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Intelligent Ultrasonic Obstacle Detection System for Visually Impaired using AI and IoT

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Abstract: *This review paper offers a detailed study of assistive technologies for visually impaired individuals. It focuses on ultrasonic-based obstacle detection systems, AI-powered object identification, and IoT-enabled smart blind sticks. The paper critically looks at existing research in this area, identifying key issues such as limited sensing capabilities, a lack of real-time intelligence, and poor integration between hardware and software components.*

To tackle these challenges, the paper suggests a system that combines an ESP32 microcontroller with several environmental sensors, including ultrasonic, water, and rain sensors. It also uses an ESP32-CAM module for AI-based image recognition. Furthermore, the system includes a cloud-hosted Python backend server for effective data processing and communication. An Android mobile application has been developed as well, offering features like voice assistance for navigation and an SOS emergency alert system to improve user safety.

By merging hardware-level obstacle detection with software-based artificial intelligence and IoT communication, the proposed solution offers a more complete and reliable assistive system. The paper also discusses system architecture, hardware components, software design, and communication frameworks, while outlining its advantages, limitations, and potential future research directions.

Keywords: *visually impaired*

I. INTRODUCTION

Among humans mobility impairments that affect independence, visual impairment is one of the most significant mobility handicap. The World Health Organization (WHO) estimates that approximately 2,2 billion people globally experience at least some form of vision impairment. An estimated 39 million are completely blind. In developing countries like India, these barriers to mobility become even worse due to lack of paved sidewalks and roads, unpredictable traffic, unattractive or hazardous pedestrian environments, etc.

The most common mobility aid for the blind has been a white cane for many years. While the white cane is effective in detecting ground obstacles, it does not provide users with details about the type or location of the obstacles (i.e., above the waist), the environment (i.e., wet surfaces, rain), or any type or amount of connectivity or intelligent feedback to the user.

Advancements in technology, including the development of embedded systems, the Internet of Things (IoT), and artificial intelligence (AI), have opened the door for the creation of "smart" assistive devices. Modern microcontroller technology such as the ESP32 provides high-performance processing capabilities, integrated Wi-Fi, and support for a wide variety of sensors, all in a compact form factor at a low cost. Camera modules such as the ESP32-CAM facilitate low-cost image capture on these devices, while cloud-based platforms provide users with advanced AI processing capabilities.

In this paper, we will review state-of-the-art developments and create a prototype for an integrated smart blind stick.

Background and Motivation

Background and motivation..........Visually impaired people have seen the development of assistive technology in 4 major generations. The first generation was made up of mechanical devices, such as the white cane and guide dogs. The white cane became widely available in the middle of the last century and was used to discover objects on the ground via tactile sense. Whereas a dog could guide a person with intelligence, the expense of both training a guide dog and providing for it is high.

The second generation includes the introduction of the first Electronic Travel Aids (ETA) in the 1960s. The design of these devices utilized ultrasonic or infrared sensors for the purpose of obstacle detection and the output provided to the user is through audio or vibrations. Some examples of these devices include the Mowat sensor and Sonic guide; however, these devices have inherent limitations such as being too cumbersome to carry, being too expensive, and the limitations associated with the sensors not being able to perform effectively.

The third generation started with the introduction of GPS-based navigation systems for the visually impaired. Applications developed for GPS, such as Blind Square and Lazarillo assist the user by interpreting to them voice directions via GPS and digital maps; however, their effectiveness indoors is severely limited, and there are no methods for real-time detection of objects that may be immediate obstacles to the user.

The fourth and present generation utilizes Artificial Intelligence (AI) and IoT technology; they all incorporate the use of multiple sensors to provide an understanding of the environment, cameras to detect objects, cloud computing for processing power, smartphones for interacting with the assistive technology user, and the proposed system developed in this project would use the aforementioned technologies to deliver a comprehensive solution for visually impaired individuals.

II. LITERATURE SURVEY

1 Title: Ultrasonic Blind Walking Stick Using Arduino
Authors: S.Bharambe; R. Thakare; H. Patil; K. Phalke
Published in: International Journal of Engineering Research and Technology (IJERT)
Abstract: Discusses a low cost and simple device (Blind Walking Stick) which can be used to assist in walking and detecting obstacles. This is accomplished through the use of an Arduino Uno and an ultrasonic sensor as its primary tool. It has many limitations including one way sensory input, no artificial intelligence, connectivity, and no advanced features outside of obstacle identification.

2 Paper Title:** IoT-Based Smart Blind Stick with ESP8266
Authors:** P. More, S. Wandhare, R. Gaikwad (2020)
Journal Name:** International Research Journal of Engineering and Technology (IRJET)
Summary:** A smart blind stick using the internet of things (IoT) for monitoring through the cloud, via the ESP8266 module. The smart blind stick works but only with one sensor and lacks artificial intelligence (AI), a mobile app for control and an emergency service.

3 **Article Title:** Raspberry Pi-based Assistive System with Artificial Intelligence.
Author(s): Sharma, A., Kumar, P., Mathur, M. (2021)
Publication Venue: IEEE International Conference on Intelligent Systems and Signal Processing (ISSP).
Research Abstract: An assistive system developed using Raspberry Pi and a camera to allow visually impaired people to identify objects using real-time image processing and getting voice feedback about those identified objects; however, this project is limited due to high power consumption of the hardware used (Raspberry Pi), overall size of the system, total costs associated with the project, and potential for future enhancement (i.e., sensor-based detection and IoT integration).

4 Title: Android Navigation System for Blind Using Sensors
Authors: Patil, D.; Nemade, V.; and Jadhav, S. (2022).
Publication: International Journal of Innovative Research in Computer and Communication Engineering.

Abstract: A smartphone based navigation system with integrated sensor solutions along with GPS voice guided assistance, however cannot detect immediate obstacles in real time, are dependent on GPS positioning systems, and cannot detect environmental hazards such as rain or water.

5 **Title of Article**: Cane Using Sensors to Detect Obstacles And Water
Authors: R. Kumar, V. Sridhar, K. Mohan (2021)
Journal: Journal of Embedded Systems and Applications
Summary: The smart cane in this article utilizes ultrasonic and water sensors to detect obstacles and wet surfaces and emits sound and vibration alerts when either condition is detected; however, there is no Internet connectivity or "smart" (AI) features associated with the device. Additionally, it is built on a PIC microcontroller that has minimal power and therefore limited feedback functions.

III. PROBLEM STATEMENT

A critical analysis of the literature surrounding assistive technologies for people who are blind has noted that there are several limitations in the current state of the art technology which affects the ability for these devices to be effective. Specifically, most systems currently use either single sensor/single direction to detect obstacles, which limits the amount of information available to the user regarding environmental awareness or safety from hazards. In addition, while some have incorporated an Internet of Things capability, they lack any advanced processing capabilities, real-time intelligence, or mobile application support. A number of artificial intelligence-based solutions provide improved object recognition; however, they're frequently bulky, power-hungry and expensive (due to their utilization of a Raspberry Pi/Arduino type platform). Conversely, smart phone solutions rely heavily on GPS which, when used inside buildings, results in poor performance and can not recognize any immediate obstacles or hazards within the environment (e.g., pooling/puddles of water or rain). Further, several of the devices do not offer emergency communications, nor do they provide a fully integrated and real-time assistive experience. As such, there is a need for a low cost, lightweight, integrated solution that provides multi-sensor obstacle detection, artificial intelligence-based object recognition, Internet of Things communication and mobile application support to assist with safely, easily and independently navigating through life.

IV. OBJECTIVES

1. To design and develop a smart blind stick embedded with ultrasonic, water, and rain sensors using the ESP32 microcontroller platform.
2. To integrate an ESP32-CAM module for real-time image capture and AI-based object detection.
3. To build a cloud backend that processes sensor data and image analysis results.
4. To develop an Android mobile application that provides real-time voice alerts based on environmental data.
5. To implement an SOS emergency system that sends the user's GPS location to pre-configured emergency contacts via SMS.
6. To ensure data security through AES-256-GCM encryption for sensitive user information.

V. PROPOSED SYSTEM

The BlindAssistAI solution is an advanced IoT based assistance systems which are designed to improve the mobility and safety for persons who are visually impaired. This solution incorporates sensing, intelligence and communication technologies into a single solution and is built on an ESP32 Development Board (DB) as the main controller and sensor hub for these systems. This controller monitors the various environments using multiple sensors, including an ultrasonic sensor (to sense obstacles); a water sensor (to detect wet surfaces); and a rain sensor (to detect environment weather condition). In general, each of these three sensors can detect the types of objects in an environment; the types of weather in an environment; and the location of where a person has fallen. When all three sensors are in use with the combined able to identify a person through their specific style of walking.The ESP32-CAM will be added to the system to expand its capabilities from basic sensing to detection and identification of an object upon detecting an obstacle. When the camera module detects an obstacle, it will take a picture of it and send the data to a cloud AI service for object recognition. This will create much more meaningful feedback to the end-user, since they will now be able to see the exact location of an obstacle and the nature of the obstacle.

A backend in Python is hosted on Render.com and will serve as the interface between the hardware and software. The backend processes the sensor data (and manages the requests for image analysis), and it stores the results for retrieval later. The mobile app, developed in Kotlin and using the MVVM architecture, will communicate with the backend in real-time to send voice-based alerts (Text-to-Speech) and to send GPS-based emergency alerts to caregivers using the SOS emergency alert feature in the app.

VI. SCOPE OF THE PROJECT

The proposed BlindAssistAI project aims to create a comprehensive intelligent assistive solution for people with visual impairments by integrating technology in conjunction with both hardware and software. It will develop a 'smart cane' using an ESP32 Development Board and associated hardware devices (like an 'ESP32-CAM' camera, ultrasonic sensor to detect obstacles, water and rain sensors to provide basic environmental awareness). Other supporting output devices are also included in the project (buzzer, LED; SOS button). The firmware for the device will be developed using the Arduino framework to capture sensor data (real-time), capture images, and provide an interface (via Wi-Fi) for communication with the cloud-based back-end (on support from Amazon) to manage the sensor data, perform AI-based object recognition search on captured images, and facilitate communication between the honeycomb-based device and the user's native Android Mobile Application using REST API calls. The 'native' Android Mobile Application, developed in Kotlin using the MVVM design pattern, provides users with real-time voice alerts (via text-to-speech), GPS location services, and SMS communication services in an emergency situation. Security features include AES-256-GCM encryption and data storage methodologies. Ultimately, this project aims to provide a 'safe, reliable, and user-friendly' assistive device for mobility, freedom, and safety for visually impaired individuals.

VII. BLOCK DIAGRAM & BLOCK DIAGRAM DESCRIPTION

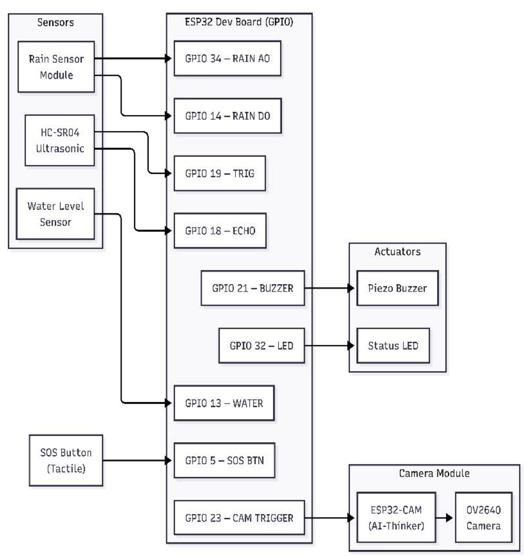

Fig.(1)

The following diagram is the complete configuration of the BlindAssistAI Smart Cane system, including how the hardware, cloud services and Android app connect together.

There is a device (the smartphone) that enables visually impaired users to communicate with the system (the blind

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stick). At the Android app level, there are several background services (accessibility, notifications, etc.), as well as different features (Text to Voice, GPS location determination, and Emergency SOS SMS system). The user's data (contacts and event logs) will be stored securely in an encrypted database and through secure key management.

The hardware for the blind stick is based on an ESP32 Dev Board (which is the main controller) with multiple sensors connected to it. Ultrasonic sensors are used to detect obstacles, and water and rain sensors are used to keep track of the environment. There is a button for SOS use in emergency situations. A buzzer and vibration motor are used to provide immediate notifications to the user. The ESP32-CAM captures images when it is triggered, allowing for the collection of visual data.

The communications layer receives sensor data and images sent from the hardware to the cloud via Internet (WiFi) through HTTP requests.

The cloud processing layer is Python based and will receive any incoming data, store the events, and send images to an AI object detection engine for processing. Once processed the results will be sent back to the mobile app. Overall, the diagram depicts an Integrated Network of IoT Devices; Sensing - AI Processing - Real Time User Interaction.

VIII. FLOWCHART OF THE PROJECT

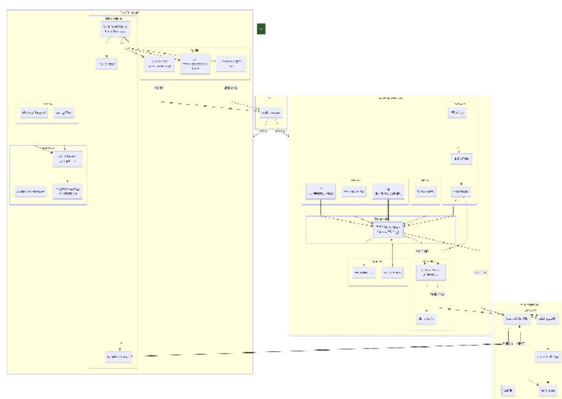

Fig.(2)

IX. COMPONENT REQUIRED

1 ESP32 Dev Board

The ESP32 is a low-cost, low-power system-on-chip (SoC) microcontroller developed by Espressif Systems. It features a dual-core Xtensa LX6 processor running at up to 240 MHz, 520 KB of internal SRAM, built-in WiFi (802.11 b/g/n) and Bluetooth 4.2, and up to 34 GPIO pins. The ESP32 is chosen as the main controller due to its WiFi capability (essential for IoT communication), sufficient GPIO pins (for connecting multiple sensors and actuators), low power consumption, and affordable price (approximately ₹400-500 in India).

In our system, the ESP32 Dev Board reads sensor data, controls the buzzer and LED, triggers the ESP32-CAM, and sends HTTP requests to the Python backend.

2 ESP32-CAM Module (AI-Thinker)

The ESP32-CAM is a compact development board that combines an ESP32 chip with an OV2640 camera module. It supports image resolution up to 1600×1200 (UXGA) and includes 4MB of PSRAM for frame buffer storage. In our system, the camera is configured for VGA (640×480) resolution with PSRAM or QVGA (320×240) without PSRAM, using JPEG compression at quality level 12. The module also has a built-in flash LED on GPIO4 that briefly activates during image capture for better image quality in low light.

3 HC-SR04 Ultrasonic Sensor

The HC-SR04 is a widely used ultrasonic distance sensor with a measuring range of 2 cm to 400 cm and accuracy of ±3 mm. It operates at 40 kHz and uses the time-of-flight principle. The ESP32 sends a 10µs trigger pulse, and the sensor returns an echo pulse whose duration is proportional to the distance. The distance formula used in the firmware is: distance = duration × 0.034 / 2 (in cm). A timeout of 30ms is set to handle "no object" scenarios where the echo pulse never returns.

4 Water Sensor

The water sensor used is a conductivity-based module that detects the presence of water on a surface. It produces a digital output — HIGH when water is present and LOW when the surface is dry. The sensor is connected to GPIO13 of the ESP32 Dev Board with an internal pull-up resistor. Detection of water on the ground is essential to alert the user about slippery or flooded surfaces.

5 Rain Drop Sensor

The rain drop sensor provides both digital and analog outputs. The digital output (GPIO14) indicates the presence of rain (LOW when rain is detected, using inverted logic with a pull-up resistor), while the analog output (GPIO34) provides a value proportional to rain intensity. The sensitivity of the digital output can be adjusted via an onboard potentiometer. This sensor helps alert the user about rainfall conditions that could make navigation more difficult.

6 Buzzer

An active piezoelectric buzzer operating at 5V DC is connected to GPIO21 of the ESP32 Dev Board. The buzzer activates continuously when an obstacle is detected within 30 cm. For SOS events, the buzzer produces three short beeps (200ms ON, 200ms OFF pattern) to give audible confirmation that the emergency signal has been sent.

7 SOS Push Button

A momentary push button is connected to GPIO5 with an internal pull-up resistor. When the button is pressed (active LOW), it triggers the SOS emergency flow — sending an "S O S" event to the backend server. The button is placed in an easily accessible position on the blind stick for quick activation during emergencies.

8 LED Indicator

A standard 5mm LED connected to GPIO32 blinks continuously at a 500ms interval to indicate that the system is powered on and active. This serves as a visual indicator for sighted people nearby, letting them know that the user is using an electronic assistive device.

9 Power Supply

The system is powered by a 3.7V lithium-ion rechargeable battery with 2000mAh capacity. A TP4056 charging module provides micro-USB charging capability with overcharge and over-discharge protection. A voltage regulator (AMS1117 or LM7805) provides stable 3.3V and 5V output for the ESP32 boards and sensors respectively

X. WORKING PRINCIPLE

The ESP32 Dev Board uses a recurring data-sensing and response cycle to control the various sensors that collect the information needed for obstacle detection via ultrasonic sensor; wet surface detection via water sensor; and weather conditions via rain sensor, in order for the system to perform its function.

Once an obstacle is detected within a predetermined distance from the sensors, the system will activate a buzzer to inform the user of the immediate danger and send an image to an ESP32-CAM while also transmitting data regarding the event to a cloud server. Similarly, if water or rain is detected, the system will send the appropriate alert and transmit

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relevant data to the cloud server.

There is an SOS button located on the system that allows the user to send an emergency signal to the backend, receiving a buzzer signal from the system immediately. The system will be tracking state of each event, as well as putting each event on a cooldown period, to prevent the user from receiving repeated alerts on the same event. Normal operation of the system will be indicated by a blinking LED light.

Overall, the system is designed to provide real-time sensing and intelligent response to provide a safe working environment for users using the system, as well as an efficient method of communicating information regarding emergencies to save user lives.

Hardware Images

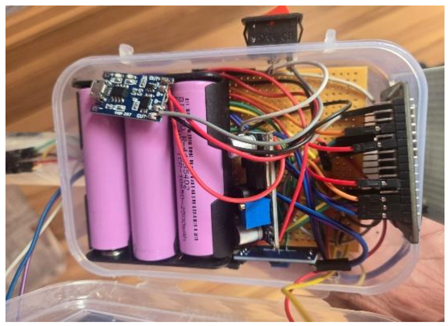

Fig.(3)

Fig.(4)

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RESULT

Fig.(5)

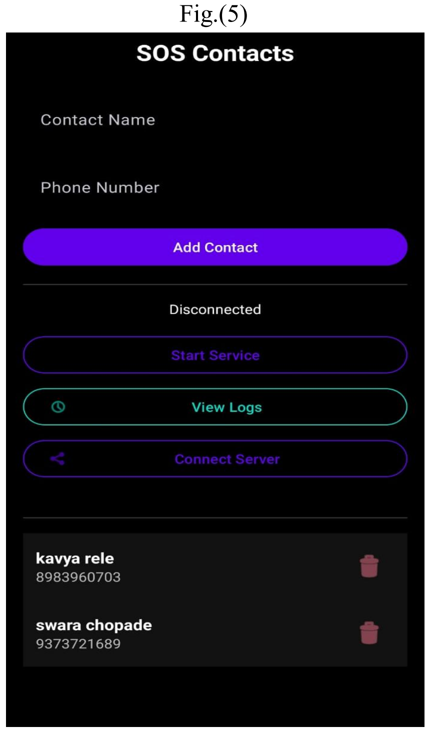

Fig.(6)

XI. FUTURE SCOPE

1. Multi-Sensor Integration — Successfully integrated ultrasonic distance, water level, and rain sensors on a single ESP32 Dev Board with edge detection and cooldown logic to produce meaningful, non-redundant event data.
2. AI-Powered Object Identification — The ESP32-CAM module, triggered automatically upon obstacle detection, captures and uploads images to a cloud-based AI Vision API. The resulting object identifications are delivered to the

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user as natural-language voice alerts (e.g., "There is a chair in front of you").

3. Cloud-Mediated Architecture — The Python backend hosted on Render.com acts as a reliable intermediary between the hardware stick and the mobile application, enabling event storage, AI processing, and efficient event polling via incremental IDs.

4. Production-Quality Mobile Application — The Android application follows industry-standard MVVM Clean Architecture with Hilt dependency injection, Room persistence, Retrofit networking, and Kotlin Coroutines. The foreground service ensures continuous operation even when the app is in the background.

5. Robust SOS Emergency System — The one-press SOS button triggers an end-to-end emergency pipeline: hardware buzzer feedback → cloud notification → mobile app detection → GPS location fetch → SMS delivery to all configured emergency contacts with a Google Maps link.

6. Data Security — Contact phone numbers are encrypted with AES-256-GCM using the Android KeyStore, and API keys are stored in EncryptedSharedPreferences, ensuring sensitive data is never stored in plaintext.

7. Low-Cost Solution — The entire hardware prototype can be assembled for under ₹3,000 using readily available ESP32 modules and sensors, making it significantly more affordable than commercial alternatives.

XII. ADVANTAGES &LIMITATIONS

Advantages

1. Comprehensive Sensing: The integration of ultrasonic, water, and rain sensors provides multi-dimensional environmental awareness that no single-sensor system can achieve.

2. AI-Powered Intelligence: The ESP32-CAM + cloud AI combination enables object identification beyond simple distance measurement, telling the user WHAT is in front of them, not just that something is there.

3. Voice-Based Interaction: The Android TTS engine converts all alerts into natural spoken language, making the system intuitive and hands-free for visually impaired users.

4. Emergency Safety Net: The SOS emergency system with GPS location and SMS communication provides a critical safety feature that is absent in all reviewed existing systems.

5. Low Cost: Using ESP32 boards and commonly available sensors, the total hardware cost is approximately ₹2,000-3,000 (USD 25-35), making it affordable for a wide range of users.

6. IoT Connectivity: Cloud-based processing allows the system to leverage powerful AI models without requiring expensive hardware on the stick itself.

Limitations

1. WiFi Dependency: The system requires WiFi connectivity for IoT communication with the cloud backend. In areas without WiFi coverage, only the local buzzer alert from the ultrasonic sensor will work, while AI detection and voice alerts will be unavailable.

2. Backend Latency: The polling-based communication between the Android app and backend introduces a delay of up to 5 seconds between event occurrence and voice alert delivery. Addition of Render's cold start time (if the server has been idle) can further increase this delay.

3. Power Consumption: Continuous WiFi communication, sensor reading, and camera operation drain the battery faster than a simple passive blind stick. The estimated battery life with the 2000mAh battery is approximately 4-6 hours of continuous use.

4. Weather Dependence of Camera: The ESP32-CAM's image quality degrades in poor lighting, heavy rain, or fog conditions, reducing the accuracy of AI object detection.

5. Single Direction Sensing: The ultrasonic sensor detects obstacles only in the forward direction. Side obstacles and overhead hazards remain undetected.

6. Smartphone Required: The voice alert and SOS features require the user to carry an Android smartphone with the app installed, adding dependency on another device.

XIII. CONCLUSION

This review paper has presented a comprehensive study of assistive technologies for visually impaired individuals, covering the evolution from traditional white canes to modern AI and IoT-enabled systems. Through the review of six relevant research papers, we identified significant gaps in existing solutions — primarily the lack of multi-sensor integration, AI-powered object identification, mobile voice assistance, and emergency communication features in a single affordable device.

The proposed Intelligent Ultrasonic Obstacle Detection System addresses these gaps by integrating an ESP32 Dev Board with three environmental sensors (ultrasonic, water, rain), an ESP32-CAM module for AI-powered image capture, a cloud-hosted Python backend server for intelligent processing, and an Android mobile application with Text-to-Speech voice alerts and SOS emergency capabilities. The system demonstrates that modern embedded systems, IoT, and AI technologies can be effectively combined to create practical, affordable, and comprehensive assistive devices.

The system has been implemented using Kotlin MVVM architecture for the Android app, Arduino/C++ for ESP32 firmware, and Python for the backend, following industrial-standard software engineering practices including dependency injection (Hilt), encrypted data storage (AES-256-GCM), and clean architecture patterns. The modular design allows each component to be independently updated and improved.

While the system has limitations related to WiFi dependency, power consumption, and single-direction sensing, the future research directions outlined in this paper — including on-device AI, LiDAR sensing, GPS navigation, and BLE communication — provide a clear path for advancement. The proposed system serves as a strong foundation for further research and development in the field of intelligent assistive technology for the visually impaired.

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