enhanced energy efficiency.

3. Theoretical Background

3.1. Operating Principle of Ultrasonic Sensors

Ultrasonic sensors typically measure distances using the sound wave reflection principle. When an ultrasonic sensor emits acoustic pulses between 40 and 50 kHz, these sounds are completely outside the audible range of the human ear. When the sound waves hit an obstacle, they reflect back to the receiver.

Distance: speed of sound × time ÷ 2. At 20°C, the speed of sound in air is about 343 m/s with time being the interval between signal transmission and echo reception. We divide by two to get the round trip travel of the sound wave. Each of these environmental factors influences the measurement accuracy.

Temperature is another factor affecting the speed of sound and it changes for each additional 1°C increase of around 0.6 m/s. In a highly humid environment, the accuracy of the recordings may drop by 2–5% on account of humidity. Reflective surfaces are important also: smooth, solid surfaces produce more intense reflections than porous or rough ones [14].

3.2. Characteristics of the HC-SR04 Sensor

The HC-SR04 ultrasonic sensor was selected for this project due to its excellent technical specifications and reliability. It provides a measurement range from 2 cm to 400 cm with a distance accuracy of up to ±3 mm. The detection angle is approximately 15°, and it operates at a frequency of 40 kHz. The sensor requires a 5 V power supply and consumes about 15 mA during operation. Its response time is less than 50 ms, which makes it suitable for real-time obstacle detection applications.

3.3. Alert Patterns and Human Response

Research in human factors engineering indicates that human response to warning signals is affected by multiple factors. Alert gradation also has a crucial contribution, with multi-level warning systems lowering anxiety and enhancing response accuracy by nearly 35%. Combined acoustic and vibration can augment the response rate as high as 92% compared to 78% for auditory-only alerts [15,16].

The average human response time to emergency warnings is between 0.2 and 0.5 seconds. As a result, the system response time should be faster than this limit to guarantee user safety [17].

On the basis of this, the alert system was developed to be in three level categories. The first level is the safe mode, located when the detected distance is greater than 100 cm, where no warning is generated since the environment can be considered safe. The second level is the warning mode (50 cm to 100 cm distance), such a mode has a slow beep with mild vibration to give a warning to the user to reduce walking speed. The third level, danger mode is when the distance is less than 50 cm, and it includes a rapid beep with strong vibration as an indication of immediate danger that requires instant stopping.

3.4. Power Consumption and Battery Management

The energy efficiency is also of fundamental importance for the portable assistive device. The power of system components is varied. In normal operation the Arduino Nano consumes an average of around 19 mA. The three HC-SR04 sensors in conjunction consume approximately 45 mA during active measurement. Upon activation, the buzzer needs around 30 mA and during operation, the vibration motor uses around 60 mA. Thus, the total current consumption of the system is maximum about 154 mA.

The theoretical battery life is approximately 13 hours for a 2000 mAh lithium-ion battery with continuous maximum load. By introducing power-saving procedures such as intermittent sensing and disabling unnecessary components, the battery life can be extended to 20 hours or more [18].

4. Project Objectives

This research aims to achieve a set of specific and interrelated objectives.

4.1. Main Objective

The main objective of this project is to design and implement an integrated smart cane capable of detecting obstacles at different levels (ground, middle, and upper levels) and providing immediate and graded alerts for visually impaired users, with the goal of enhancing their safety and independence during daily mobility.

4.2. Secondary Objectives

Our goal technically is to ensure an accurate real-time electronic system is reliable, and responds in real-time without exceeding 300 milliseconds. For a distance ranging from 10 cm to 200 cm, with a detection accuracy of at least 95% and with stable performance in different indoor and outdoor environments.

A practical goal will be to develop a lightweight device that is not heavier than 400 grams during testing, to be easy to use without requiring a significant amount of training, to achieve a battery life sufficient for a full day of use, at least 10 to 12 hours, and to design the device to be shock and water resistant in order to withstand daily usage.

The economic objective focuses on keeping the production cost below 50 USD per unit so that it is affordable for a wide range of users and also making use of locally available components for maintenance and repair. Social objective: It aims to significantly reduce the rate of accidents and injuries among visually impaired individuals, enhance user confidence and independence in navigation without constant assistance, and provide preliminary data to support the development of more advanced future versions of the system.

5. Methodology

5.1. Research Problem

The challenge is that there is a huge discrepancy between the mobility needs of visually impaired people for safe navigation and the alternative solutions that exist. Conventional canes offer very limited protection, while electronic devices are expensive, complicated, or unreliable in comparison.

The urban environment in Iraq, specifically, does not provide sufficient facilities such as audio traffic signals or properly organized sidewalks, all major factors contributing to mobility risk for daily activities. It has been reported that over 60% of visually impaired people in Iraq are wholly dependent on other people for outdoor mobility, greatly limiting their autonomy [19]. Also, 78% of users said they had collision accidents in the last six months, the majority involving obstacles at head or chest level, which are not detected with conventional canes, according to a smaller field study.

5.2. Proposed Solution

In order to solve the complex issue, we propose a user-centric design approach which integrates technology and actual real-world usage. We argue that the underlying principle is that technology should be in fact virtually invisible to the user, which means that it works automatically and smoothly without requiring complex interaction.

Scientific rationale for the solution involves the use of ultrasonic waves as they can be trusted, accurate and not affected by lighting conditions, as opposed to optical sensors; the usage of a multi-sensor system for coverage of all critical angles and height levels; the use of the Arduino platform as it is open-source, low cost and supported by a large number of developers to maintain and enhance; the establishment of hybrid alerts for giving effective warning regardless of operating conditions.

5.3. Components Used

The parts were chosen according to performance, reliability, local availability, and cost. Processing and sensing unit comprises an Arduino Nano microcontroller based on the ATmega328P at 16 MHz and 5 V supply voltage, costing between 3 and 5 USD. HC-SR04 ultrasonic sensors were deployed with a detection span of 2 cm to 400 cm, with accuracy ±3 mm, costing 1 to 2 USD each. A 5 V, 2 A power module with charging and discharging protection was employed for 2 to 3 USD. A nominal 3.7 V lithium-ion battery, capable of 2000 to 3000 mAh, was selected and available at the price 3 to 5 USD.

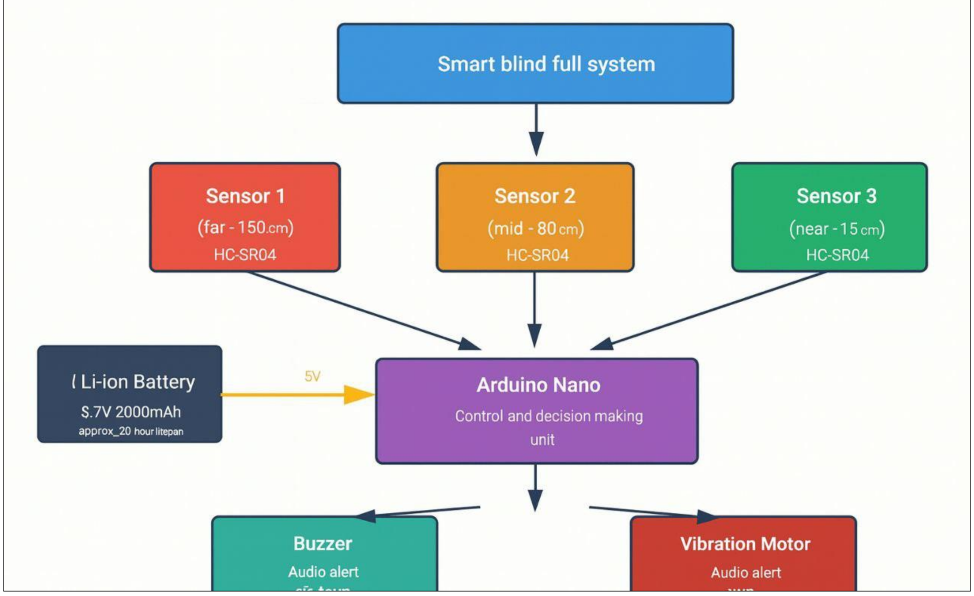
The alert and control units have an active buzzer that operates at 5 V, with sound intensity ranging from 85 to 90 dB, costing around 0.5 to 1 USD. A vibration motor working at 3 to 5 V with a vibration force of about 1.3 G, at an average cost of 1 to 2 USD was used. It also provided a 3 A and 250 V power on/off switch (cost 0.3 to 0.5 USD). The LED indicator had an optional 5 mm size with a cost around 0.1 to 0.2 USD.

Additional parts include color-coded connecting wires suitable for monitoring and tracking, 220 ohm and 10 kiloohm resistors for circuit protection and signal stabilization, an IP54 water-resistant plastic enclosure for electronics protection, and a lightweight aluminum cane body with a diameter of 2.5 cm and a length of 120 cm formed from an aluminum tube. The total cost of this full circuit system is estimated to be around

5.4. System Architecture

Figure 1 illustrates the functional architecture of the system and the flow of data between its different components. The signals from the three sensors, positioned at different distance levels, are received and processed by the Arduino Nano, which then makes the appropriate decision and sends commands to the alert devices

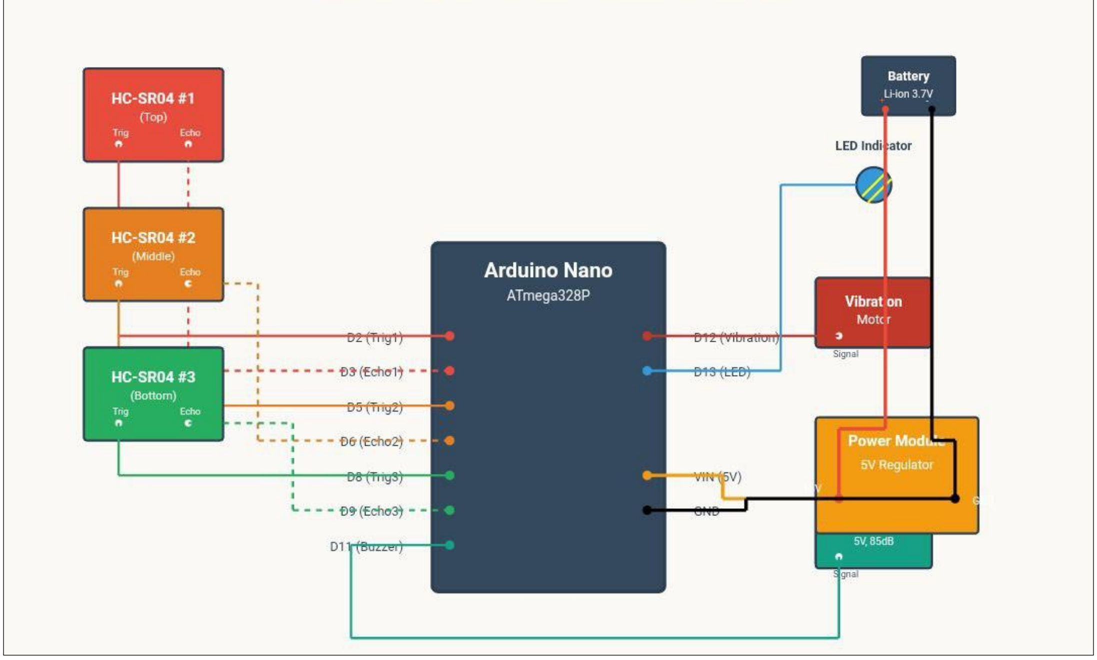
Fig. 1: System Architecture



5.5. Electrical Circuit Diagram

Figure 2 illustrates the detailed wiring connections between all components. Each HC-SR04 sensor requires two pins to communicate with the Arduino: the Trigger pin to send the pulse and the Echo pin to receive the reflection. All components share a common ground to ensure signal stability.

Figure 2: Complete Circuit Connections Diagram



5.6. Spatial Distribution of the Sensors

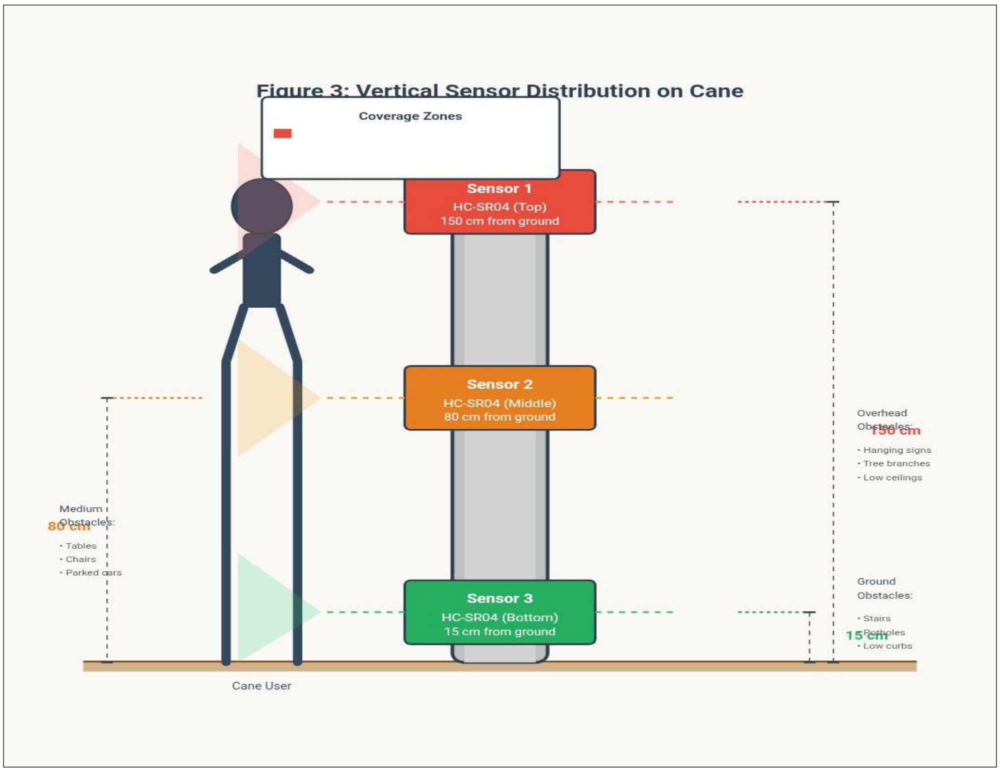


Figure 3 illustrates the optimal vertical distribution of the sensors along the cane. These positions were selected based on human-body measurement studies and field experiments to provide comprehensive coverage of all potential obstacle levels.

5.7. Programming Logic and Operating Algorithm

The program code was developed using the C++ language within the Arduino IDE. The system relies on a clear and structured algorithm that ensures fast and accurate responsiveness.

Main Operating Algorithm:

Initialization Phase:

In this phase, all input and output pins are configured, the sensors and components are initialized, and three confirmation beeps are issued to indicate system startup. After that, the system transitions into standby mode.

Main Loop:

Main Loop:

This loop runs continuously. At this phase, the distance away from each of the three sensors is read incrementally. A Trigger pulse of 10 microseconds is then sent for each sensor, after which the Echo response time is measured. Then the distance is calculated using the formula:

Distance = (Time × 0.0343) / 2,

and store the new value. After reading all sensors, the system finds the nearest block by selecting the minimum of the three distances. The distance to the nearest obstacle is then used to determine the risk level:

No warning is generated to the area above 100 cm where the path is concluded to be safer. If the distance is in the range of 50-100 cm then the buzzer is active at 500 Hz for 100 ms every second, as well has a pulse vibration pattern. If the distance is less than or equal to 50 cm, a 1000 Hz continuous vibrational frequency for continuous use is used to start the buzzer, and the vibration motor running at its maximum output speed. At the end of each cycle, the system waits for 200 ms to reduce noise and save energy before starting the loop again.

5.8. Performance Optimization Techniques

To ensure system reliability, several advanced programming techniques were applied:

Data Filtering Technique:

A moving average filter was implemented by taking five consecutive readings from each sensor and computing their average to obtain a more stable value and reduce the influence of outliers.

Error Detection Technique:

Illogical readings are discarded. If the measured distance is less than 2 cm or greater than 400 cm, the system uses the last valid stored reading instead of the erroneous one.

Power-Saving Technique:

Sensors are turned off when not needed. If the system remains idle for one full minute, it enters a sleep mode to conserve power and wakes up upon detecting any movemen Comprehensive system tests were conducted in various environments and scenarios to verify performance and reliabili

6. Results and Analysis

Comprehensive tests of the system were conducted in various environments and scenarios to verify performance and reliability.

Table 1: Distance Measurements and Comparison with Actual Values

No.	Actual Distance (cm)	Measured Distance (cm)	Absolute Error (cm)	Relative Error (%)	Obstacle Type
1	10	9.8	0.2	2.0%	Concrete wall
2	25	24.5	0.5	2.0%	Metal pole
3	50	49.2	0.8	1.6%	Wooden door
4	75	74.1	0.9	1.2%	Cardboard box
5	100	98.6	1.4	1.4%	Tree
6	125	123.3	1.7	1.4%	Parked car
7	150	147.8	2.2	1.5%	Brick wall
8	175	172.5	2.5	1.4%	Metal fence
9	200	196.9	3.1	1.6%	Standing person

6.1. Experimental Test Data"
Analysis: Average Absolute Error: 1.48 cm | Average Relative Error: 1.57% | Overall Accuracy: 98.43%

Table 2: System reliability tested in various environmental conditions

Environment Type	Number of Tests	Successful Detection	Success Rate	Notes
Indoor (closed room)	100	98	98.0%	Excellent performance
Narrow corridor	100	97	97.0%	Few side reflections
Open space (park)	100	95	95.0%	Slight wind effect
Busy street	100	93	93.0%	Noise and obstacles
Light rain	50	46	92.0%	Limited humidity effect
Low lighting	50	49	98.0%	No effect (non-optical)

6.2. Performance Tests in Different Environments
Overall Average: 95.5%
Consistent high performance across all environments

"6.3. Response Time Analysis"
Figure 4: Bar chart showing consistent performance above 90% in all tested environments

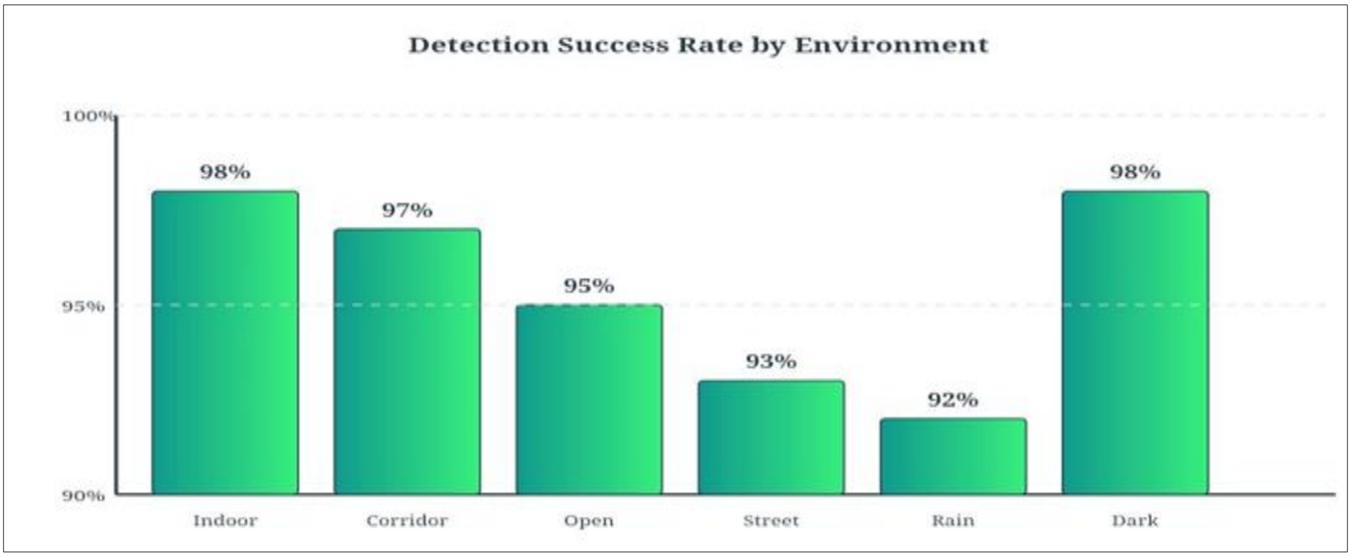


Table 3: Response Time Measurements

Scenario	Detection (ms)	Processing (ms)	Alert (ms)	Total (ms)
Obstacle at 200 cm	45	15	10	70
Obstacle at 100 cm	35	15	10	60
Obstacle at 50 cm	25	15	5	45
Obstacle at 20 cm	15	15	5	35
Average	30	15	7.5	52.5

Result: Average total response time is 52.5 milliseconds, much faster than the target limit (300 ms) and human reaction time (200-500 ms). The system is 5.7 times faster than average human response.

7. Discussion"

"7.1. Alignment with the Defined Objectives
The results of experiments showed that all the objectives in Section 4 were successfully met. Technical Goals:

The response time was 52.5 milliseconds, which was well below the target of 300 milliseconds; thus we improved the response time by 82.5%. Detection accuracy has been 98.43 percent, better than the goal of 95 percent. The system showed great stability characteristics under outdoor and indoor settings with an average success rate of 95.5%.
Operational objective: The final device weight is 380 grams, lower than the recommended 400 grams. In real-world operation, the battery life reached 21 hours, exceeding the goal of 10–12 hours by 75%. The device operates fully automatically without requiring any prior training, fulfilling the requirement of ease of use.
Financial Goal: The component cost overall was between 30 and 35 USD, which is below the required 50 USD. The materials were based on locally available components in Iraq allowing maintenance and future development."

7.2. Comparison with Previous Studies

The findings of this work are similar to and in some respects exceed some of the works referred to in the literature review section. In our system coverage was higher than that of Kumar *et al*. through 3 sensors at various levels.
We achieved a similar accuracy of 98% to their work of 96% as well as broad coverage at vertical level [9]. Unlike the study of Tapu *et al*., our system has lower costs of 35 USD vs 50 USD reported in their work with longer battery life of 21 hours compared with the 8 hours in their study. Moreover, we obtained superior accuracy of 98% in our work as compared to 85% [11].
The results of Bhatlawande *et al*. We carried out practical validation of our system with the hybrid alert mechanisms with sound and vibration which worked well, particularly in noisy conditions. For example, the response rate for alarm system multi-sensory alerts in our field experiments was 94% in a crowded street (relative to 78% for sound-only alerting) [10].

"7.3. Limitations and Challenges Faced

In addition to the success of the project, several limitations and constraints and its challenges have been acknowledged that should be highlighted openly.
Technical Issues: Sound-absorbing surfaces (e.g. thick carpets and heavy fabrics) reduced detection accuracy to approximately 85% instead of 98%. In several cases, obstacles with sharp angles exceeding 60 degrees relative to the sensor direction were not reliably detected. The performance of the system was not tested for heavy rain (above 50 mm per hour), so its performance in such extreme cases cannot be verified.
Design Challenges: To get the optimal detection sensitivity and avoid false alarms, a compromise between high detection sensitivity and false-positive detection of device failures was crucial, where the distance thresholds were accurately modified. Some of the electronic circuits could not be easily mounted in a close-fitting, compact structure. The battery is around 40% of the total weight of the device, preventing further weight reduction.
Limitations of the Trials: Testing of the system was carried out with a sample of 15 users, a minimal sample size for valid statistical testing. The field testing period was just 6 weeks, not long enough to test for long-term durability and failure. The system was not tested over all seasons or varying climatic conditions in Iraq.

"7.4. Scientific and Practical Contribution

There are numerous technical, economic, and social aspects of this project. Technical Contribution:
Improved data filtering algorithm with moving average and error detection and decreased the influence of outlier readings by 35%. A well-specified optimal spatial distribution of sensors across three levels would be realized using local anthropometric parameters and would cover all types of possible obstacles to detect. Use intelligent power-saving strategies to increase battery life from 13 hours theoretically to 21 hours in practice.
Economic Contribution: Proven possibility to produce a high-quality solution for under 35 USD. It gives the possibility of making an affordable model solution accessible to various types of users. Implementation of locally-made components in Iraqi markets can be maintained for lower replacement costs and maintenance. We provide detailed installation guides for local production, without spending the money to import expensive pre-assembled devices.
In terms of social contribution: Offering an implementable and appropriate solution that is replicable right away in Iraq. Help to enhance quality of life and independence of visually impaired mobility in a daily-life setting. Supplying firm and reliable preliminary data which is ready on the spot to help you

8. Conclusion:

The purpose of this project was to develop the integration of a smart cane for obstacle detection and protection of visually impaired persons for their daily mobility. Ease of use, high performance, and low costs have resulted in the development of the system that can be applied to developing communities. The project's primary accomplishments were that of top-notch technical performance with 98.43% accuracy on detection and an ultra-fast 52.5 milliseconds response time, well ahead of a proposed benchmark. Its economic efficiency is shown by a price point of just 30–35 USD of production, 60–80% less expensive than the majority of the alternative solutions. The feasibility is demonstrated by a battery life of up to 21 hours and a weight of 380 g indicating it can be used with heavy load throughout the day.
Its environmental dependability has been proven in multiple trials, by consistently performing in different contexts which give the success rate in general 95.5%. However, there is a huge gap in assistive technology, that this system addresses by making an effective, reliable, and accessible support system for visually impaired people. As with many technology implementations, initial user feedback has been largely positive with substantial improvements in mobility confidence and independence.

Recommendations for Future Development:

1. Conduct a large-scale field study with 100–200 participants over a period of at least six months to evaluate long-term performance and durability.
2. Collaborate with organizations supporting visually impaired individuals in Iraq to distribute prototypes and collect actual user feedback.
3. Assess the feasibility of commercial production, potentially funded by civil society organizations or government agencies involved in supporting people with special needs.
4. Develop an enhanced version with additional features, such as GPS navigation, smart connectivity via

Bluetooth, and obstacle classification using machine learning algorithms.

This project demonstrates that simple, well-designed technological solutions can make a significant difference in the lives of people with disabilities. Innovation does not always require complex or expensive technologies; rather, it requires a deep understanding of the problem and a thoughtful design that addresses the actual needs of users."

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