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Inclusive innovation: Implementation of low-cost proximity sensors for canes

Innovación inclusiva: Implementación de sensores de proximidad de bajo costo para bastones

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ABSTRACT

Visually impaired individuals face challenges in moving safely, affecting their independence and increasing the risk of accidents. This work presents the development of a prototype accessory for canes with ultrasonic sensors, designed to enhance mobility and independence at a low cost. The device, based on IoT, uses an Arduino Nano, an HC-SR04 ultrasonic sensor, and a buzzer, generating progressive acoustic alerts based on obstacle proximity. During testing, it demonstrated high effectiveness in detecting large objects and issuing immediate alerts; however, it showed limitations with small objects, liquids, and humid environments. The need to optimize the battery, which is currently replaceable, was identified, and as a future improvement, the incorporation of wireless charging technologies and LIDAR sensors was proposed for more precise detection. Additionally, it was recommended to include a night LED to alert others and improve the cane's materials for greater durability. The prototype's design is lightweight, accessible, and functional, prioritizing simplicity without compromising reliability. Compared to similar devices, it stands out for its effectiveness and low cost, offering a viable solution to improve the mobility and independence of visually impaired individuals, reducing risks and facilitating social integration.

Keywords: autonomy; accessibility; ultrasonic; IoT; microcontrollers

RESUMEN

Las personas con discapacidad visual enfrentan dificultades para desplazarse de manera segura, lo que afecta su independencia y aumenta el riesgo de accidentes. Este trabajo presenta el desarrollo de un prototipo de accesorio para bastones con sensores ultrasónicos, diseñado para mejorar la movilidad e independencia de estas personas a un bajo costo. El dispositivo, basado en IoT, emplea un Arduino Nano, un sensor ultrasónico HC-SR04 y un buzzer, generando alertas acústicas progresivas según la proximidad de los obstáculos. Durante las pruebas, demostró alta efectividad en la detección de objetos grandes y en la emisión de alertas inmediatas; sin embargo, presentó limitaciones con objetos pequeños, líquidos y en entornos húmedos. Se identificó la necesidad de optimizar la batería, actualmente reemplazable, y se propuso como mejora futura la incorporación de tecnologías de carga inalámbrica y sensores LIDAR para una detección más precisa. Además, se recomendó incluir un LED nocturno para alertar a otras personas y mejorar los materiales del bastón para aumentar su durabilidad. El diseño del prototipo es ligero, accesible y funcional, priorizando la simplicidad sin comprometer la confiabilidad. En comparación con dispositivos similares, destaca por su efectividad y bajo costo, ofreciendo una solución viable para mejorar la movilidad e independencia de personas con discapacidad visual, reduciendo riesgos y facilitando su integración social.

Palabras clave: autonomía; accesibilidad; ultrasónico; IoT; microcontroladores

1. INTRODUCTION

People with visual impairments face significant challenges in their daily lives that extend beyond the mere limitation of sight. These difficulties include insecurity when navigating unfamiliar environments, reliance on others for mobility, and constant concern about potential obstacles that could lead to accidents (Trujillo Mora et al., 2021; Bansal et al., 2020). According to the World Health Organization, more than 285 million people worldwide experience some form of visual impairment, underscoring the urgent need for tools that enable them to interact with their surroundings safely and effectively (Díaz Alva, 2023; Venkatraman et al., 2020).

Approximately one in six people experience some form of disability, limiting their full participation in society while restricting access to essential opportunities such as education, healthcare, and employment, creating even greater challenges for individuals with visual impairments, who often rely on adapted technological solutions like canes to navigate their environment more safely and independently (Ulfa et al., 2023; Zaidi et al., 2023). Despite technological advances in assistive devices, many available products fail to address the specific needs of visually impaired individuals, making it essential to innovate in the design of solutions that enhance their autonomy and mobility while ensuring greater accessibility and effectiveness in their daily lives (Nazri et al., 2020; Romeo et al., 2022).

The integration of IoT in canes has delivered significant benefits, enhancing users' quality of life by enabling safer and more confident mobility (Choe et al., 2023; Leporini et al., 2023); promoting greater independence while overcoming the challenges they encounter in their daily mobility (Panazan & Dulf, 2024; Paredes Orozco & Domínguez-Morales, 2024). However, they still face challenges in integrating multiple technologies to provide a more comprehensive approach to assisted navigation (Harini et al., 2024; Yam & Elshakankiri, 2024). Applying theories such as user-centered design is essential to ensure that technological solutions effectively address the needs of individuals with visual impairments (Minatani, 2024; Vineeth et al., 2021).

The integration of artificial intelligence (AI) into smart canes has demonstrated its potential to enhance the functionality of these devices, with recent studies showing that learning algorithms can significantly improve navigation by enabling the cane to adapt to the user's movement patterns and recognize common obstacles in their environment (Jang et al., 2024; Mai et al., 2024). Additionally, a system integrating AI with sensor data has been shown to enable a more seamless and personalized interaction between the user and the device, enhancing responsiveness and adaptability (Mocanu et al., 2024; Yauri et al., 2024). This adaptive capability not only enhances obstacle detection but also delivers personalized recommendations that significantly improve user mobility. The integration of AI into these devices marks a major advancement in providing more effective assistance, tailored to the unique needs of individuals with visual impairments (Jang et al., 2024; Song et al., 2024).

The research proposal focuses on developing an adaptive IoT-based prototype compatible with various canes, designed to detect obstacles using ultrasonic sensors and provide auditory alerts through a buzzer. This system emits different tones based on the obstacle's proximity, increasing in frequency and intensity as the user approaches an object, enhancing detection and allowing for better anticipation of their surroundings (Gharghan et al., 2024; Remya et al., 2023). Aiming to advance the field of assistive technology by integrating a proximity sensor into a cane designed for visually impaired individuals.

Related work

The study was conducted in China at Hainan Normal University and surrounding areas with the objective of developing a smart cane for visually impaired individuals that integrates 2D LiDAR technology and RGB-D cameras for navigation and obstacle detection while employing a methodology that involved testing in both indoor and outdoor environments using advanced algorithms such as Cartographer and enhanced YOLOv5 while also integrating the system into a lightweight and portable cane, achieving results that demonstrated high accuracy in mapping and obstacle detection with the ability to recognize up to 86 types of objects and an average processing speed ranging from 25 to 31 FPS, leading to the conclusion that the cane effectively guides visually impaired individuals by helping them avoid obstacles and identify their surroundings (Mai et al., 2024).

The study was conducted in Romania at the Technical University of Cluj Napoca with the objective of developing a smart cane to enhance the mobility of visually impaired individuals while employing a methodology that encompassed research, design, and both laboratory and outdoor testing to assess its functionality while yielding results that demonstrated a lightweight prototype equipped with ultrasonic and color sensors that improve obstacle detection and navigation while also highlighting the significance of ergonomic design and intuitive feedback to maximize user acceptance, ultimately positioning the device as a cost-effective and efficient solution for assisted mobility (Mocanu et al., 2024).

The study was conducted in India at CHRIST in Bangalore with the objective of developing a smart cane to enhance the mobility of visually impaired individuals while employing a methodology that involved designing an integrated system with ultrasonic sensors and a Raspberry Pi-based navigation module, tested through simulations and practical trials to ensure its effectiveness while yielding results that demonstrated a functional device capable of detecting obstacles and providing haptic and voice alerts while also identifying limitations in detecting water and small obstacles, suggesting areas for future improvement, ultimately positioning the cane as a significant advancement in assisted mobility and independence for its users (Muktha et al., 2024).

The project was developed in India, specifically at Sri Sairam Engineering College, Chennai, Tamil Nadu, with the objective of developing a smart cane for visually impaired people to improve their autonomy through affordable and easy-to-use technologies. An IoT device was implemented that integrates ultrasonic sensors for obstacle detection, GPS for navigation, an RTC module for medication reminders, and health monitoring with heart rate and blood oxygen sensors. The results showed significant improvements in the mobility and safety of users by reducing dependence on third parties. This cane not only facilitates mobility, but also increases the quality of life of its users by offering an inclusive and accessible solution (Harini et al., 2024).

2. MATERIALS AND METHODS

2.1. Operation of IoT device implemented

Figure 1 illustrates how the IoT device utilizes a buzzer with three intensity levels and sound frequencies to progressively alert a person to the proximity of an obstacle: at 100 cm, it emits a soft and intermittent sound; at 75 cm, a louder and more frequent sound; and at 50 cm, a continuous and powerful sound, ensuring a timely response to prevent collisions.

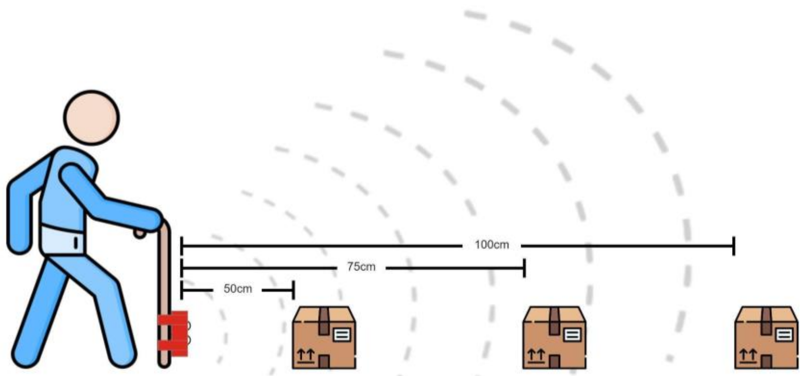

Figure 1. Device operating ranges

2.2. Hardware design

Figure 2 illustrates the schematic diagram of a real-time distance measurement system implemented with an Arduino Nano. The circuit consists of an HC-SR04 ultrasonic sensor, a buzzer as an acoustic actuator, and a battery module as the primary power source. The ultrasonic sensor measures distance using echo and trigger signals, which are connected to the Arduino's digital pins. When the detected distance falls within a predefined range, the buzzer is activated as an acoustic alert. The Arduino Nano operates with a set of 18650 batteries. To ensure a stable and long-lasting power supply, two 18650 batteries were connected in series, providing a total voltage of 7.4V and a capacity of 3000mAh. This configuration efficiently powers the Arduino Nano and its peripherals, ensuring a minimum of 8 hours of continuous operation. The total estimated consumption is approximately 100-120mA, resulting in a theoretical autonomy of up to 25 hours, considering 80% efficiency due to energy conversion losses. This choice optimizes system performance without requiring frequent recharges, offering a practical and cost-effective solution.

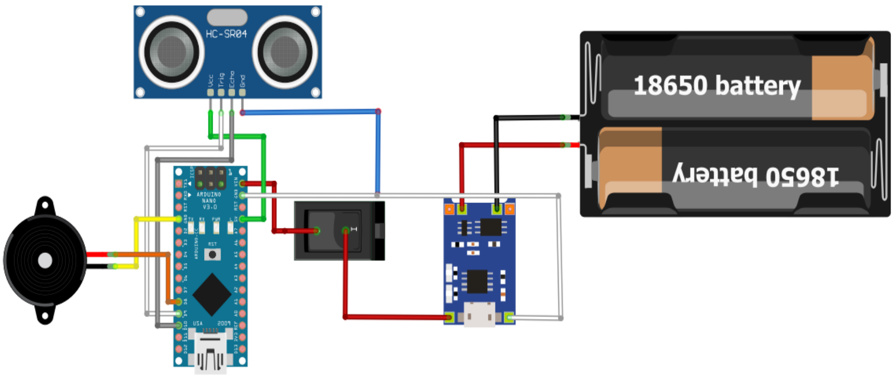

Figure 2. Circuit design

2.3. System architecture diagram

Figure 3 shows the system diagram of the device, which is divided into a control section and a sensing section. In the control section, the Arduino Nano is essential to process the data and manage the connected devices, such as the buzzer, in charge of generating sound alerts, and the ON/OFF switch, which allows turning the system on or off. On the other hand, the detection section includes the HC-SR04 ultrasonic sensor, which measures distances and detects obstacles, sending this information to the Arduino Nano for analysis. Power for the system comes from a 3.7V lithium battery connected via a battery carrier, which ensures a constant supply. This design ensures that the smart cane operates efficiently, providing safety to the user by issuing real-time alerts about nearby obstacles.

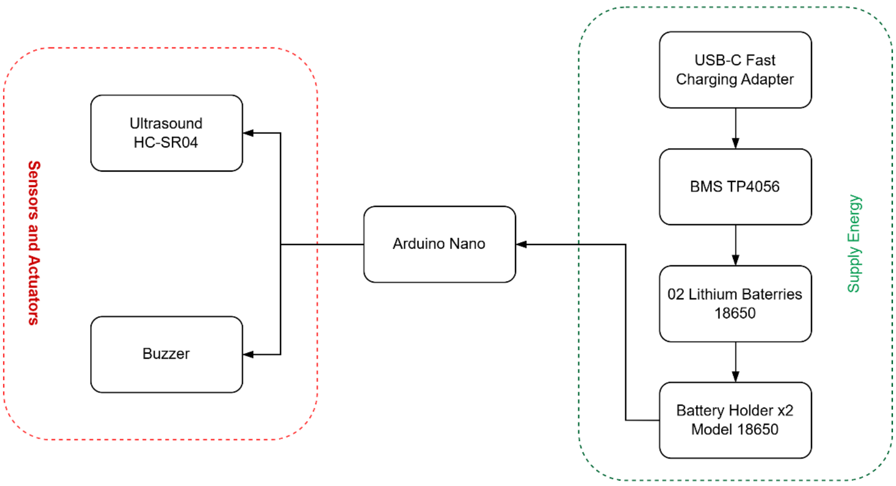

Figure 3. Block diagram design

2.4. Operating system

Figure 4 shows the connection and operation flow of an Arduino-based system. First, a lithium battery is inserted into a battery holder connected to the TP4056 BMS module, which powers the Arduino Nano. Then, an ultrasonic sensor and a buzzer are integrated to the Arduino. The sensor detects the distance and, depending on the measured values, the system emits constant or continuous audible alerts to warn of obstacles. If the distance is out of range, no sound is emitted.

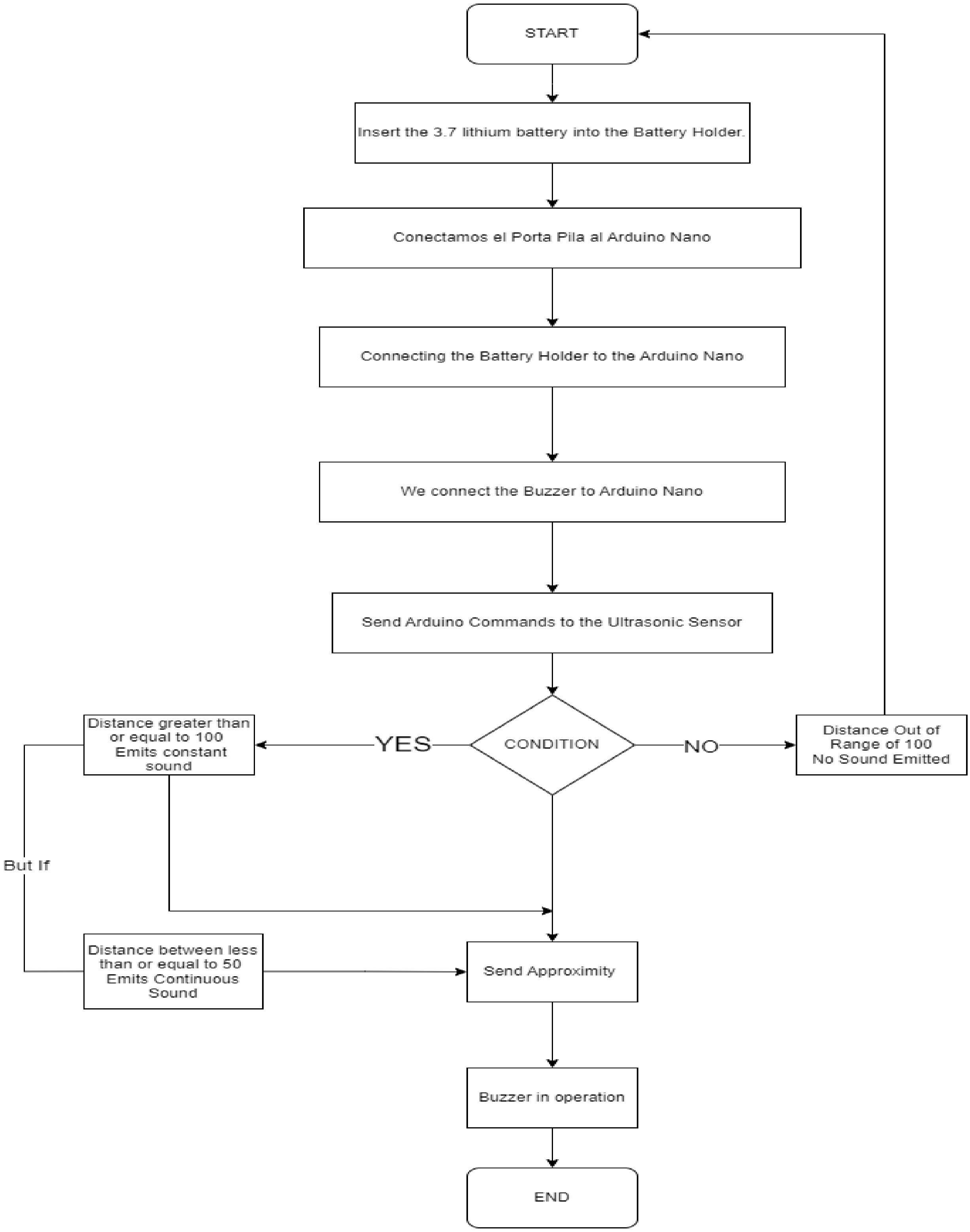

Figure 4. Device flow diagram

2.5. Device dimensions

The provided figures depict a container with main dimensions of 54 mm in width and 83 mm in height. These measurements are detailed in the front and rear view diagrams, showcasing cutouts, drill diameters, and structural elements such as supports and slots, as illustrated in Figure 5. The design and fabrication process utilized 3D technology, ensuring precision and adaptability.

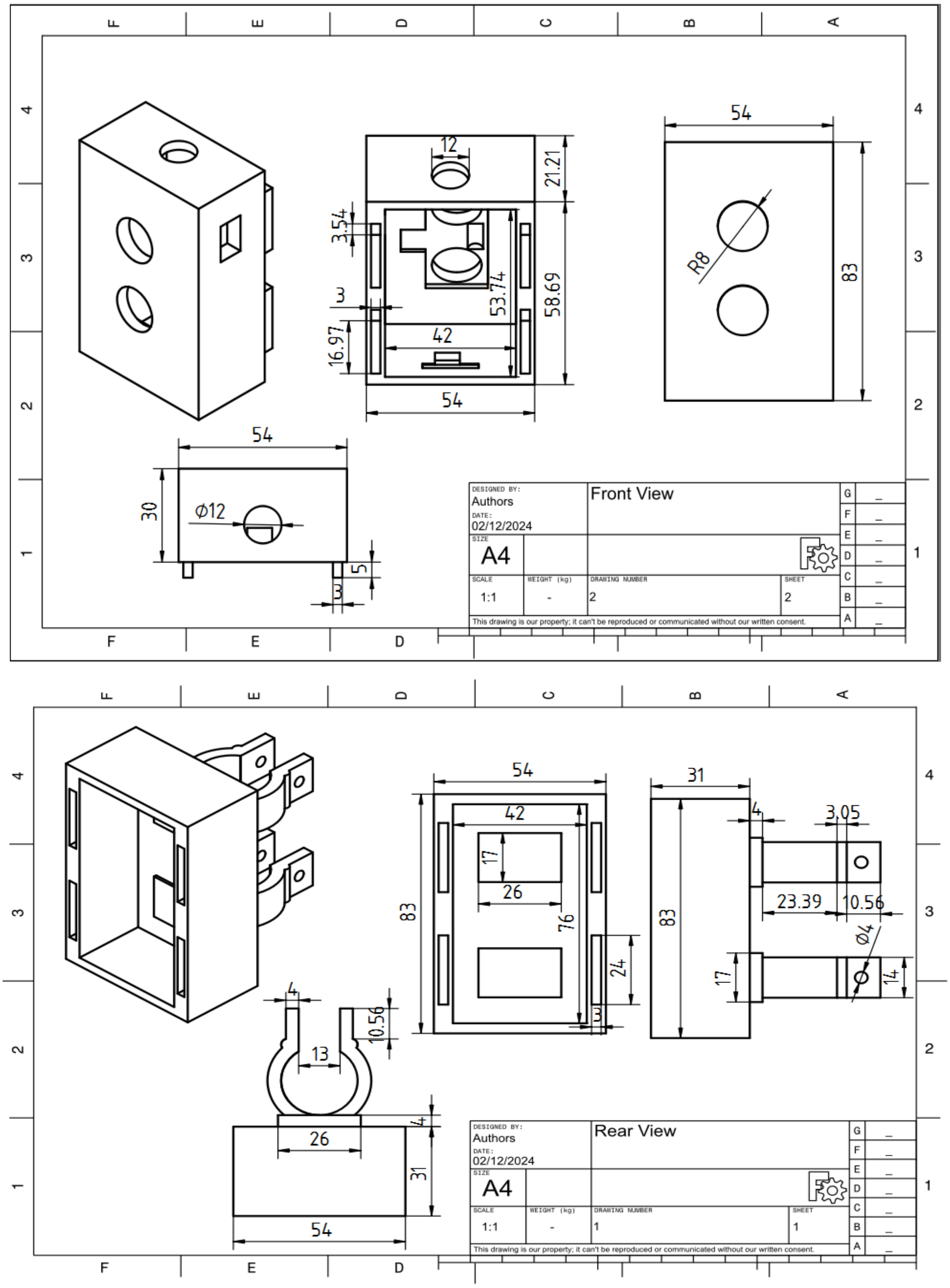

Figure 5. Isometric Perspectives

The container, primarily designed to protect and secure the circuit, was 3D printed using FreeCAD software, as shown in Figure 6. This approach highlights the versatility and user-friendliness of the software for similar projects.

Figure 6. Prototype model

3. RESULTS AND DISCUSSION

The proposed prototype exhibited efficient performance during testing, excelling in its ability to detect obstacles within preset distances and issue immediate alerts. The ultrasonic sensor demonstrated high accuracy in identifying large objects at ground level and effectively detecting obstacles, ensuring reliable navigation and enhancing user safety in various environments. Designed with accessibility and simplicity in mind, the prototype prioritizes a lightweight and practical structure, combining effective acoustic alerts with an economical and functional solution for users.

Figure 7 shows a comparison between the response times of the proposed system and the existing system for obstacle detection at different distances: 50 cm, 75 cm and 100 cm. The results show that the existing system presents a progressive increase in its response time, reaching 260 ms at 50 cm, 275 ms at 75 cm and 300 ms at 100 cm compared to the proposed system which is 250 in all measurements (Panazan, 2024).

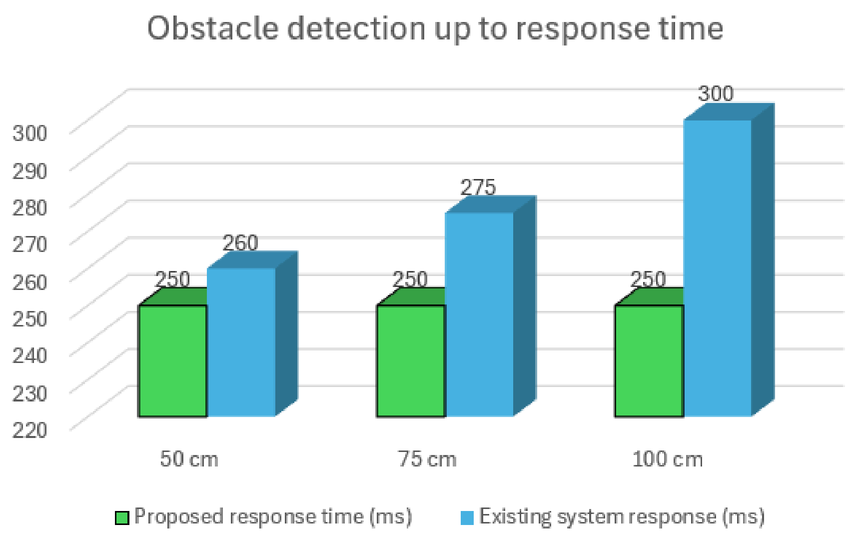

Figure 7. Comparison of results

Tabla 1 presents the detection tests conducted for each object, showing that all objects were subjected to a specific number of attempts. Panazan & Dulf (2024) also provide a detailed table summarizing the detection tests performed for each object. Additionally, the system demonstrates high effectiveness, achieving 100% accuracy in detecting objects such as cardboard, a cup, a laptop, and a wall, while maintaining 80% accuracy for a chair. Tests conducted with visually impaired individuals, including obstacle courses, have validated its reliability and precision as a trustworthy navigation tool, highlighting its potential to enhance user mobility and safety.

Tabla 1. Screening test

Object	Hits/Intents	Result [%]
Cardboard	10/10	100
Cup	10/10	100
Laptop	10/10	100
Wall	10/10	100
Chair	8/10	80

Tabla 2 shows that when the batteries are connected in series, the system voltage doubles to 7.4V, while the total capacity remains the same as that of a single battery (3000mAh). To calculate the theoretical battery lifetime, the formula 1 referenced in Tabla 3 is used. It is important to note that the Arduino consumes 55mA, the ultrasonic sensor 15mA, and the buzzer 30mA, resulting in a total consumption of 100mA. Ma et al. (2024) presents the formula for calculating theoretical lifetime at 100% efficiency.

$$Duration\ (hours) = Average\ consumption\ (mA)\ /\ Battery\ capacity\ (mAh) \qquad (1)$$

Tabla 2. Theoretical duration

<table>
<tr><th>Description</th><th>Duration</th><th>Result</th></tr>
<tr><td rowspan="2">Battery life (in hours)</td><td>3000</td><td rowspan="2">30 hours (theoretical)</td></tr>
<tr><td>100</td></tr>
</table>

Tabla 3 shows a process of efficient battery life, since in real scenario energy losses are unavoidable due to the resistance of the batteries, for this an adjustment is applied considering 85% of efficiencies in the nominal capacity of the batteries using the formula 2, Ma et al. (2024) shows the formula applied to obtain the calculations of the efficient battery at 85%.

$$Effective\ capacity = 3000mAh\ \times\ 0.85 = 2550mAh \qquad (2)$$

Tabla 3. Efficient duration

<table>
<tr><th>Description</th><th>Effective capacity</th><th>Result</th></tr>
<tr><td rowspan="2">Efficient battery life (in hours)</td><td>2550</td><td rowspan="2">25 hours 30 minutes (efficiently)</td></tr>
<tr><td>100</td></tr>
</table>

Figure 8 shows the comparison between the expected distances, the measured distances and the error rate associated with the implemented proximity sensor prototype. The green bars represent the expected distances in centimeters (cm), while the light blue bars show the distances measured by the prototype. The gray line indicates the error rate in percentage (%), calculated as the relative difference between the expected and measured distances (Panazan, 2024).

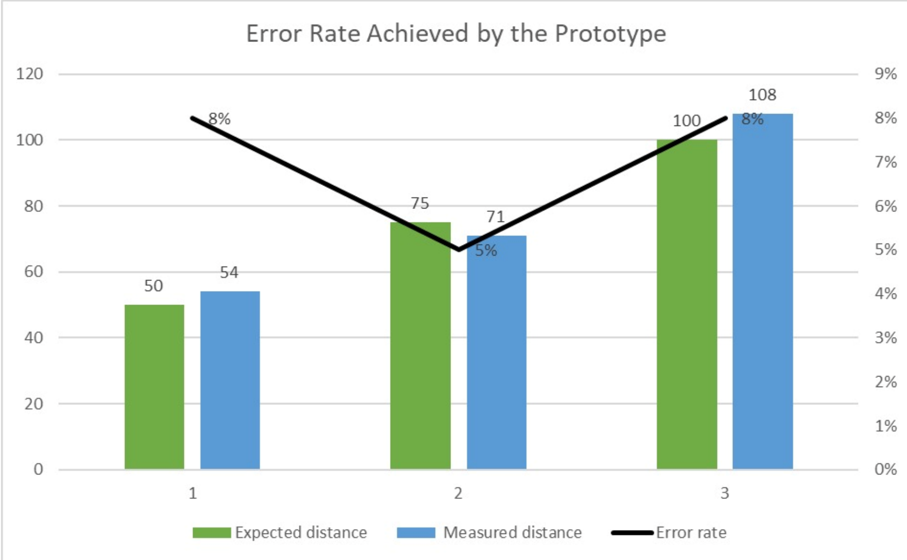

Figure 8. Prototype distance and error rate

Analyzing the device's energy consumption is crucial for assessing its autonomy and efficiency. Although a theoretical battery life of 30 hours was estimated be under 100mA consumption, real-world testing showed an actual duration of approximately 26 hours. This 13.3% discrepancy is due to energy conversion losses, temperature variations, and the natural degradation of electronic components. For more accurate energy consumption measurements, the use of a real-time current analyzer is recommended, as it would further optimize energy management. Additionally, implementing a low-power mode for the Arduino Nano could extend battery life by 15-20%.

Compared to assistance devices based on LIDAR or infrared sensors, the proposed system using the HC-SR04 ultrasonic sensor has significantly lower power consumption (15mA versus 200-500mA for LIDAR-based systems). However, its obstacle detection accuracy is lower, especially on reflective or liquid surfaces. An intermediate option would be the integration of hybrid sensors that combine ultrasound with low-power LIDAR. In terms of response time, the current system detects obstacles in 250 ms compared to 300 ms in previous systems, showing a 16.7% improvement in user alert speed.

Each component selected in the design balances cost, efficiency, and market availability. The Arduino Nano was chosen for its low power consumption (55mA in operation and 19mA in standby) and compact size. The 5V buzzer was used for its ability to generate audible alerts without requiring external amplification. The HC-SR04 ultrasonic sensor was preferred due to its low cost and ease of implementation, though it has been identified as an area for improvement in future versions. The 18650 battery offers a good capacity-to-weight ratio, but the possibility of using lighter and more energy-efficient LiPo batteries will be explored.

To allow for future improvements and adaptations, the smart cane has been designed with a modular approach. Key optimization proposals include the integration of wireless charging to eliminate the need for manual battery replacement, the addition of extra sensors such as LIDAR or infrared to enhance obstacle detection in complex environments, and the implementation of Bluetooth or Wi-Fi for mobile device connectivity, enabling real-time usage statistics and alerts.

CONCLUSIONS

The implementation of the necessary components for the IoT device was satisfactory, carrying out an exhaustive verification of its operation, from the simplest elements, such as the battery, to the ultrasonic sensor, complying with the hardware and software specifications. Appropriate operating ranges were established for each component, including the different measurement levels of the sensor. The IoT device was able to detect three levels of intensity and sound frequency to progressively alert about the proximity of an obstacle: at 100 cm it emits a soft and spaced sound, at 75 cm a louder and more frequent sound, and at 50 cm a constant and powerful sound, allowing a timely response to avoid collisions. This cost-effective approach aims to make the technology accessible to more people, especially those with visual impairments.

Furthermore, the IoT device was not only limited to object detection, but also proved to be an effective solution by improving the perception of information in visually impaired people. The device could incorporate a nighttime LED that, in addition to facilitating detection in low-light environments, would serve as a signal to alert others of the presence of a visually impaired user, increasing their safety and visibility in public spaces. A problem identified with the device is the way to recharge the battery, which currently needs to be replaced. As a future improvement, it is proposed to implement wireless power transfer technologies, which would allow the device to be charged efficiently when not in use, optimizing its autonomy and facilitating its continuous use.

Finally, it is recommended to incorporate a LIDAR sensor instead of the ultrasonic sensor to increase accuracy in obstacle detection, enhancing the effectiveness and reliability of the device. Additionally, it is suggested to include a GPS module to provide location-based assistance, further improving user autonomy and navigation. It is also recommended to consider flexibility in material selection for the IoT device, evaluating aspects such as functionality, overheating, and the potential for component upgrades in line with technological advancements.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to the development of the study.

AUTHORSHIP CONTRIBUTION

Conceptualization; Data curation; Formal analysis; Formal analysis; Research; Resources; Visualization: Herald Gonzales-Saavedra, Kenjy Garcia-Hurtado, Carlos Gallegos-Pinedo, Rodrigo Tenazoa-Bardales, Diego Hilario-Putpaña and Anthony Ordinola-Sinarahua. Methodology: Kenjy Garcia-Hurtado and Dick Diaz-Delgado. Project administration: Dick Diaz-Delgado. Software: Herald Gonzales-Saavedra. Supervision; Validation: Dick Diaz-Delgado. Writing - original draft: All authors. Writing - review and editing: Dick Diaz-Delgado.

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APPENDIX

Annex 1. Hardware specification

Component	Specification	Quantity
Arduino Nano R3	Arduino nano R3 ATmega328 Microcontroller ATmega328P-AU microcontroller Operating voltage 5V Input voltage (recommended) 7V-12V Input voltage (limits) 6V-20V Digital I/O pins 14 Analog input pins 8 DC current per I/O pin 40 mA DC Current for 3.3V Pin 50 mA 32KB Flash memory of which 2KB are used by the boot loader SRAM 2 KB EEPROM 1 KB Clock speed 16 MHz Dimensions: 45 mm * 18 mm * 20 mm	1

Ultrasonic Sensor HC-SR04	Operating Voltage: 5V DC Standby current: < 2mA Working current: 15mA Measuring Range: 2cm to 450cm, Accuracy: +- 3mm Opening angle: 15°. Ultrasonic frequency: 40 KHz, Minimum duration of TRIG trigger pulse (TTL level): 10 µS, Duration of ECO output pulse (TTL level): 100-25000 µS Dimensions: 45*20*15 mm	1
Buzzer	Voltaje de operación: 5V Corriente máxima: 30 mA Dimensiones:12 mm x 9.5 mm Peso: 2 g Frecuencia de resonancia: 23K Hz Salida de sonido mínimo a 10 cm: 85 dB	1
Abutment carrier UM-18650X2	Dimensions 58 mm x 30 mm x 14 mm AA battery type Plastic material It has holes to screw it to a chassis or a plate. Cable length: 10 cm.	1
Lithium battery 18650	Voltage: 3.7v Capacity: 3000mAh Size: 65mm x 18mm Includes IGV.	2
SW-102 Kapton HARDEN ON/OFF	Material: Plastic Voltage: 125V Measurement/Volume:1 Unit of measure: Ampere Amperage:6A	1
TP4056 load plate module	Power supply voltage: 4.5V to 5.5V DC Charger type: DC/DC DC charging current set to 1A Charging voltage in CV: 4.2V USB-C type input Red LED indicator when charging Green LED indicator when charging complete Charging chip: TP4056 Protection chip: DW01G Charge/discharge mosfet: ML8205A Dimensions: 28*17 mm Weight: 2 grams	1