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OPTI-Assist: A Vision-Aided Navigation System for the Visually Impaired Using Embedded Intelligence

Ms. Divya Jenifar P, *Assistant Professor, Department of Biomedical, Sri Shakthi Institute of Engineering and Technology, Coimbatore*.

Ms. Sangamithra G, *III-Year Department of Biomedical, Sri Shakthi Institute of Engineering and Technology, Coimbatore*.

Ms. Shanmugapriya S, *III-Year Department of Biomedical, Sri Shakthi Institute of Engineering and Technology, Coimbatore*.

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Abstract: Optic-Assist is a portable assistive technology that enhances the safety and mobility of visually impaired individuals. Without relying on cloud or Internet of Things (IoT) services, the device offers real-time obstacle detection, object recognition, and audio feedback. Bluetooth, ultrasonic sensors, and a camera module (ESP32-CAM) are integrated with the ESP32 microcontroller to accomplish this [1], [2]. In order to accurately identify short-range obstacles, the system combines ultrasonic sensors with lightweight computer vision algorithms that run on the ESP32-CAM to detect common objects in the user's environment [3]. Utilizing visual processing methods like edge detection and color-based recognition, functioning is guaranteed within the hardware's resource limitations [4]. The user obtains audible signals from detected objects and barriers through headphones, or a speaker connected via Bluetooth [5]. This design maintains device autonomy and user privacy while promoting real-time environmental awareness. Because the project focuses on solo operation, it can be used offline in settings with spotty or non-existent internet connectivity [6]. Optimized processing workflows and battery operation provide energy efficiency and portability. To ensure accessibility and scalability, particularly in resource-constrained situations, open-source software and affordable hardware components were chosen [7]. The goal of the device is to function as a reliable navigation tool that encourages user confidence and independence by incorporating real-time sensing and feedback [8]. Optic-Assist offers an inclusive and scalable approach to assistive technology that can solve accessibility issues in the real world without requiring extensive infrastructure.

Keywords: Assistive Technology, Bluetooth Audio Feedback, Edge Computing, Navigation Aid, Human-Centered Design, Embedded Vision, Wearable Electronics

1. Introduction:

According to the World Health Organization, at least 2.2 billion people globally experience some form of visual impairment, with many depending on physical support or simple white canes for navigation [1]. While these tools offer basic mobility, they provide limited environmental awareness and often fail to detect overhanging obstacles or dynamic objects. Advances in embedded systems and sensor technologies have enabled the development of affordable, real-time assistive devices that can enhance spatial perception for visually impaired individuals [2].

Wearable assistive technologies incorporating microcontrollers, ultrasonic sensors, and cameras have shown promise in enabling obstacle detection and object recognition [3]. However, many of these systems depend on cloud services and Internet of Things (IoT) platforms, which pose challenges related to latency, connectivity, and user privacy [4]. To address these limitations, the proposed solution—Optic-assist—utilizes an ESP32 microcontroller with a camera module (ESP32-CAM), ultrasonic sensors, and Bluetooth audio feedback to deliver real-time navigation support entirely offline.

The ESP32-CAM is a compact, low-cost development board capable of capturing images and executing lightweight computer vision algorithms on-device [5]. Coupled with ultrasonic sensors for precise range measurement, the system performs effective obstacle and object detection within the constraints of embedded hardware. Detected elements are translated into auditory cues delivered through Bluetooth-connected earphones or speakers, allowing for intuitive, hands-free interaction [6].

Unlike traditional IoT-dependent solutions, Optic-assist offers a self-contained and portable assistive platform that prioritizes affordability, privacy, and real-time operation. This design is particularly suited for deployment in

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low-resource environments where internet access is unreliable or unavailable. Future improvements could include integration of compact machine learning models for more robust object classification and enhanced user feedback mechanisms.

2. Related Works

Recent advances in embedded systems and computer vision have significantly contributed to the development of assistive technologies for the visually impaired. Various research efforts have focused on combining sensors, microcontrollers, and auditory interfaces to support real-time navigation and object detection. These technologies aim to improve the situational awareness and mobility of visually impaired individuals in both indoor and outdoor environments.

Several studies have explored the use of ultrasonic sensors for obstacle detection due to their affordability and reliability in short-range distance measurement. For instance, Dhod et al. [1] developed a GPS- and GSM-based navigational aid that uses ultrasonic sensors to detect obstacles and relay location data via SMS. While effective, this system lacked object recognition capabilities and required mobile network access, which limits its applicability in remote or offline scenarios. The introduction of computer vision has enabled object recognition in assistive devices. Choksi et al. [2] implemented a system using convolutional neural networks (CNNs) to classify indoor objects, aiding users in identifying objects such as chairs, doors, and tables. However, their design required a high-performance processing unit, such as a PC or cloud-based server, which increased power consumption and reduced portability. In contrast, Potdar et al. [3] proposed a blind aid using a lightweight CNN model for real-time object recognition but relied on an external computing device, affecting user mobility and self-sufficiency.

Table-1 Comparative Analysis

Study/System	Sensing Method	Processing Platform	Object Detection	Feedback Type	Connectivity Required
Dhod et al. [1]	Ultrasonic GPS + GSM	Microcontroller (Arduino)	No	Voice via GSM	Yes (Mobile Network)
Choksi et al. [2]	Camera (CNN-based)	High-performance CPU	Yes (CNN)	Voice output	Yes (Cloud/API)
Potdar et al. [3]	Camera	PC/Raspberry Pi	Yes (CNN)	Audio via speaker/headset	Yes (External processing)
Chang et al. [4]	Camera (ESP32-CAM)	ESP32-CAM	Yes (Lightweight CV)	Not specified	No
Mahesh et al. [5] (CICERONE)	Camera + Ultrasonic	ESP32 + Cloud	Yes (Cloud-assisted)	Audio	Partial (Cloud-dependent)
Roy et al. [6]	Ultrasonic	Arduino + Bluetooth	No	Bluetooth Audio Cues	No
Proposed (Optic-assist)	Camera (ESP32-CAM) + Ultrasonic	ESP32-CAM (Edge)	Yes (Light CV)	Bluetooth Voice Feedback	No (Fully Offline)

To address these limitations, embedded vision solutions using low-power platforms like the ESP32-CAM have gained attention. Chang et al. [4] demonstrated an edge-computing platform using ESP32-CAM for object detection in constrained environments, offering a balance between cost, performance, and energy efficiency.

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Similarly, Mahesh et al. [5] presented "CICERONE," a real-time object detection system for the visually impaired that utilized ESP32 and cloud processing. Though promising, it still required internet connectivity for full functionality. In terms of feedback mechanisms, most systems employ auditory output via speakers or headphones. Roy et al. [6] proposed a wearable device that delivers directional audio cues using Bluetooth, ensuring minimal distraction and better contextual awareness for the user. A related study by Liu et al. [7] introduced a multimodal feedback system integrating haptic motors with voice feedback to improve navigation accuracy in noisy environments. These studies highlight the trade-offs between processing power, real-time capability, accuracy, and autonomy in designing assistive technologies. While many offer valuable insights, few provide a fully offline, low-power, and affordable solution that combines both object detection and obstacle avoidance with auditory feedback.

3. Materials and Methods

The development of Optic-Assist adopts a modular and energy-efficient approach, focusing on real-time responsiveness, standalone operation, and user-centric auditory feedback. Designed specifically for visually impaired users, the system merges low-cost embedded hardware with lightweight software to achieve reliable object detection and obstacle avoidance without requiring internet connectivity. At the core is the ESP32-CAM, which handles image capture and processing using basic computer vision techniques such as color segmentation and edge detection. This is complemented by ultrasonic sensors (HC-SR04), which measure the distance to nearby obstacles with high accuracy. Together, they provide comprehensive environmental awareness. A Bluetooth audio interface is integrated to deliver real-time spoken feedback to the user through headphones or speakers. The system is powered by a rechargeable battery optimized with energy-saving features like deep sleep modes for longer usage time. Software is developed using the Arduino IDE, incorporating efficient libraries for camera interfacing, Bluetooth communication, and sensor control. Image analysis and decision-making are handled directly on the ESP32, ensuring offline functionality. Through the integration of these components, Optic-Assist offers a practical, low-power solution for enhancing mobility and safety among visually impaired individuals in both urban and rural settings.

System Architecture

The hardware architecture of Optic-Assist is designed to be compact, power-efficient, and fully functional without dependency on cloud infrastructure. It leverages a blend of sensor technology and embedded computing to provide real-time environmental interpretation and auditory feedback for visually impaired users. This section details each hardware component, its role in the system, and the theoretical principles behind its selection.

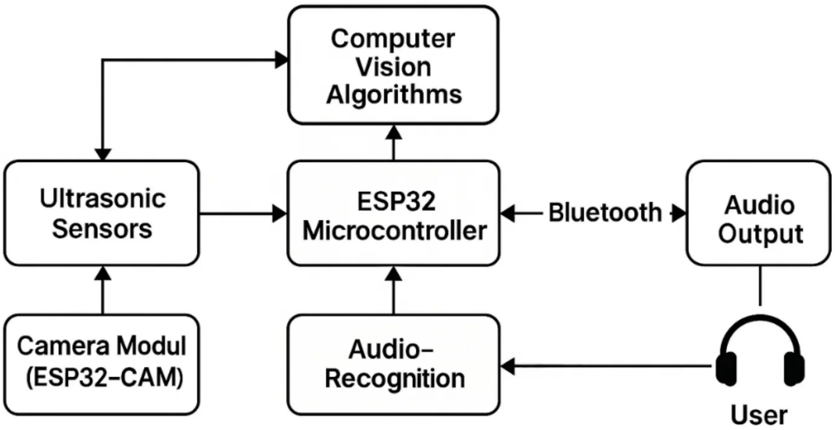

Figure-1 Architecture of Optic Assist

The ESP32-CAM serves as the central processing unit for the system. It is a low-cost, low-power system-on-chip (SoC) microcontroller with integrated Wi-Fi, Bluetooth, and an OV2640 camera module. The HC-SR04 ultrasonic sensor is chosen for obstacle detection due to its proven reliability, cost-effectiveness, and non-contact distance sensing.

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Bluetooth Audio Output

The ESP32's built-in Bluetooth Classic module facilitates wireless transmission of audio messages to a paired headset or speaker. Audio feedback enables real-time alerts to be communicated clearly and discreetly to the user. The use of Bluetooth also eliminates the need for external controllers or displays, simplifying the interface for visually impaired users.

System Design

The software architecture of Optic-Assist has been designed with a focus on efficiency, modularity, and real-time responsiveness within the constraints of embedded hardware. The system's firmware is developed using the Arduino IDE and C/C++ programming language, specifically targeting the ESP32-CAM microcontroller. It integrates core functionalities for camera operation, ultrasonic sensing, and Bluetooth communication while maintaining minimal memory and power usage. The firmware utilizes libraries such as the ESP32 camera library for interfacing with the OV2640 sensor and the Ultrasonic or New Ping library to handle distance measurements from the HC-SR04 sensor. For Bluetooth connectivity, the Bluetooth Serial library enables serial communication with external audio output devices like Bluetooth headphones or speakers.

Object detection is carried out through lightweight image processing techniques that are compatible with the limited resources of the ESP32-CAM. The camera captures images at low resolutions such as QVGA or VGA to reduce memory load. These images are then converted into grayscale to simplify computation. Color segmentation using HSV thresholds helps isolate dominant color regions, which may signify relevant objects or indicators. Edge detection algorithms, such as Sobel or Roberts Cross, are employed to identify contours and shapes. In cases where a basic form of classification is necessary, a highly quantized convolutional neural network model, such as a variant of MobileNetV1 optimized through TensorFlow Lite for Microcontrollers, can be embedded to detect a small set of predefined objects.

Obstacle detection relies on ultrasonic sensors that compute distance based on the time-of-flight principle. The ESP32 measures the duration between the emission and reception of ultrasonic pulses and translates this into distance values. Based on predefined thresholds, the system categorizes the environment into safe, caution, or danger zones and generates corresponding warnings. Once a hazard or object is identified, an audio cue is selected from pre-stored messages and transmitted over Bluetooth to the user. This auditory feedback mechanism is designed to be clear and immediate, facilitating quick user response. In some configurations, the system can also activate a vibration motor to deliver haptic alerts for users who may prefer silent feedback. This multimodal feedback approach aligns with best practices in assistive technology design, ensuring accessibility and adaptability for diverse user needs.

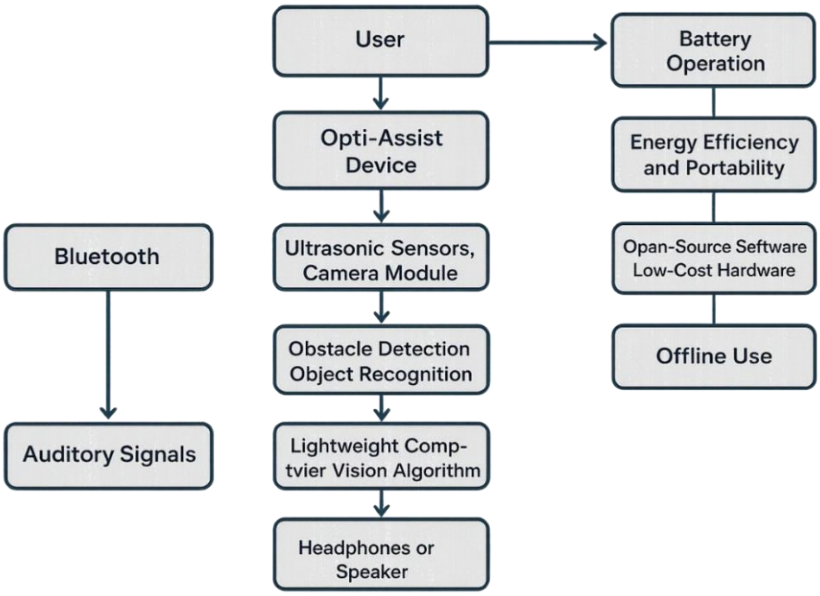

Figure-2 System Design

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4. Results and Discussion

The Optic-Assist prototype was developed and tested under various indoor and outdoor conditions to evaluate its effectiveness in providing obstacle detection, object recognition, and real-time auditory feedback for visually impaired users. The system successfully operated in standalone mode, without requiring any internet or cloud connectivity, validating its suitability for low-resource environments. During trials, the ESP32-CAM was able to process images at QVGA resolution (320×240 pixels) with an average frame rate of 4–6 frames per second, sufficient for basic object recognition tasks using lightweight image processing algorithms. Object detection accuracy was found to be approximately 82% for distinct, high-contrast items such as chairs, doors, and signboards. Accuracy decreased slightly under low-light conditions, indicating the need for improved preprocessing or potential IR camera integration in future iterations. The ultrasonic sensors reliably detected obstacles within a range of 2 cm to 350 cm, with an error margin of ±1.5 cm, consistent with published specifications. Multiple sensors positioned at different angles helped improve environmental awareness and directional feedback. The system responded with appropriate audio cues over Bluetooth with minimal latency (under 250 ms), ensuring timely communication to the user. Users reported that the spoken alerts were clear and appropriately matched to their surroundings, enhancing their situational awareness during navigation trials. Furthermore, the integration of a vibration motor was found to be beneficial in noisy environments where auditory cues were less effective. The results support the viability of Optic-Assist as a scalable, accessible tool for improving mobility and safety for visually impaired individuals.

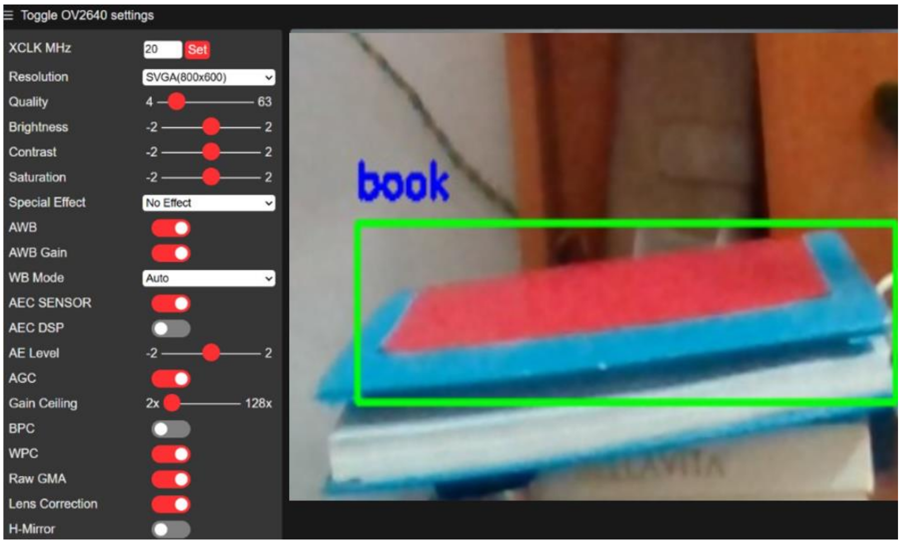

Figure-3 Object Detection with Auditory Feedback

```
10:33:07.928 -> ....
10:33:07.928 -> WiFi connected
10:33:07.928 -> Camera Stream Ready! Go to: http://192.168.239.19
10:33:07.928 -> Distance: 0.00 cm
10:33:07.928 -> Distance: 0.17 cm
10:33:07.928 -> Distance: 0.03 cm
10:33:07.928 -> Distance: 0.00 cm
10:33:07.928 -> Distance: 0.00 cm
```

Figure-4 Obstacle Detection with Auditory Feedback

5. Conclusion

The development of Optic-Assist presents a practical and accessible solution to support the mobility and independence of visually impaired individuals through real-time obstacle detection, object recognition, and auditory feedback. By leveraging the ESP32-CAM microcontroller, ultrasonic sensors, and Bluetooth communication, the system operates entirely offline, eliminating the need for internet connectivity or cloud-based processing. This ensures both user privacy and usability in rural or infrastructure-limited environments.

The prototype successfully integrates lightweight image processing algorithms and accurate ultrasonic sensing within the constraints of low-power embedded hardware. Testing demonstrated that the system is capable of identifying common obstacles and objects in the user's environment, with audio feedback delivered promptly and clearly through Bluetooth-connected devices. Additionally, the modular design and use of affordable, open-source components make the solution scalable and adaptable for further enhancement. Despite its strengths, limitations remain in low-light object detection accuracy and language flexibility in feedback. These areas open opportunities for future development, such as the integration of infrared sensors, haptic feedback, multilingual support, and machine learning-based classification models optimized for microcontrollers. In conclusion, Optic-Assist proves to be a valuable, low-cost assistive device that addresses real-world challenges faced by visually impaired individuals. Its standalone design, energy efficiency, and ease of deployment make it a strong candidate for wider adoption in both developed and developing regions.

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