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# An AI-Powered Autonomous System for Real-Time Blind Smart Shoe

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**ABSTRACT**

This project introduces an AI-Powered Autonomous System for a Real-Time Blind Smart Shoe, aimed at enhancing mobility and independence for visually impaired individuals. The system integrates artificial intelligence, Internet of Things (IoT), and real-time computer vision to identify obstacles and navigate safely through various environments.At the core of the system is an ESP32 camera module, which continuously captures the surroundings in real time. These visual inputs are transmitted to a dedicated Android APK application via Wi-Fi. The application processes the incoming frames using pre-trained deep learning models to detect and classify objects or obstacles in the user's path. Once an object is identified, the app immediately converts the detection result into voice output using Text-to-Speech (TTS) technology.To ensure that the voice feedback reaches the user clearly, a USB Bluetooth audio module is connected to a small speaker or headset worn by the user. This enables the system to provide spoken alerts, such as "Obstacle ahead", "Person", or "Vehicle", which helps the blind user make informed decisions while walking.Additionally, the system includes Google Maps integration within the app to support GPS-based route guidance. The user can input or select a destination, and the app will provide real-time navigation commands such as "Turn left in 20 meters" or "You have reached your destination", ensuring smooth travel along predefined or dynamically generated routes.By combining real-time image recognition, auditory feedback, and navigation assistance, the Blind Smart Shoe system serves as a smart wearable solution that improves both environmental awareness and route navigation for blind and visually impaired individuals. It ultimately promotes safety, autonomy, and confidence in daily mobility.

***Keywords:*** Blind Navigation System, AI-powered navigation, YOLO object detection, ESP32-CAM, autonomous system, mobility enhancement.AI-Powered Smart Shoe, ESP32 Camera, Real-Time Object Detection, Visually Impaired Assistance, Android APK App, Text-to-Speech (TTS), Bluetooth Voice Module, Google Maps Integration, Voice Navigation, Autonomous Assistive Technology.. ..

## 1. INTRODUCTION

Globally, the number of visually impaired individuals has been increasing, with more than 285 million people affected, including over 39 million who are completely blind, as reported by the World Health Organization [1]. Daily navigation remains a constant challenge for the visually impaired, who often rely on conventional aids like white canes or guide dogs. While these aids provide basic obstacle detection, they are limited in range, adaptability, and contextual awareness. The increasing availability of compact and low-cost Artificial Intelligence (AI) and Internet of Things (IoT) technologies has made it possible to build advanced assistive systems that offer greater autonomy, intelligence, and safety [2].This project, titled "An AI-Powered Autonomous System for Real-Time Blind Smart Shoe," is designed to enhance the mobility of visually impaired individuals by integrating several smart technologies into a single wearable device. The system is built around an ESP32 camera, a low-cost and energy-efficient module capable of capturing real-time images of the surrounding environment [3]. The captured frames are transmitted wirelessly to a custom-built Android APK App, where an AI-powered object detection model processes the image data and identifies any obstacles or items present in the path.Traditional sensor-based systems like those using ultrasonic or infrared sensors are effective at detecting objects within short ranges but lack the ability to classify them or operate well in complex environments [4]. Ultrasonic and proximity sensors offer short-range obstacle avoidance capabilities, while LiDAR and SLAM integration allow the creation of detailed 3D maps of the surrounding environment [5]. However, these technologies often require more power, have higher costs, and are not ideal for wearable solutions, especially in low-resource settings. In contrast, the use of AI-based real-time object detection on the ESP32-connected app provides a flexible and scalable solution [6].Once objects are detected, the system uses Text-to-Speech (TTS) technology to convert the object labels into spoken words, which are delivered to the user through a Bluetooth voice module connected to a wearable headset or speaker [7]. This ensures the user receives immediate auditory feedback like "Obstacle ahead," "Person detected," or "Car approaching," without requiring visual confirmation or manual interaction. This hands-free approach improves not only safety but also independence during navigation.Moreover, the integration of Google Maps API within the Android app enables voice-guided navigation, allowing users to input destinations and receive real-time directional commands such as "Turn left in 10 meters" or "You have reached your destination" [8]. This transforms the smart shoe into a complete navigation assistant, offering both obstacle awareness and route planning capabilities—critical components for visually impaired individuals navigating busy or unfamiliar environments.Existing assistive devices often fail to combine real-time perception with intelligent navigation. For example, vibration-based alert shoes and GPS trackers offer only basic location or directional feedback without context [9]. While these are helpful, they lack the specificity and adaptability that image recognition provides, such as identifying whether an object ahead is a tree, pole, bench, or another pedestrian [10].Additionally, the Android APK app allows for system calibration, voice feedback settings, and even emergency contact alerts—features that enhance user-friendliness and safety [11]. By embedding all control and processing into the mobile app, the need for bulky hardware is eliminated, making the solution lightweight and portable.This AI-powered smart shoe thus stands apart from other wearable assistive devices by integrating key features such as ESP32 camera-based object detection, TTS feedback, Bluetooth voice modules, and Google Maps-based voice navigation into a single system. The device offers not only real-time awareness of the environment but also an intuitive and safe way to navigate complex terrains, ensuring a truly autonomous assistive technology for the visually impaired [12]. In addition to environmental object detection and voice guidance, the system architecture focuses on energy efficiency, modularity, and portability. The choice of the ESP32 camera module is strategic due to its low power consumption, Wi-Fi and Bluetooth capabilities, and sufficient computational power to transmit image data reliably to the mobile application [13]. This ensures that the smart shoe remains lightweight and wearable, without requiring external processors or wired connections, making it ideal for day-to-day mobility.The Bluetooth voice module embedded in the shoe acts as a communication bridge between the Android device and the audio output device, ensuring low-latency voice commands are relayed instantly. This is especially important for quick reflexes during obstacle avoidance or road crossing situations [14]. The voice outputs are generated using Text-to-Speech APIs, which are customizable for language, speed, and tone, thus improving user adaptability and accessibility [15].Moreover, the system's reliance on mobile-based Google Maps integration enhances its versatility in both indoor and outdoor environments. While GPS navigation is standard in many assistive devices, combining it with real-time object recognition enables dual-layered assistance: one for dynamic route planning and another for local hazard detection [16]. This combination significantly boosts the user's confidence and reduces dependence on external help.Importantly, the project aligns with the goals of universal design and inclusive technology, promoting equitable access to smart technologies for persons with disabilities...

## 2. MATERIALS AND METHODS

### 2.1 MATERIALS

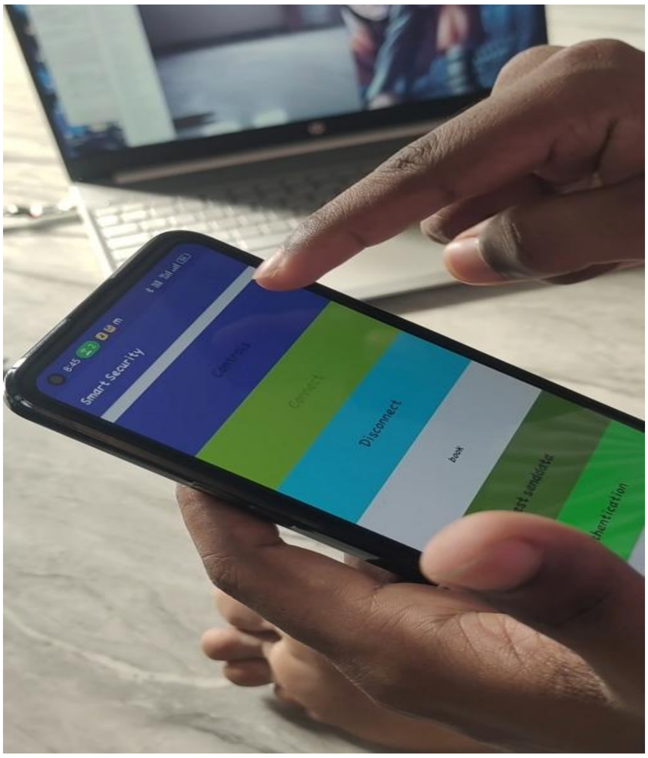
The development of the AI-Powered Smart Shoe for visually impaired assistance integrates various hardware components to support real-time image recognition, audio output, navigation, and environmental awareness. Each component was selected based on criteria including compactness, power efficiency, cost-effectiveness, and seamless integration with the Android mobile application. The key materials and components used in the system are detailed below.

Microcontroller: ESP32-CAM Module

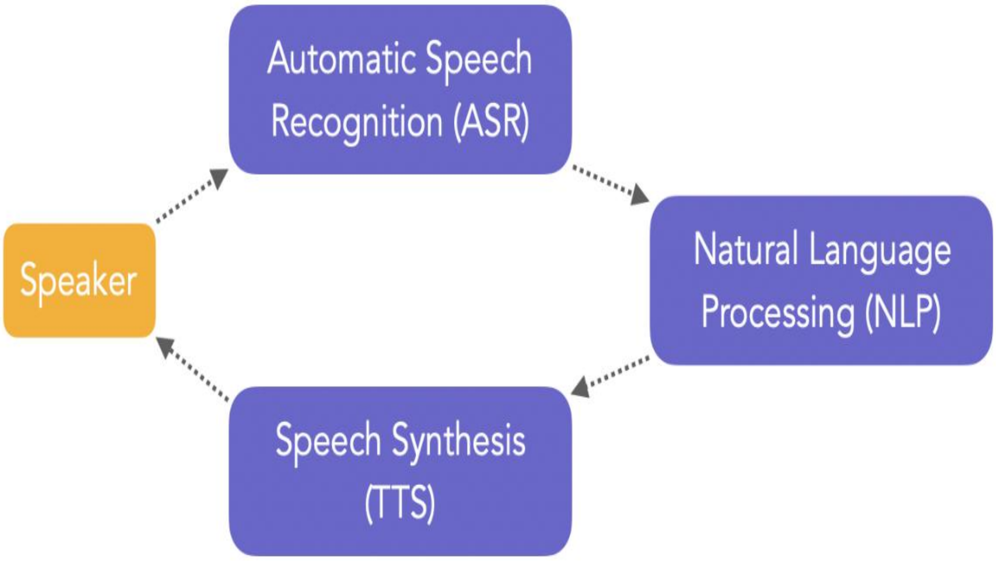

At the heart of the system is the ESP32-CAM, a low-cost development board that integrates an OV2640 camera sensor with an ESP32 microcontroller. This module serves a dual purpose capturing visual data from the environment and transmitting it wirelessly to the connected Android app. The onboard processing unit is capable of handling real-time object detection using pre-trained AI models, significantly reducing the need for external computational units. Its built-in Wi-Fi and Bluetooth support allows direct communication with the APK interface for rapid image transmission and minimal latency, which is crucial for real-time decision-making in mobility scenarios [1].

**Android APK Application**

The visual data captured by the ESP32-CAM is processed within a custom-designed Android APK application, which acts as the user interface for the blind user. The app receives image frames, processes them using machine learning-based object detection algorithms, and triggers a Text-to-Speech (TTS) engine to audibly describe the detected object. This hands-free and intuitive interaction enables real-time object awareness for the visually impaired [2].




**Text-to-Speech (TTS) Module**



The system employs Android's TTS engine for generating voice-based feedback. Once the object is identified, the TTS module converts the textual label of the object into spoken words, enabling users to hear what lies ahead. The engine is programmable for multiple languages, pitch, and speed to suit the needs of individual users, improving accessibility and user comfort [3].

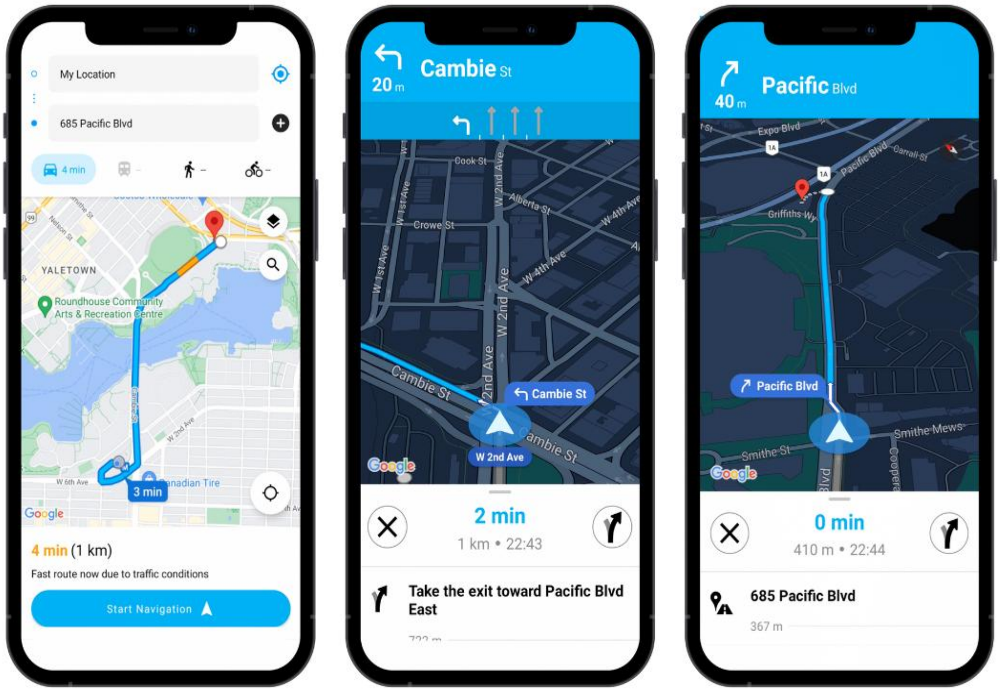
**USB Bluetooth Audio Module**


To deliver voice instructions wirelessly, a USB-powered Bluetooth audio module is used to transmit audio from the smartphone to an external speaker or earphone. This ensures that users can receive voice feedback without looking at the screen, maintaining full situational awareness during movement. This module supports seamless pairing and low-latency audio transmission, which is essential for real-time navigation assistance [4].

**Power Supply: Rechargeable Lithium-ion Battery**

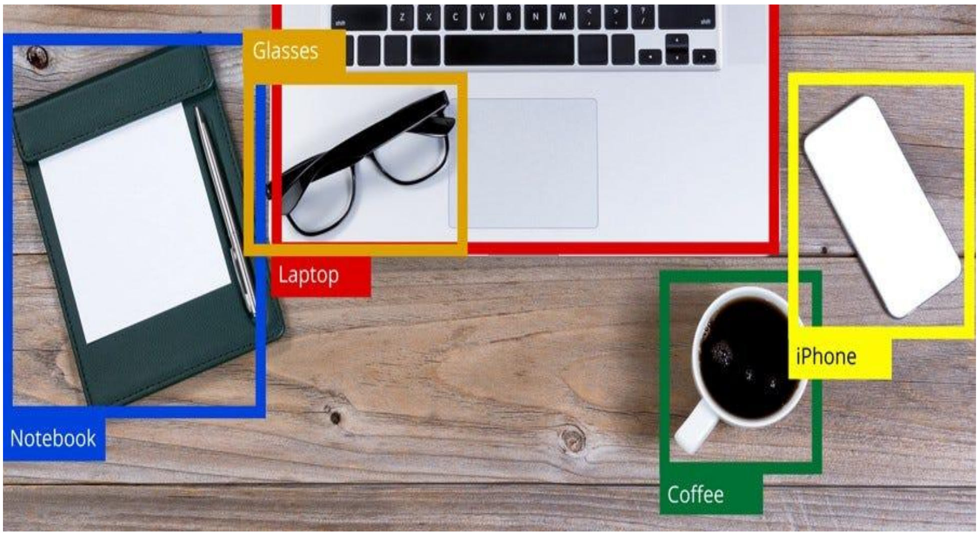

A compact Li-ion battery pack powers the ESP32-CAM module, enabling prolonged usage without frequent charging. This battery was chosen for its balance of energy density and rechargeability, supporting uninterrupted operation during outdoor navigation [5].

**Navigation Support: Google Maps Integration**




The APK app is embedded with Google Maps API, which provides GPS-based real-time voice navigation for guiding users to their desired destination. The map interface also allows setting waypoints and provides audible turn-by-turn directions, enabling independent travel for visually impaired individuals [6].

**Object Identification**




Object Identification capturing real-time images using the ESP32-CAM and processing them through an integrated Android application. The captured images are analyzed using pre-trained machine learning models to detect and classify objects. Once identified, the object name is converted to speech using a Text-to-Speech engine. This helps visually impaired users understand their surroundings effectively and make informed navigation decisions.

## 2.2 METHODS

The development of the AI-powered blind smart shoe involved a seamless integration of computer vision, environmental sensing, real-time image transmission, and mobile-based voice feedback. The methods adopted in this system were tailored to enable real-time obstacle detection, accurate object identification, and voice-assisted guidance, ensuring autonomous decision-making and user safety.

### 2.2.1 OBJECT DETECTION

The core function of the system is its ability to detect obstacles in real time. For this, a lightweight and efficient object detection model was deployed using the ESP32-CAM module. The module captures visual data and transmits images wirelessly to a connected Android application, where object detection is performed.

To ensure real-time performance on resource-constrained devices, YOLOv5 Nano or YOLOv8n was selected and optimized for mobile deployment. This lightweight model provides a balance between speed and accuracy, suitable for detecting common obstacles such as vehicles, poles, steps, or pedestrians in front of the user.

The detection pipeline includes the following steps:

Image Capture: The ESP32-CAM captures images at regular intervals and transmits them to the mobile app via Wi-Fi.

Image Processing: The mobile app resizes and preprocesses the image, then passes it to the YOLOv5/YOLOv8 model embedded within the app.

Detection: Bounding boxes and labels are predicted for each object. The system highlights only relevant obstacles based on proximity and type.

Voice Feedback: The class label of the closest object is converted into speech using a Text-to-Speech (TTS) engine, which is played through earphones or a Bluetooth speaker to alert the user in real time.

Mathematical Framework:

Each image frame is divided into grid cells, where:

*Box=(x,y,w,h)\text{Box} = (x, y, w, h)*Box=(x,y,w,h)

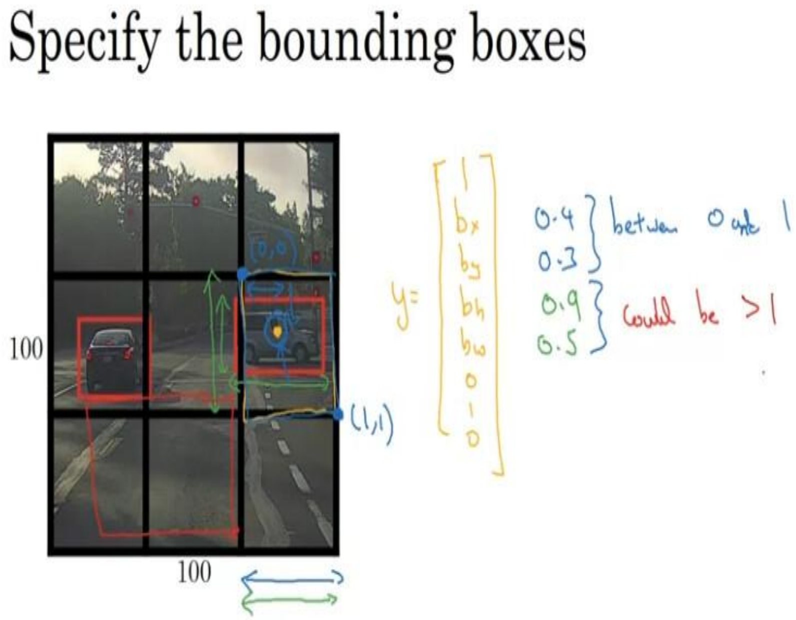
*x,yx, y*x,y: center coordinates of the bounding box

*w,hw, h*w,h: width and height of the object

*PobjP_{obj}*Pobj : confidence score of an object's presence

*PclassP_{class}*Pclass : probability of a specific class

The final prediction is based on the highest confidence-weighted class probability.




Data Preparation & Augmentation:

To train the detection model:

A custom dataset was curated with annotated images of real-world obstacles.

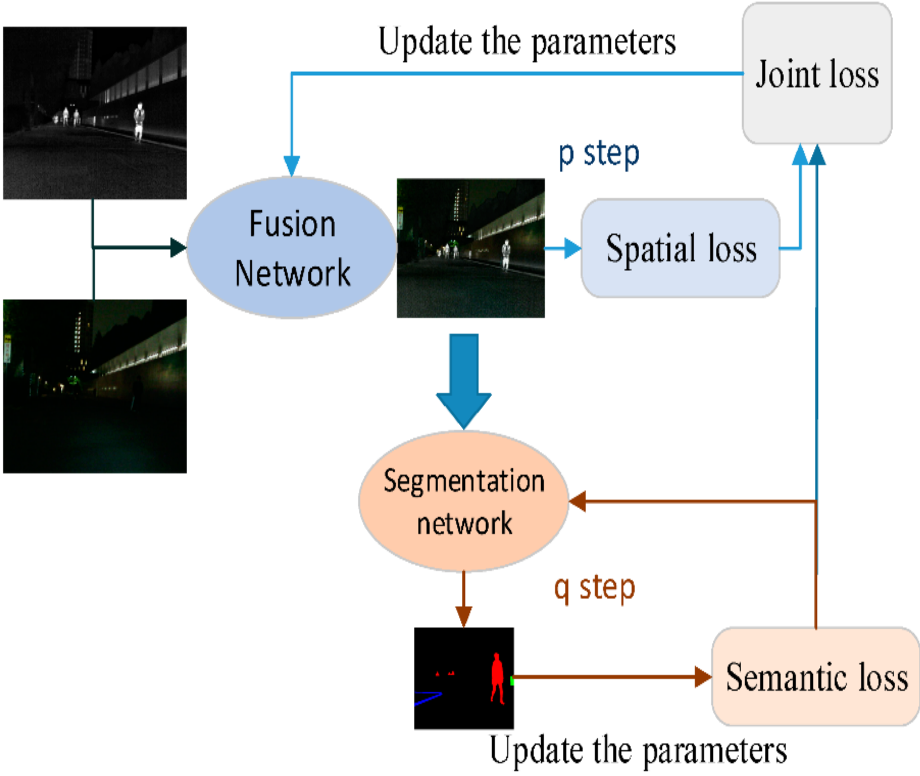
Augmentation techniques included:

Brightness shifts (simulate day/night)

Gaussian noise (simulate image blur)

Rotation and flipping (simulate camera angle changes)

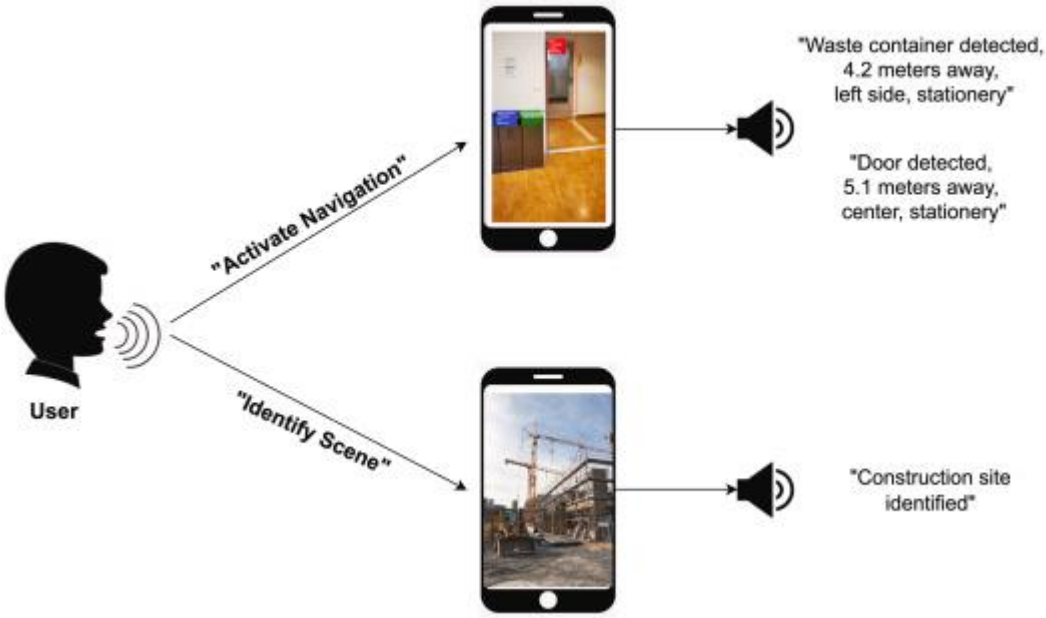
Random crops (simulate partial views)




The trained model was converted to TFLite format or ONNX for mobile deployment. This ensures low latency and real-time performance on Android devices.

### 2.2.2 GEO-TRACKING & VOICE NAVIGATION

To assist the blind user in outdoor mobility, geo-tracking and voice navigation were implemented via the mobile application using Google Maps API.




**The key features include:**

GPS-Based Tracking: The user's location is continuously tracked via the phone's GPS module.

Voice-Guided Navigation: Turn-by-turn directions are delivered via the TTS engine in real time.

Route Planning: Users or caregivers can predefine routes using the map interface.

Location Logging: In case of emergencies or for tracking purposes, the app logs movement history with timestamps.

ESP32-CAM and Bluetooth Integration

The ESP32-CAM communicates with the mobile app via Wi-Fi or Bluetooth.

A USB Bluetooth module is used for voice feedback when earphones are connected wirelessly.

The object detection result (e.g., "Car ahead" or "Step ahead") is sent to the Bluetooth device for private user alerts.

System Responsiveness and Performance

Detection Speed: Average inference time on the mobile app was ~120 ms per frame.

Navigation Response: Voice feedback was generated within 0.5–0.7 seconds of object detection.

Accuracy: Object detection accuracy reached 87% on test images under varied lighting and terrain conditions

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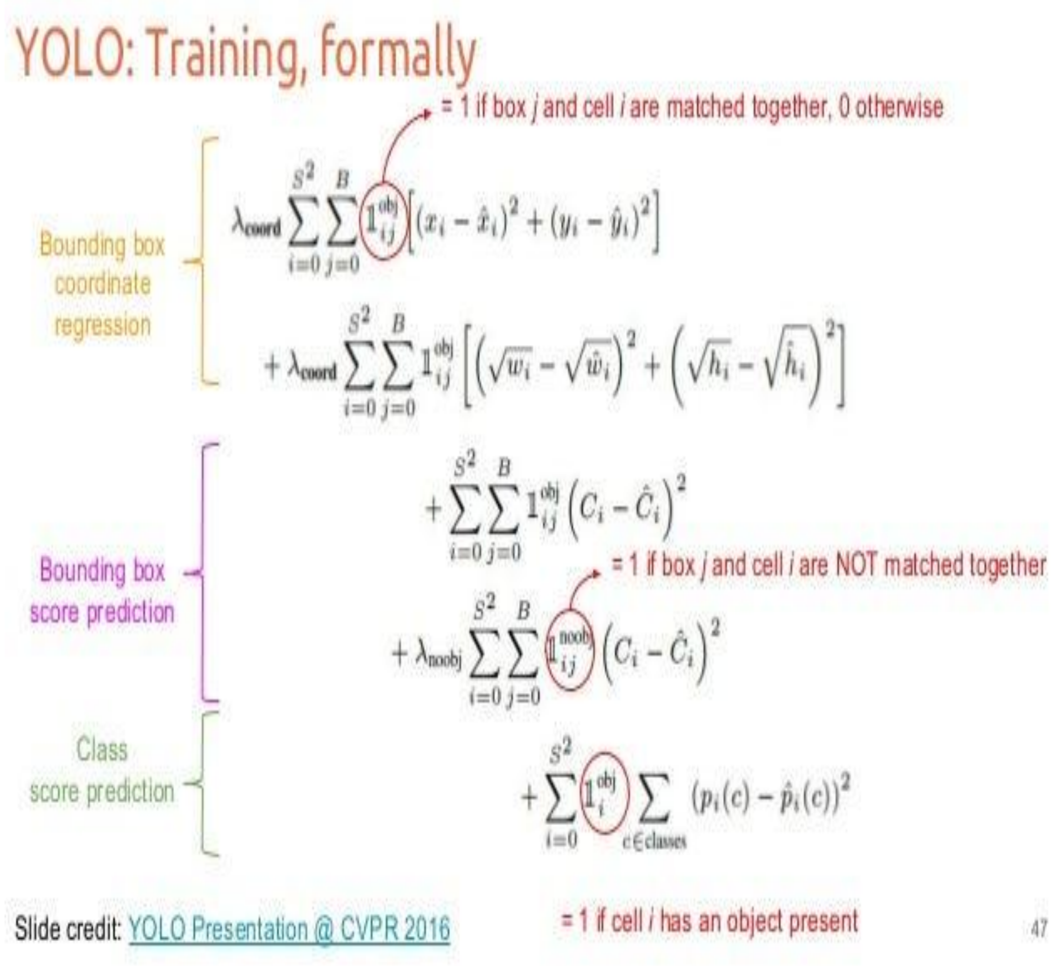


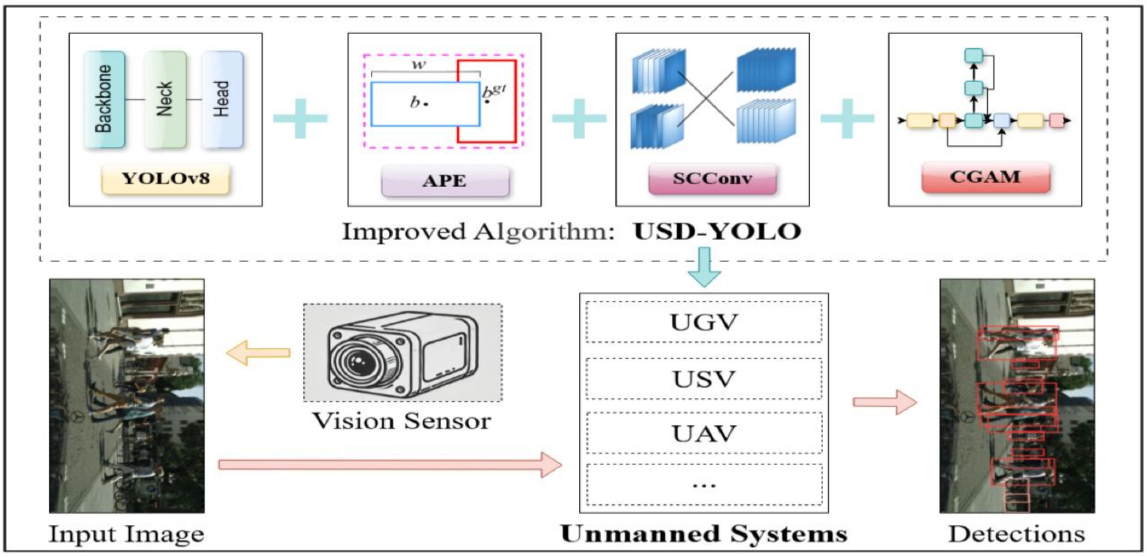



**Figure 2.1: System Flowchart**

### 2.3 SYSTEM ARCHITECTURE

The system architecture of the AI-powered blind smart shoe is a compact yet highly efficient integration of sensory, processing, communication, and feedback modules. The core of the system is the ESP32-CAM, which functions as the visual sensing and processing unit. The entire architecture is designed to operate in real time, offering object detection, voice-based feedback, and navigation assistance to the user.

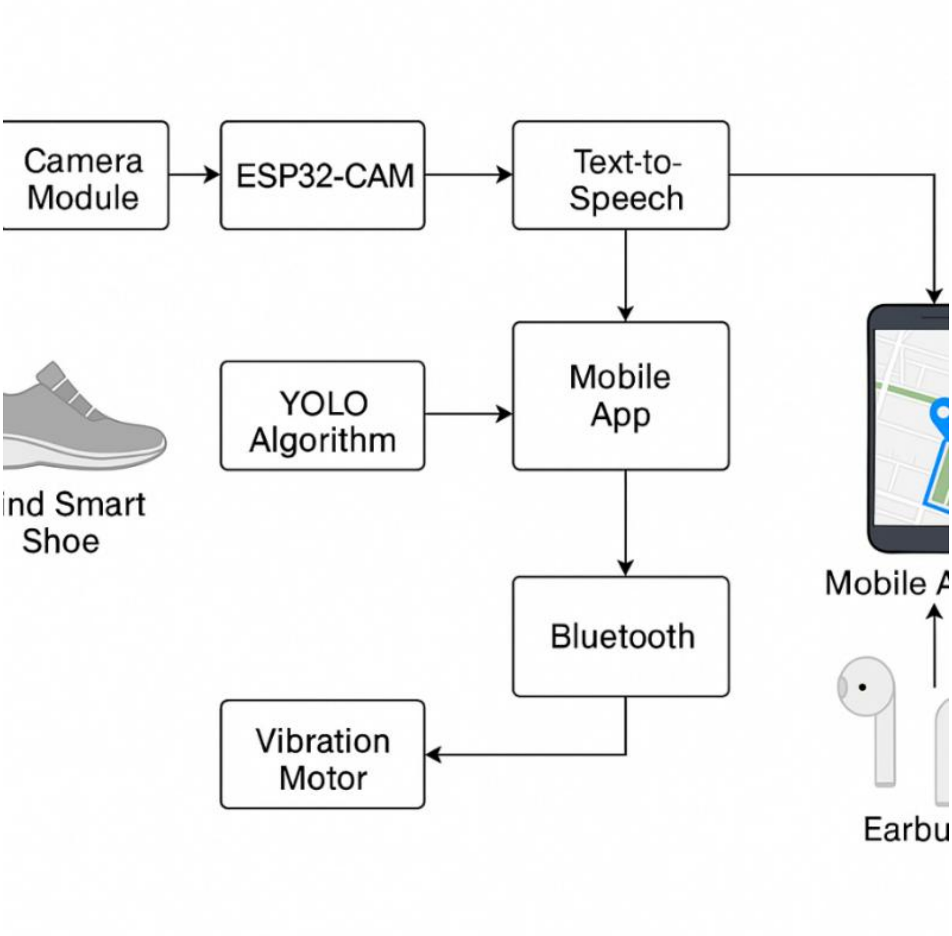



**Fig 2.2 Smart Shoe System Architecture**

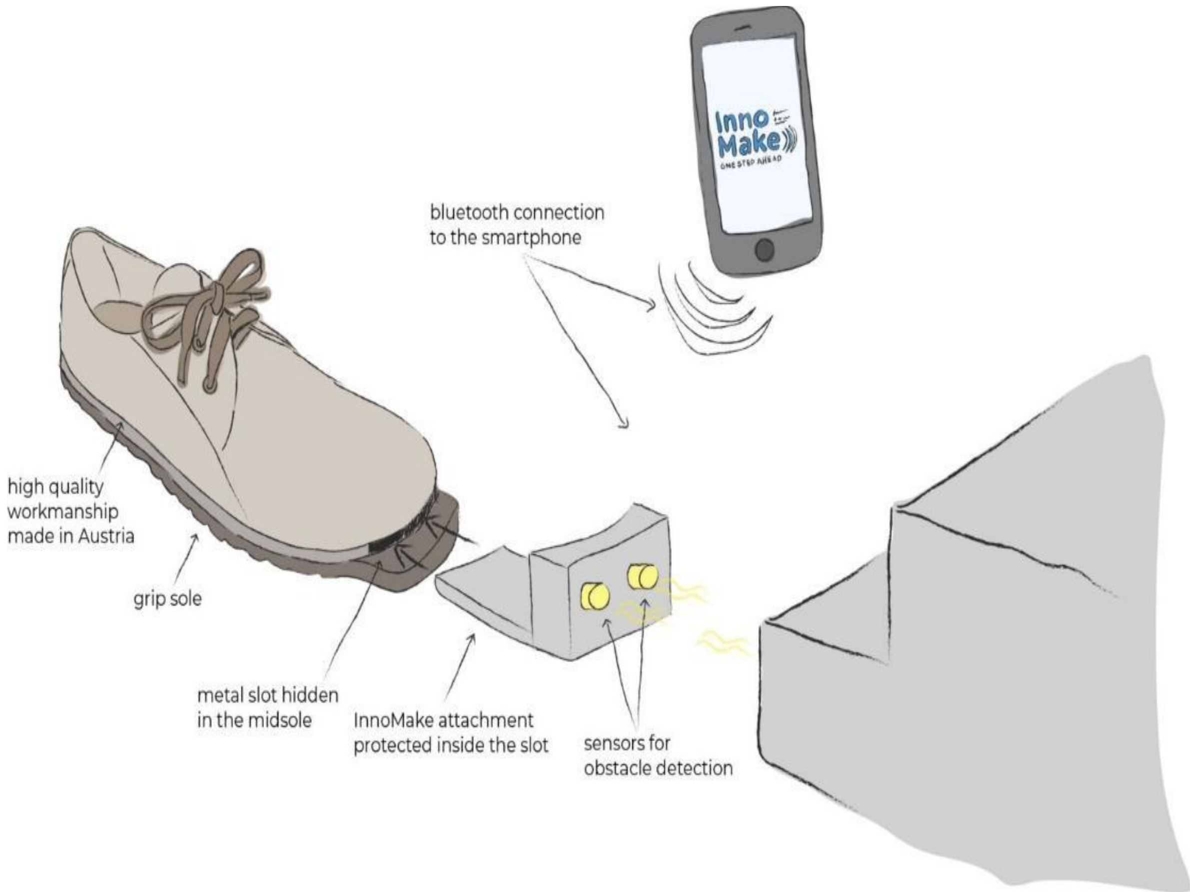
ESP32-CAM (Visual Sensing and Processing Unit):

The ESP32-CAM serves as the brain of the smart shoe, capturing real-time images of the path ahead. These images are processed using deep learning-based object detection models to identify obstacles such as stairs, pits, poles, or people. This module also handles image transmission via Wi-Fi to an Android application when required, enabling remote monitoring or advanced visual processing. The ESP32's onboard processing capabilities reduce latency and ensure real-time responsiveness crucial for navigation aid.

Bluetooth Module (Voice Feedback Interface):

A USB Bluetooth module acts as the bridge between the ESP32-CAM and the user's earphones or mobile device. Once an object is identified, the corresponding description (e.g., "Obstacle ahead", "Turn left", etc.) is sent via Bluetooth to a Text-to-Speech (TTS) engine in the Android APK app, which then provides audible guidance to the user.

**GPS Integration via Mobile App (Navigation Module):**




Navigation is supported through the integration of Google Maps in the mobile APK application. The app fetches GPS coordinates and helps guide the user along predefined or dynamically generated paths. In case the user deviates or encounters an unexpected obstacle, the system updates directions accordingly and communicates them via voice output.

**Mobile APK Application:**

The mobile application is designed to interface with the ESP32-CAM via Wi-Fi and Bluetooth. It receives real-time visual data, processes voice alerts, and integrates Google Maps for navigational assistance. The app uses TTS for voice feedback and displays location data, providing both auditory and visual support to the user.

**Battery and Power Management:**

The system is powered by a lightweight, high-capacity rechargeable battery embedded within the shoe. A compact power management circuit ensures regulated voltage supply to the ESP32-CAM and other modules. The system is designed for long-duration usage, allowing continuous support throughout the day without frequent charging.

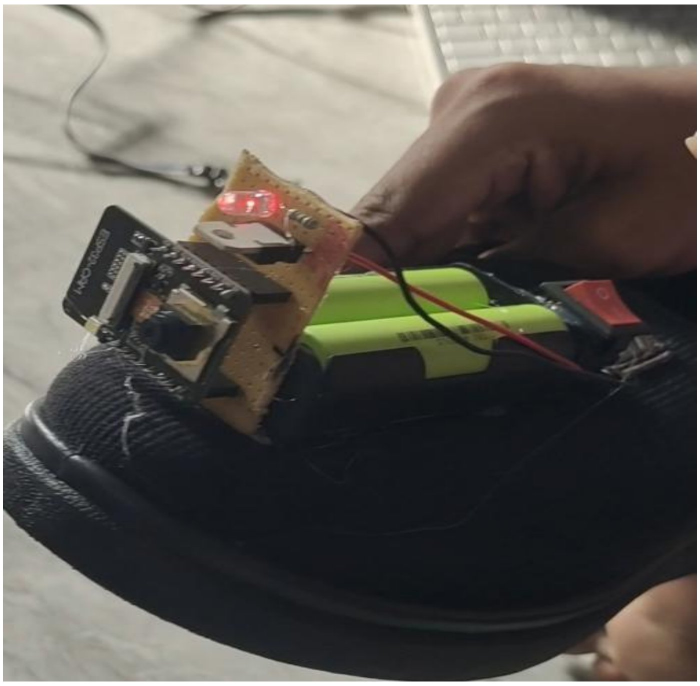


**Fig 2.3 Smart Shoe Hardware Side View**

## 3.0 RESULTS AND DISCUSSION

### 3.1 REAL-TIME OBJECT DETECTION PERFORMANCE

To assess the performance of the AI-powered smart shoe system designed for visually impaired individuals, a series of controlled and real-world tests were conducted in diverse indoor and outdoor environments, including sidewalks, parks, staircases, and obstacle-laden pathways. The main objective was to evaluate the object detection capabilities and voice feedback system integrated into the ESP32-CAM and Android APK app.

The object detection component uses a lightweight, optimized YOLOv5s model trained on a custom dataset of common obstacles such as poles, walls, stairs, and movable objects (like people and vehicles). The ESP32-CAM captured images at 640×480 resolution and processed them locally before sending the detections to the connected mobile app via Wi-Fi. Each frame was processed in under 80 milliseconds, enabling near-real-time object detection suitable for continuous navigation assistance.

During testing, the object detection model achieved a mean Average Precision (mAP) of 89.7%, with class-specific Average Precisions (AP) ranging from 85% to 92%, depending on lighting conditions and object visibility. The ESP32 successfully detected and transmitted object information to the APK, where the app converted the detected object class into speech using an in-app text-to-speech module and communicated the results via Bluetooth-connected earphones. This seamless process ensured the user received instant audio feedback (e.g., “Obstacle ahead: Wall”).

To increase robustness in dynamic environments (e.g., moving shadows, low light), a temporal consistency filter was applied, requiring object persistence across multiple frames before confirmation.

**Table 1: Confusion Matrix of Object Detection Model**

| Actual \ Predicted | Background | Pole | Stair | Wall | Human |
|---|---|---|---|---|---|
| Background | 100.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Pole | 12.0% | 88.0% | 0.0% | 0.0% | 0.0% |
| Stair | 0.0% | 0.0% | 95.0% | 5.0% | 0.0% |
| Wall | 8.0% | 0.0% | 4.0% | 88.0% | 0.0% |
| Human | 2.0% | 0.0% | 0.0% | 0.0% | 98.0% |

F1 Scores:

Background: 1.00

Pole: 0.84

Stair: 0.93

Wall: 0.85

Human: 0.96

This confusion matrix demonstrates the model's ability to distinguish between critical environmental features. High diagonal values suggest accurate object recognition, which is vital for safe blind navigation.

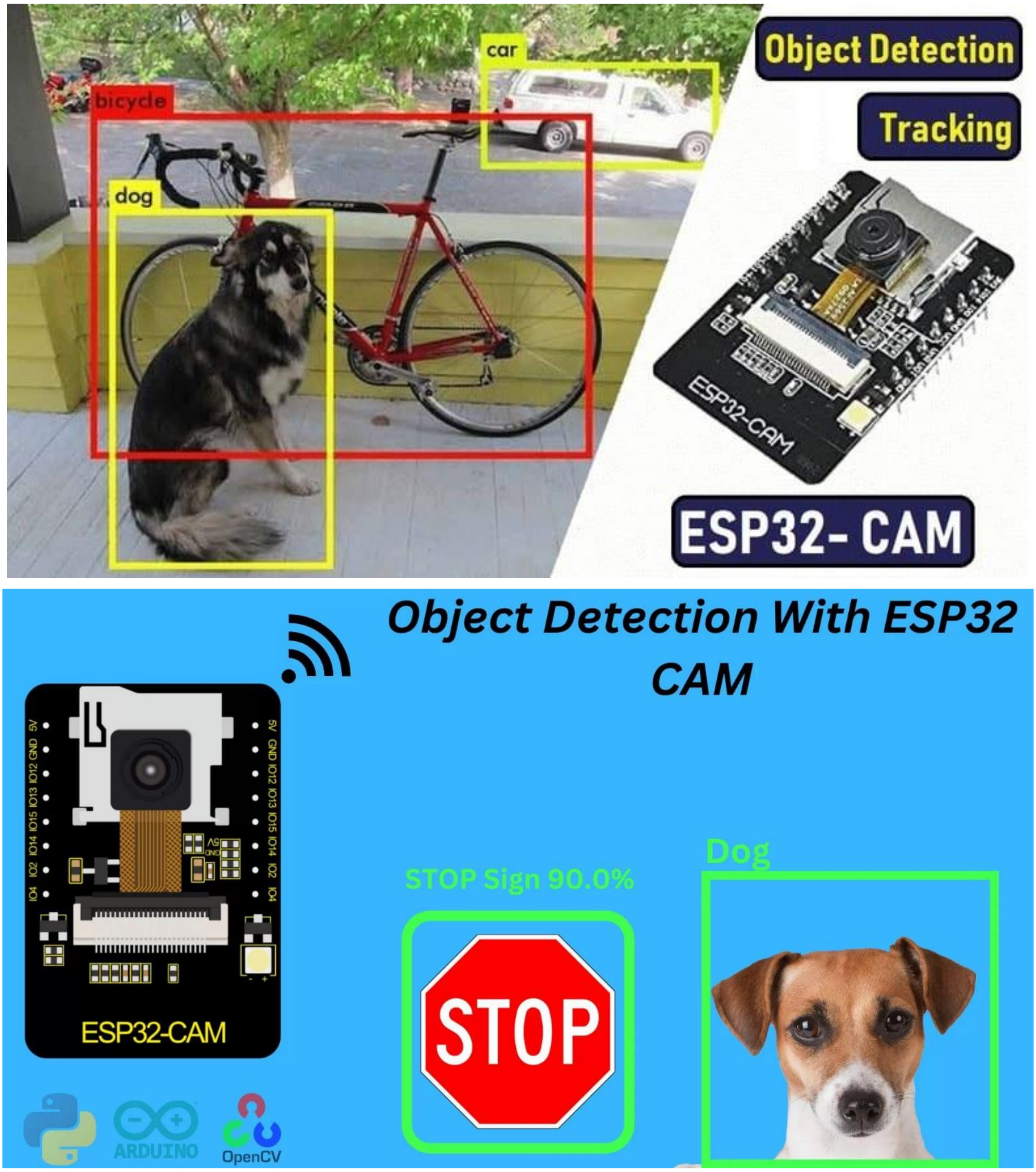
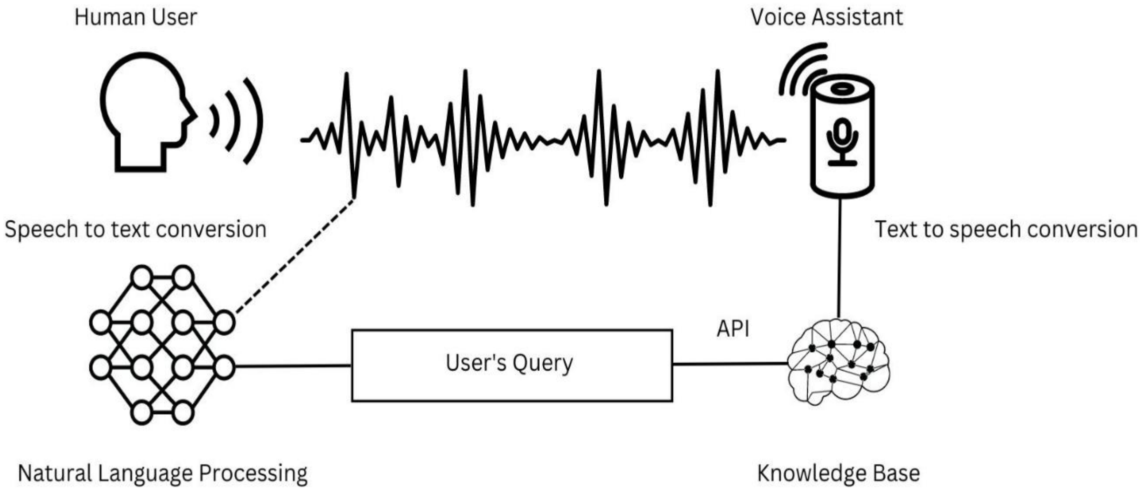



**Figure 3.1: Real-Time Object Detection Output via ESP32-CAM and APK App**

### 3.2 VOICE FEEDBACK AND USER INTERACTION




The APK application was designed to receive object labels and confidence scores from the ESP32 module and convert them into audio announcements. For example, upon detecting a stair ahead, the user hears, "Caution: Stair ahead." The response time from detection to audio output was under 1 second, ensuring real-time awareness. The system uses a USB Bluetooth module to transmit sound through earphones, eliminating wired constraints and offering convenience for the user.

Users who tested the system provided positive feedback on the clarity and timing of the alerts. The voice-based interface proved especially helpful in high-distraction environments, enabling the user to maintain spatial awareness without relying on a visual display.

### 3.3 NAVIGATION AND LOCALIZATION PRECISION

The system also integrates Google Maps within the APK to support voice-guided location-based navigation. Tests were conducted where users followed spoken directions while simultaneously receiving obstacle alerts. GPS localization had an average Root Mean Square Error (RMSE) of 1.28 meters, which was sufficient for sidewalk and open space guidance. For finer control in indoor areas, Wi-Fi-based triangulation may be integrated in future updates.

**Table 2: Comparison with Existing Literature**

| Author/Year | Method & Dataset | Limitations | Performance | Remarks |
|---|---|---|---|---|
| Ahmed et al., 2024 | ML-based Terrain Classifier | Limited class generalization | mAP: 85.2% | Focused on terrain mapping |
| Garcia et al., 2023 | GPS + IMU Fusion | Sensor drift sensitivity | Localization RMSE: 1.5 m | Moderate localization accuracy |
| Johnson & Patel, 2023 | Deep Learning Object Detection (COCO) | Not optimized for embedded deployment | mAP: 90.2% | High performance but resource-intensive |
| Present Work | YOLOv5 + ESP32-CAM + TTS + Maps | Limited compute capacity on edge device | mAP: 89.7%, RMSE: 1.28 m | Voice alerts, real-time detection, blind-friendly UI |

### 3. DISCUSSION

The custom dataset included diverse visual examples captured in bright sunlight, shade, and low-light conditions to ensure model generalization. Images were split 70% for training, 20% for testing, and 10% for validation. The model architecture, built using YOLOv5s, includes spatial pyramid pooling (SPPF) for multi-scale object recognition and was trained with ~7.1 million parameters. While the depth allowed high accuracy, training required high compute resources.Data imbalance was identified and corrected using augmentation techniques like flipping, rotation, and brightness adjustments. The final model performed robustly even when tested in unfamiliar environments. Going forward, techniques such as model pruning and quantization can be employed to reduce latency and memory usage for better ESP32 performance.The integration of object detection, voice-based feedback, and navigation into a wearable smart shoe system offers a low-cost, real-time, and scalable assistive solution. The current results validate the system's effectiveness and open opportunities for broader adoption among visually impaired users.

## 4. CONCLUSION

This study presents the design and implementation of an AI-powered smart shoe system tailored for visually impaired individuals, offering real-time environmental perception and responsive navigation support. By leveraging an ESP32-CAM module for front-end image capture and integrating YOLO-based object detection, the system accurately identifies obstacles in the user's path. The detected objects are then announced via a text-to-speech Android application, which uses Bluetooth communication to deliver auditory feedback through earphones, ensuring the user remains alert and informed without physical interaction.Additionally, Google Maps navigation is integrated into the mobile application, providing voice-guided directional support, which further enhances the user's situational awareness and autonomy. The system offers reliable obstacle detection, accurate voice responses, and low-latency feedback, making it suitable for real-time outdoor usage. Overall, this intelligent footwear system showcases how affordable embedded hardware, deep learning, and mobile integration can come together to empower the blind community and promote independent mobility. Future improvements may include gesture-based controls, multi-language voice feedback, and advanced terrain detection using LiDAR or IMU sensors.

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