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Obstacle Detection System and Haptic Alert for Mobility Assistance for People with Visual Impairments

González Sánchez América M.[1], Mejia Contreras Ma. Alba[1], González Sánchez Ma. Teresa[2]

[1]*Ingeniería en Comunicaciones y Electrónica, Escuela Superior de Ingeniería Mecánica y Eléctrica, Unidad Zacatenco, Instituto Politécnico Nacional, CDMX, México.*

[2] *Academia de Ciencias, Centro de Bachillero Tecnológico Industrial y de Servicios No. 103*

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Abstract:

Background: *Visual impairment can significantly affect safety and independence when moving around, especially in unfamiliar environments. This paper presents an assistive technology system that integrates a quadruped robot, computer vision, wireless communication, and haptic feedback to provide obstacle alerts without relying on an auditory interface.*

Materials and Methods: *The system consists of a dog-shaped robotic device and a haptic wristband. A Raspberry Pi 5 captures images via a camera and processes them using OpenCV and YOLOv8n. The detected object is associated with a vibration code that is transmitted via Bluetooth Low Energy (BLE) to an ESP32-C3. The microcontroller drives a vibration motor via PWM according to predefined timing patterns. Additionally, a VL53L0X distance sensor is incorporated to support proximity detection and prevent collisions.*

Results: *Functional tests were conducted with the integrated system in three scenarios. The first evaluated the detection of a person at a distance of less than 20 cm; the second evaluated a person at a greater distance; and the third evaluated a chair at an even greater distance. The documented tests verified BLE communication, the detection of the objects under evaluation, and the generation of the corresponding haptic alerts. The scenarios lasted 1, 3, and 5 minutes, respectively.*

Conclusion: *The results demonstrate the functional feasibility of combining object recognition on an embedded platform with a wearable haptic interface. The main contribution lies in integrating object differentiation and wireless communication via vibration patterns. Future work will focus on quantifying detection latency and accuracy, improving the bracelet's ergonomics and energy consumption, and expanding the set of recognizable obstacles.*

Key Word: *visual impairment; obstacle detection; YOLOv8n; computer vision; Raspberry Pi 5; ESP32-C3; Bluetooth Low Energy; haptic feedback; assistive robotics.*

I. Introduction

The World Health Organization notes that approximately 2.2 billion people have some degree of near or far-sightedness. In Mexico, data from the 2020 Population and Housing Census indicate that approximately 2.691 million people have some degree of visual impairment or disability. Visual impairment can affect the perception of objects, shapes, distances, and environmental information, leading to difficulties with orientation and independent mobility. Traditional assistive devices, such as the white cane and guide dogs, remain essential tools. However, they have certain limitations related to the scope of available information, the training and ongoing care of guide dogs, and the environmental conditions in which they are used. In recent years, assistive systems have been developed that incorporate sensors, computer vision, artificial intelligence, wearable devices, and alternative feedback channels.

In this context, this paper proposes an architecture consisting of two devices. The first is a dog-shaped robot that perceives its environment using a camera and processes the images on a Raspberry Pi 5. The second is a haptic wristband based on an ESP32-C3. When the robot identifies an obstacle, it wirelessly transmits a code associated with the detected object, and the wristband converts it into a vibration pattern.

The objective of the project is to design and develop an obstacle detection and alert system to support the mobility of people with visual impairments using two interconnected devices: a robot equipped with a camera and a Raspberry Pi 5, and a haptic wristband responsible for communicating alerts through distinct vibration patterns. The system is intended for a fixed and partially controlled environment, with a detection range of approximately 2 m. The system's main contribution lies in combining the identification of different types of objects through computer vision with an independent, portable haptic interface. In this way, the system

does not merely indicate the presence of an obstacle but can associate different objects with different vibration patterns.

II. RELATED WORKS

Assistive technologies for people with visual impairments include traditional aids, sensor-based electronic devices, software systems, and robotic platforms. Related work includes a modular device integrated into a cane that uses sensors and alerts to detect pits, uneven surfaces, and obstacles ahead. A robotic system has also been developed to improve indoor mobility through line following, RFID, ultrasonic sensors, and voice communication.

Another related project uses a wearable harness with multiple ultrasonic sensors and vibrating motors to detect obstacles ahead. The sensor layout allows for coverage at different heights, although limitations related to power supply, humidity, terrain variations, and certain objects have been reported. The proposed solution differs by separating environmental perception from the user interface. The robot performs object detection and classification, while the wristband provides haptic feedback. Additionally, BLE communication eliminates the need for wiring between the two modules.

TABLE 1 COMPARISON OF RELATED STUDIES.

Feature	Cane Device [7]	Guide Robot [8]	Haptic harness [9]	Proposal
Purpose	Detect obstacles/voids	Guiding Mobility	Detect obstacles ahead	Detect and alert
Interface	Vibration/Audio	Voz	Vibration	Haptic bracelet
Wireless Communication	No	Yes	No	Yes, BLE
Object Differentiation	Limited	Yes	Limited	Yes
Robotic motion	No	Yes	No	Yes

III. Material And Methods

3.1. System Architecture

The architecture is organized into three main modules: perception, communication, and haptic feedback. The information flow is environment → camera → Raspberry Pi 5 → OpenCV/YOLOv8n → detected object → vibration code → BLE → ESP32-C3 → PWM vibration motor → user. The Raspberry Pi acts as the device responsible for transmitting the information, while the ESP32-C3 receives the code and executes the corresponding vibration pattern. The system also incorporates a VL53L0X distance sensor. The sensor provides distance measurements in millimeters and is used to detect nearby obstacles and stop the robot when an object comes within approximately 20 cm.

3.2. Robotic platform

The robotic platform was developed with a four-legged structure like that of a guide dog. The structure incorporates components manufactured using 3D printing and servomotors to move the legs. The final prototype integrates eight servomotors controlled by a PCA9685 module. The Raspberry Pi generates the angles required to execute the locomotion movements.

The structure supports the perception elements necessary for the system, including a camera and sensors. Figure 1 shows the CAD design on the left, the main electronic components in the center, and the final physical prototype with the electronic components on the right.

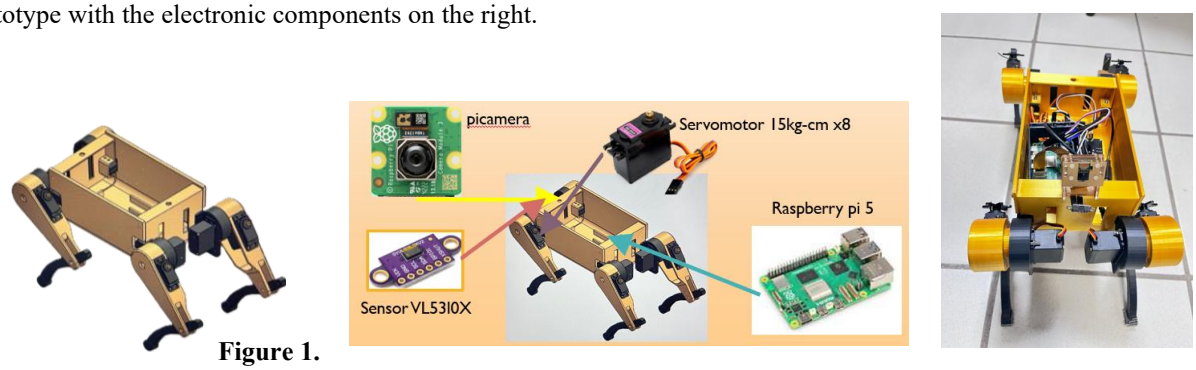


Figure 1.
The left image shows the CAD design, the center image shows the main electronic components, and the right image shows the physical prototype with the electronic components.

3.3. Embedded Processing and Computer Vision

The Raspberry Pi 5 is used as the main processing unit. The camera is controlled using the Picamera2 library, which provides the images frames used by the computer vision system. OpenCV is used for image acquisition

and processing, while YOLOv8n, via the Ultralytics library, is used to detect objects in the captured frames. The implementation considers 20 object classes within the detection area, including people, chairs, bicycles, cars, buses, and backpacks.

3.4. Object-Vibration Coding

Each recognized object is associated with a vibration code. The Raspberry Pi compares the detected code with the previously transmitted code. When the code remains unchanged, repetitive transmission of the same information is avoided. When a new object is detected, the code is converted to bytes and transmitted to the ESP32-C3.

The wristband's firmware uses a three-dimensional matrix of patterns, where the first index represents the object, the second represents the stage of the sequence, and the third represents the motor action and its duration. For example, the pattern documented for a person corresponds to 100 ms of vibration followed by a 1,000 ms pause. Twenty patterns were established, associated with 20 possible detection scenarios.

3.5. BLE (Bluetooth Low Energy) Communication

It is used to establish wireless communication between the Raspberry Pi 5 and the ESP32-C3. The Python implementation uses the Bleak Client library to manage the connection and data transmission. If the connection cannot be established, the system waits two seconds and retries the connection until it is reestablished. Once communication is established, the system proceeds with image acquisition and object detection. When a new vibration code is generated, it is transmitted to the wristband. The use of asynchronous programming allows BLE communication to be coordinated with image processing.

3.6. Haptic bracelet

The left side of Figure 2 shows the electronic components of the wristband, which are: an ESP32-C3 Super Mini, a 400 mAh power supply, a battery charger, and a vibration module. In the center, all the wristband's components are integrated. The right side of Figure 2 shows the wristband's design, which resembles a watch case. The ESP32-C3 controls the motor via a PWM output.

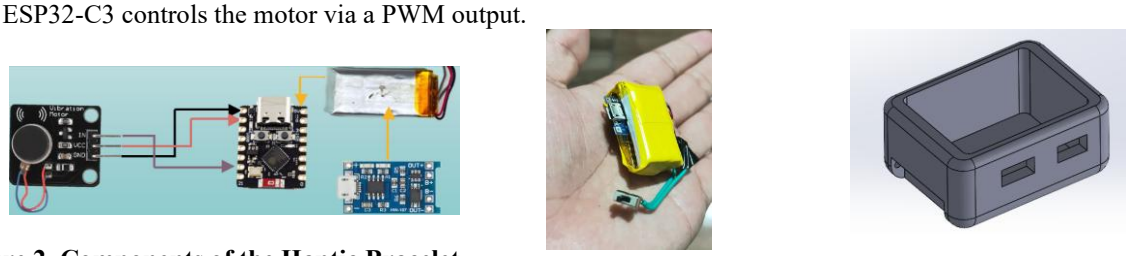


Figure 2. Components of the Haptic Bracelet.

The wristband serves as a portable interface for communicating with the user. The duration and sequence of the vibrations make it possible to distinguish between the different categories of obstacles identified by the robot.



Figure 3. Final prototype of the Haptic Bracelet.

3.7. Experimental Procedure

The evaluation was conducted using the integrated system and by placing objects in the robot's path. The distance indicated by the system was monitored via the Raspberry Pi terminal. Three scenarios were considered: close-range detection of a person, detection of a person at a greater distance, and detection of a chair at an even greater distance.

IV. RESULTS

The final prototype integrated the quadruped robot and the haptic wristband. Functional tests verified system startup, program execution on the Raspberry Pi, BLE communication, object detection, and the generation of vibration alerts.

In Scenario 1, a person was detected at less than 20 cm. This test also verified the proximity behavior associated with the VL53L0X sensor. In Scenario 2, a person was placed at a greater distance, centered in the robot's path, and their detection and the corresponding alert were verified. In Scenario 3, a chair was placed at an even greater distance, and the identification of the object and the generation of the corresponding alert were verified. Table 2 summarizes the documented experimental results. The thesis provides categories for distance and test duration but does not present numerical values for precision, recall, mAP, or latency; therefore, these metrics are not presented as quantitative results in this article.

TABLE 2: SUMMARY OF THE DOCUMENTED EXPERIMENTAL RESULTS.

Scenario	Detection Result	Distance	Duration
1	Person detected and alert triggered	(<20 cm)	1 min
2	Person detected and alert triggered	50cm	3 min
3	Seat detected and alert triggered	100cm	5 min

Overall, the tests demonstrated the functionality of the entire chain of perception, processing, communication, and haptic alerts. The tests reported favorable results from the field trials, and it is considered that the stated objectives were satisfactorily achieved within the defined limits.

V. DISCUSSION

The experimental results support the functional feasibility of the proposed architecture for object detection and haptic alert generation in a partially controlled environment. An important feature is the separation between perception and feedback: the Raspberry Pi 5 handles the processing, while the ESP32-C3 functions as a dedicated interface for haptic communication.

The use of YOLOv8n allows for the identification of object categories rather than merely indicating the presence of an obstacle. This capability makes it possible to associate different objects with different vibration patterns. Furthermore, the code comparison implemented on the Raspberry Pi prevents the same code from being transmitted repeatedly while the object continues to be detected.

BLE communication eliminates the need for a cable between the two devices and enhances portability. The automatic reconnection strategy improves operational continuity when communication is interrupted. However, the thesis does not present a numerical characterization of end-to-end latency; therefore, this variable must be evaluated experimentally before making quantitative statements about response time.

A major limitation of the current evaluation is the absence of numerical metrics for accuracy, false positives, false negatives, frame rate, and latency. Furthermore, the evaluated scenarios are limited, and the scope of the project establishes a defined and partially controlled environment. These conditions must be considered before extrapolating the system's performance to uncontrolled urban environments. Compared to the systems reviewed, the proposal integrates a mobile robotic platform, object differentiation via computer vision, wireless communication, and a wearable haptic interface. Its main contribution lies in the integration of these technologies within assistive architecture.

VI. CONCLUSIONS

A prototype for obstacle detection and haptic alerts was developed and functionally evaluated to support the mobility of people with visual impairments. The system integrates a quadruped robot equipped with a Raspberry Pi 5 and a camera, YOLOv8n and OpenCV for visual perception, a VL53L0X sensor for proximity detection, BLE for wireless communication, and a haptic wristband based on the ESP32-C3.

The tests conducted demonstrated the operation of the entire detection and alert chain in three scenarios, including the detection of a person at short and longer distances and the detection of a chair at a longer distance. In the evaluated cases, the corresponding haptic alerts were generated.

The system's main contribution is the combination of object recognition and differentiated haptic feedback via a standalone portable device. This architecture provides a discrete communication channel and can help support mobility within the defined environment. However, this study constitutes a functional validation of the prototype and does not constitute a clinical validation nor is it intended to replace established mobility aids. Future work will focus on incorporating GPS and voice commands, reducing communication latency, improving detection accuracy using neural networks, improving the ergonomics of the wristband, reducing energy consumption, integrating a voice command application, and expanding the number of detectable obstacles.

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