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AI-Powered Multi-Functional Vision Assistant System for Visually Impaired

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***Abstract:** Visually impaired individuals face significant challenges in safe navigation, obstacle avoidance, and real-time environmental awareness, which restrict their independence and mobility in daily life. Traditional assistive tools such as the white cane primarily rely on tactile feedback and are limited in detecting distant obstacles, surface hazards, and dynamic environmental conditions. To overcome these limitations, this paper presents an AI-powered multi-functional vision assistant designed to enhance safety, situational awareness, and autonomous navigation. The proposed system integrates ultrasonic sensing, AI-based hazard detection, GSM communication, and solar-powered energy management into a compact and cost-effective device. An Arduino Mega microcontroller coordinates system operations, while an ESP32- CAM module enables vision-based analysis using an Edge Impulse-based FOMO (Faster Objects, More Objects) model for real-time water hazard detection. Multiple ultrasonic sensors provide approximately 180° obstacle coverage, ensuring reliable detection with feedback delivered through audio or vibration alerts. The integration of a GSM module enables emergency communication and location sharing during critical situations. A solar-powered rechargeable system ensures continuous operation without dependence on external power sources. The system is designed to be lightweight, portable, and easy to use, making it suitable for real-world deployment. Furthermore, its low-cost implementation ensures accessibility for a wider population of visually impaired users. Experimental results demonstrate effective real-time performance, high detection accuracy, and robust operation across various conditions, making the proposed system a reliable, affordable, and user-friendly assistive solution for visually impaired individuals.*

***Keywords:** Assistive Technology, Ultrasonic Sensors, GSM, AI Vision, ESP32-CAM, Arduino Mega*

I. INTRODUCTION

Globally, more than 250 million people experience some form of visual impairment, a condition that significantly restricts their mobility, safety, and daily independence. For decades, the traditional white cane has been the primary tool for navigation; however, it is fundamentally limited by its reliance on physical contact, offering no proactive information regarding the distance or specific type of environmental hazards. The lack of early warning systems often leads to accidents, particularly when encountering dynamic obstacles or liquid hazards like water puddles. The proliferation of affordable microcontrollers, sensors, and machine learning algorithms over the past decade has catalyzed the development of intelligent Electronic Travel Aids (ETAs) designed to augment traditional methods. Initial research established the viability of Arduino-based systems using ultrasonic sensors for fundamental obstacle detection [3], [8]. Subsequent advancements integrated powerful single- board computers like the Raspberry Pi [6] and utilized deep learning architectures. Specifically, Convolutional Neural Networks (CNNs) and object detection algorithms such as YOLO (You Only Look Once) have enabled these systems to transition from simple distance measurement to identifying and classifying specific objects in the user's path [5], [12], [17]. Despite these technological strides, existing electronic assistive devices face significant hurdles that prevent widespread adoption. Many high-end solutions based on Raspberry Pi architectures suffer from high power consumption and limited battery life, while more affordable Arduino-based sticks often lack sophisticated hazard classification and multi-sensor integration. Furthermore, the absence of integrated emergency communication modules and sustainable power sources remains a critical gap in current state-of-the-art designs.

This paper proposes an AI-Powered Multi-Functional Vision Assistant designed to bridge these gaps. By utilizing a dual-controller architecture featuring an Arduino Mega for real-time sensing and an ESP32-CAM for AI-based water hazard recognition, the system provides a comprehensive "secondary sight." Key contributions of this work include a 180° multi-directional obstacle detection array, the implementation of a FOMO-based AI model for puddle detection, and a GSM-based emergency communication system. To ensure long-term portability and cost effectiveness, the system is designed to be fully solar-powered, offering a robust and sustainable navigation tool for visually impaired individuals.

II. LITERATURE SURVEY

A model for assisting visually impaired individuals through obstacle and moisture detection using ultrasonic sensors and an Arduino microcontroller was presented by Dada Emmanuel Gbenga et al. in 2017 [3]. Visual impairment poses a significant challenge to mobility and independence, motivating the development of intelligent assistive devices. The proposed smart walking stick consists of ultrasonic sensors, a water sensor, a buzzer, and an RF transmitter–receiver system controlled by an ATmega328P-based Arduino UNO. The methodology involved integrating ultrasonic and moisture sensors with the Arduino microcontroller to detect obstacles and water within a range of approximately two meters, providing audio alerts via a buzzer. The system also incorporated an RF transmitter–receiver setup to help locate the stick when misplaced. The authors detailed the system's design, programming in C using the Arduino IDE, hardware interfacing, and testing through simulation and real-world validation. Experimental results demonstrated reliable obstacle and moisture detection with distinct beeping patterns to differentiate hazard types. The proposed system was lightweight, portable, and efficient for indoor and outdoor navigation, offering a significant improvement over conventional white canes and costly assistive technologies. The study demonstrated that the device is affordable, easy to use, and capable of guiding the visually impaired with precision. The paper concluded by suggesting future enhancements, including GPS integration, GSM-based location alerts, and vibration feedback for increased user safety and convenience, thereby advancing the scope of assistive navigation systems for visually impaired persons.

In 2025, Shahzor Memon et al. presented a sophisticated, multi-sensor smart walking stick that enhances navigation and safety for visually impaired individuals by integrating ultrasonic, smoke, water, light, and clap sensors with Arduino and Raspberry Pi platforms [4].The methodology involved interfacing these sensors with microcontrollers to detect obstacles, stairs, water puddles, and fire, while providing auditory feedback through earphones and buzzers. The ultrasonic sensor (HC-SR04) served as the primary component for detecting objects and floor variations up to a range of 400 cm, while additional sensors such as MQ-2 and HW-482 were used for fire and water detection respectively. A Light Dependent Resistor (LDR) sensor ensured visibility in dark conditions, and a clap sensor allowed the user to locate the stick when misplaced. The system was programmed in C, and its experimental validation demonstrated accurate identification of even surfaces, ascending, and descending stairs using statistical features like mean and standard deviation extracted from smoothed ultrasonic signals. This design produced a lightweight, low-cost, and user-friendly mobility aid capable of distinguishing different walking surfaces and obstacles. The study concluded that the proposed smart stick significantly improves independence and safety for visually impaired users and suggested future enhancements, including real-time data integration, advanced pattern recognition, and machine learning-based surface classification for improved environmental adaptability.

Vidya M. Shinde et al. 2025 study, Smart Assistive Stick for Visually Impaired People [5], introduces an innovative mobility aid integrating real-time object detection and audio feedback to enhance navigation safety for the visually impaired. The system employs the YOLO (You Only Look Once) algorithm to accurately detect nearby obstacles, while an ultrasonic sensor mounted on a servomotor measures object distance. The architecture, powered by an ESP32 microcontroller, processes data from sensors and delivers feedback through vibration motors and audio alerts, enabling users to perceive obstacles intuitively. Evaluation results demonstrate reliable real-time detection and user-friendly interaction across various environments. By combining computer vision, sensor fusion, and machine learning principles, the study highlights the potential of assistive technology to foster independence and improve spatial awareness for visually impaired individuals.

In 2025, Dipta Paul et al. published [6], presents an advanced assistive solution that merges artificial intelligence, embedded systems, and sensor fusion to support independent navigation for visually impaired individuals. The proposed model integrates Arduino Mega as the core processing unit, coordinating five ultrasonic sensors, GPS, GSM, and a water detection module to identify environmental hazards within a 0–30 cm range. The incorporation of a Raspberry Pi module and camera enables AI-powered object detection through a Convolutional Neural Network (CNN)-based

YOLO algorithm, allowing real-time recognition of people, vehicles, and other obstacles. Audio and vibration feedback are provided to the user, alongside emergency communication via GSM, ensuring both mobility and safety. Simulation and hardware implementations validated the system's accuracy and responsiveness across multiple terrains. This dual-layered architecture, combining IoT, machine learning, and embedded control, highlights a significant leap toward affordable, intelligent navigation aids for visually impaired individuals, fostering autonomy and situational awareness.

In 2014, K. Ramarethinam et al. study, Navigation System for Blind People Using GPS & GSM Techniques [8], presents a comprehensive assistive device designed to improve the independent mobility of blind and visually impaired (BVI) individuals in both familiar and unfamiliar environments.

The core of their system integrates GPS for outdoor navigation and GSM for emergency communication. Navigation begins when the user provides a destination as a voice command; the system then uses a GPS receiver and a path detector to find the shortest route, conveying directions via audible messages. A key feature is an emergency button that, when pressed, triggers an SMS containing the user's current GPS coordinates to a pre-set phone number. The system is built around a 32-bit ARM Cortex-M3 embedded controller and features a Braille capacitive touch screen for user-friendly input. Beyond navigation, the device provides a suite of auxiliary functions, including obstacle detection using an ultrasonic SRF02 sonar sensor (with feedback delivered via a vibrating motor), as well as audio information on time, calendar, object color, ambient light, and temperature. The authors conclude that this portable, self-contained system represents a significant tool to enhance the communication ability and mobility of BVI persons, reducing their dependence on others.

In 2020, Shalini Singh et al. study, Intelligent Walking Stick for Elderly and Blind People [9], presents a multi- functional electronic walking stick designed to enhance the safety and independence of blind and elderly users by integrating navigation assistance with health monitoring. The core of their system is a PIC16F877A microcontroller that coordinates a suite of sensors, including an ultrasonic sensor for frontal obstacle detection, a PIR sensor for pit detection, electrodes for water detection, a TCRT1000 sensor for pulse rate measurement, and an NTC thermistor for body temperature monitoring. A key feature is an emergency alert system where pressing a panic button triggers a GSM module to send an SMS containing the user's location, obtained via GPS, to a pre-stored contact. All alerts are communicated to the user through an audio voice alert system using an APR33A3 module. The system was empirically validated with blind users, demonstrating a significant performance improvement over a traditional white cane, increasing walking speed by over 20% on tested routes by providing proactive warnings. The authors conclude that this all-in-one, cost- effective solution significantly boosts user confidence and safety, and suggest future enhancements such as integrating diabetes monitoring, cameras for object identification, and neural networks for path planning.

In 2016, L. D´ıaz-Vilar´ıno et al. published the study Indoor Navigation from Point Clouds: 3D Modelling and Obstacle Detection [11], which introduces a methodology for generating navigable indoor models from 3D laser scanner data. The authors utilize point clouds not only to reconstruct semantically-rich 3D building models but also to detect real-world obstacles, such as furniture, that are typically absent in as-designed building layouts. The process involves segmenting the point cloud to identify structural elements (walls, floors, ceilings) and potential obstacles, followed by the reconstruction of navigable spaces and openings like doors and windows. A key innovation is the integration of detected obstacles into a navigable network, where a buffer representing a person's space is used to dynamically recalculate the shortest path using Dijkstra's algorithm whenever an obstruction is encountered. This approach provides a more accurate representation of the actual indoor environment, enhancing path planning for applications such as emergency evacuation or assisted navigation for people with disabilities. The methodology was validated in a real case study, demonstrating its capability to adapt routes dynamically based on the presence of obstacles.

Pruthvi S et al. 2019 study, Smart Blind Stick using Artificial Intelligence [12], presents an electronic travel aid that leverages modern computer vision to assist visually impaired individuals. The system integrates a Raspberry Pi microcomputer with a high-resolution camera and an ultrasonic sensor. It employs the YOLO (You Only Look Once) object detection algorithm, implemented via the Darkflow framework, to identify and classify up to 80 different object categories in the user's environment in real-time. Detected objects and their counts are processed into a text file, which is then converted into audible speech using the eSpeak text-to-speech engine. Simultaneously, an ultrasonic sensor measures the distance to the nearest obstacle, which is also relayed to the user. This combination provides a descriptive understanding of the surroundings, offering a form of "secondary sight". The authors note an average processing time of 1.22 seconds per detection cycle and suggest future enhancements such as integrating facial recognition and optical character recognition to further aid users.

In 2024, Laurence Kenneth A. Balomaga et al. study, ProxiSense: IoT Smart Blind Stick with Voice Alerts for Obstacle and Water Hazard Detection [13], presents a sophisticated Arduino-powered assistive device designed to enhance the outdoor navigation and safety of visually impaired individuals. The core of the system integrates multiple sensors an ultrasonic sensor for obstacle detection, a water sensor for hazard detection, and a TCS3200 color sensor for traffic light recognition with three key algorithms: the Traffic Light Crossing (TLC) algorithm for safe road crossing, the A* algorithm for optimal pathfinding to user-selected Points of Interest (POIs), and a Sliding Window algorithm for real-time weather forecasting. A significant feature is the accompanying mobile application, developed with Android Studio and Firebase, which allows users or caregivers to set destinations, view trip history, and check weather conditions. The system provides multi-modal feedback through voice alerts, sound alarms from a piezo buzzer, and vibrations from a motor. The device was rigorously evaluated against the ISO 25010:2011 software quality standard by 50 respondents (comprising visually impaired users and caregivers), achieving an overall mean score of 3.50, which is classified as "Very High" across all criteria, including Functional Suitability, Reliability, Safety, and Interaction Capability.

The authors conclude that ProxiSense is a highly functional and reliable system for everyday navigation and recommend future work on integrating additional hazard detection sensors, iOS compatibility, and alternative power sources like solar-charged batteries.

In 2022, Mrs. K.P.Kamble et al. study, Voice Assisted Smart Blind Stick [15], presents an advanced electronic aid designed to provide artificial vision and real-time assistance for blind individuals. The system is built on an Arduino UNO platform integrated with a Raspberry Pi, which serves as an intelligent hub. It utilizes ultrasonic sensors for real-time obstacle detection within a 3-meter range and a Pi camera with the OpenCV library for facial recognition, achieving an average accuracy of 90%. Auditory feedback is delivered through a dual-alert system: a buzzer provides immediate alerts, while the Google Text-to-Speech (GTTS) library generates natural-sounding voice messages to inform the user about the proximity of obstacles and the identity of recognized individuals. Additionally, the system incorporates GPS and GSM modules for location tracking and emergency communication, allowing users to send their coordinates via SMS to designated contacts. The authors conclude that this integration of cutting-edge hardware and intelligent software offers a user-friendly, cost-effective solution that significantly enhances navigational safety and social interaction for the visually impaired.

In 2024, Ahmed Ben Atttallah et al. study, An effective obstacle detection system using deep learning advantages to aid blind and visually impaired navigation [17], presents a sophisticated obstacle detection system designed to enhance the safety and autonomy of Blind and Visually Impaired (BVI) individuals in both indoor and outdoor environments. The core of their system is a modified and optimized YOLOv5 neural network architecture. To ensure robustness, the model was trained and evaluated on two benchmark datasets: the IODR dataset for indoor objects and the MS COCO dataset for outdoor objects, focusing on 40 landmark object classes critical for BVI navigation. A key contribution of this work is the implementation of several model compression techniques including model width scaling, channel pruning, and post- training quantization to create a lightweight version suitable for deployment on embedded devices with limited resources. The optimized model achieved a competitive mean Average Precision (mAP) of 76.41% and a processing speed of 89 frames per second (FPS), demonstrating an effective trade-off between detection accuracy and real-time performance. The authors conclude that this deep learning-based system represents a significant step forward in creating practical, efficient, and deployable assistive technology that can help BVI persons navigate unfamiliar spaces more safely and independently.

Ammar Almomani et al. 2023 study, Smart Shoes Safety System for the Blind People Based on (IoT) Technology [18], introduces a wearable assistive device designed to enhance the mobility and safety of visually impaired individuals. The system incorporates multiple sensors, including three ultrasonic sensors for obstacle detection, a water level sensor, a flame sensor, and a DHT11 temperature and humidity sensor, all managed by an Arduino microcontroller. It utilizes GPS for location tracking and a GSM module for emergency communication and alerts. When obstacles, water, fire, or extreme temperatures are detected, the system provides audio warnings via a BY-8001 MP3 module and vibrations to alert the user. The design aims to offer comprehensive environmental awareness and promote independent navigation. The system was evaluated through a questionnaire administered to 100 participants, with 99.1% indicating that the product meets their needs. The authors highlight the system's potential for future improvements, such as wireless connectivity, enhanced sensor range, and additional features like speed detection of approaching obstacles and integration of cameras for more detailed environment analysis.

Thayer Corbin's 2023 study, Vision-Based Autonomous Navigation and Obstacle Avoidance in Mobile Robots Using Deep Reinforcement Learning [19], presents a hybrid navigation system that integrates vision-based deep reinforcement learning (DRL) with a visual simultaneous localization and mapping (SLAM) module. The framework employs a convolutional neural network and the Proximal Policy Optimization (PPO) algorithm to learn control policies directly from raw RGB images, enabling end- to-end navigation and obstacle avoidance. To enhance localization accuracy, ORB-SLAM2 is incorporated as a geometric backbone, providing real-time pose feedback to the policy network. Experiments in simulated and real-world environments demonstrate that the combined DRL+SLAM architecture outperforms classical and vision-only navigation baselines in success rate, path efficiency, and collision avoidance. The system highlights the benefits of fusing learned perception with geometric reasoning to achieve robust and generalizable autonomy in complex indoor settings.

Sangam Malla et al. 2023 study, Obstacle Detection and Assistance for Visually Impaired Individuals Using an IoT-Enabled Smart Blind Stick [21], presents an advanced electronic travel aid designed to enhance the mobility and independence of visually impaired users. The system integrates an Arduino UNO microcontroller with ultrasonic sensors, a water sensor, and a camera. It employs the Viola-Jones algorithm for real-time object detection and classification, capable of identifying obstacles such as walls, staircases, and water bodies. The stick provides multi-modal feedback through a voice playback module and vibrations, alerting users to both the presence and type of hazards.

Additionally, the design incorporates Bluetooth Low Energy (BLE) for low-power communication and includes self- debugging capabilities to improve distance measurement accuracy. Experimental results demonstrated high detection accuracy across various ranges and conditions, with the system effectively reducing navigation errors and increasing user confidence during mobility.

In 2025, P. Vennila et al. study, Smart IoT Navigation System for Visually Impaired Individuals: Improving Safety and Independence with Advanced Obstacle Detection [22], introduces an IoT-based assistive device that integrates a smart walking stick with a smartphone application to enhance environmental perception for the visually impaired. The system employs an ESP32 microcontroller to process data from an HC-SR04 ultrasonic sensor, which detects both static and dynamic obstacles, as well as pits and uneven surfaces. A key feature is the communication between the hardware and a custom Android application, developed using MIT App Inventor, which delivers real-time, audible navigation instructions to the user via Bluetooth. The prototype demonstrated high-performance accuracy, achieving 99.54% at a distance of 250 cm and 99.03% at 450 cm, with an effective angular detection range of up to 90 degrees. The authors conclude that this system provides precise voice feedback and real-time guidance, significantly improving the confidence, independence, and safety of visually impaired users when navigating unfamiliar indoor and outdoor environments, representing a substantial advancement in accessible and cost-effective assistive technology.

III. PROPOSED METHODOLOGY

The proposed AI-powered multi-functional vision assistant system is designed to improve the mobility, safety, and independence of visually impaired individuals by integrating sensing, artificial intelligence, communication, and renewable energy technologies into a unified framework. The system is built around an Arduino Mega microcontroller, which acts as the central processing unit, coordinating the operation of all hardware components. For obstacle detection, three ultrasonic sensors are strategically placed to provide approximately 180° coverage, enabling detection of objects in the left, center, and right directions. These sensors continuously monitor the surroundings, and when an obstacle is detected within a predefined range, the system provides immediate feedback through a buzzer along with directional indication, allowing users to take corrective action before physical contact occurs. To enhance environmental awareness beyond obstacle detection, the system incorporates an AI-based water hazard detection module using an ESP32-CAM. This module captures real-time images and processes them using a machine learning model developed with Edge Impulse, specifically the FOMO (Faster Objects, More Objects) algorithm. This enables accurate identification of water puddles and slippery surfaces, which are otherwise difficult to detect using conventional sensors. Upon detection, the system generates alert signals to warn the user, thereby reducing the risk of accidents. Additionally, an emergency communication module based on a GSM unit is integrated to improve user safety. In emergency situations, a push button triggers an automatic call or message to predefined contacts, ensuring timely assistance.

The system is powered by a sustainable energy solution that includes a solar panel, charge controller, and recharge- able battery. The solar panel provides renewable energy, while the charge controller regulates the charging process to prevent overcharging and ensure battery longevity. This power management module enables continuous and reliable operation without dependency on external power sources, making the system suitable for extended outdoor use. All modules are seamlessly integrated to function as a uni- fied system. The Arduino Mega ensures real-time processing and coordination between sensor inputs, AI-based detection, and output alerts. The combined use of multi-sensor data, embedded AI, and communication technologies enables the system to provide comprehensive environmental awareness. This integrated methodology significantly improves navigation assistance compared to traditional systems by offering early hazard detection, intelligent classification, and immediate user feedback.

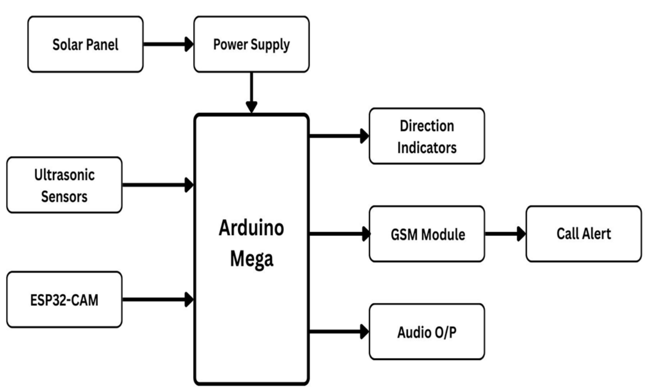

Fig. 1. System Architecture

The system architecture illustrates the integration of key components including ultrasonic sensors, ESP32-CAM, GSM module, power supply unit, and output devices such as buzzer and directional indicators. The Arduino Mega serves as the central controller, receiving inputs from sensors and coordinating outputs based on processed data. The ESP32-CAM handles AI-based image processing, while the GSM module ensures communication during emergencies. The power unit supplies regulated energy to all components, ensuring uninterrupted operation.

A. System Design and Hardware Structure

The physical design of the proposed system is developed with a focus on compactness, durability, and efficient com- ponent integration. A custom enclosure is designed using 3D modeling techniques to securely house all hardware compo- nents, including the Arduino Mega, ESP32-CAM module, ul- trasonic sensors, GSM module, and power unit. The enclosure is fabricated using PLA (Polylactic Acid) material, which is lightweight, cost-effective, and suitable for rapid prototyping through 3D printing.

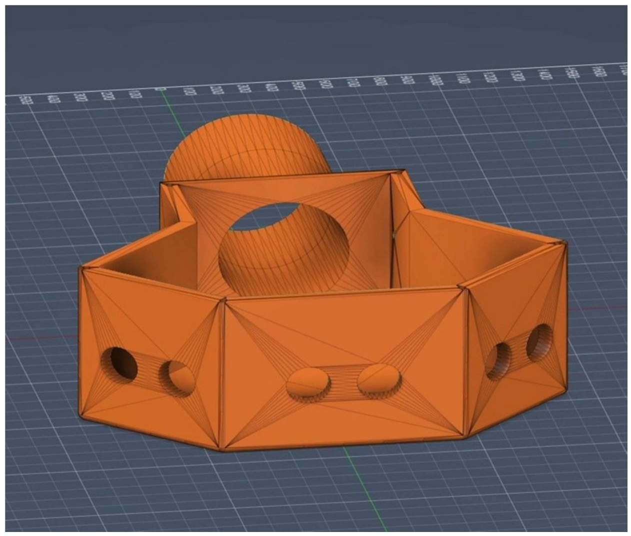

Fig. 2. System Design

The design incorporates strategically placed openings and mounts to ensure optimal sensor performance. Dedicated cir- cular slots are provided for ultrasonic sensors to enable multi- directional obstacle detection, while a front-facing aperture is designed for the ESP32-CAM module to capture real- time environmental images. The internal layout ensures proper alignment of components, efficient cable management, and adequate ventilation. The modular structure of the enclosure allows easy assembly, maintenance, and future upgrades. Overall, the design ensures a balance between robustness, functionality, and user comfort, making it suitable for real- world assistive applications.

B. AI Model Development

The AI-based water hazard detection system is developed using the Edge Impulse platform, utilizing the FOMO (Faster Objects, More Objects) algorithm for efficient object detection on embedded systems. The model is trained on a dataset consisting of labeled images representing water puddles and non-hazardous background surfaces. Data preprocessing and augmentation techniques are applied to improve generalization under varying environmental conditions such as lighting changes and surface textures. The trained model is optimized for embedded deployment and converted into a quantized (int8) format, significantly reducing memory usage and improving inference speed. The optimized model is deployed on the ESP32-CAM module, where it performs real-time image capture and inference. This enables the system to detect water hazards efficiently within the constraints of low-power hardware, ensuring reliable operation in real-world scenarios.

IV. MODULES OF THE PROPOSED SYSTEM

A. Obstacle Detection Module

This module uses three ultrasonic sensors to provide 180° coverage for detecting obstacles in multiple directions. The sensors continuously measure distance using ultrasonic wave reflection, and the Arduino Mega processes this data to identify nearby objects. When an obstacle is detected, the system generates an alert through a buzzer and indicates the direction, enabling safe navigation.

B. AI-Based Water Detection Module

The ESP32-CAM captures real-time images of the environment and processes them using an Edge Impulse FOMO model. This module detects water puddles and slippery surfaces with high accuracy. Upon detection, an alert is generated to prevent accidents, enhancing user safety in challenging environments.

C. Emergency Communication Module

This module integrates a GSM unit with the Arduino Mega to provide emergency support. When the user presses a dedicated button, the system automatically initiates a call or sends a message to predefined contacts, ensuring quick assistance during emergencies.

D. Power Management Module

The system uses a solar panel combined with a charge controller and rechargeable battery for power supply. This en- sures continuous, energy-efficient, and eco-friendly operation, reducing dependency on external charging sources.

E. System Integration Module

This module ensures seamless interaction between all hard- ware and software components. The Arduino Mega coordinates sensor inputs, AI processing outputs, and alert mechanisms, enabling real-time performance and reliable system functionality.

V. SYSTEM WORKFLOW

1) The ultrasonic sensors continuously scan the surround- ings in left, center, and right directions to detect obstacles within a predefined range.
2) The ESP32-CAM captures real-time images of the ground environment and processes them using the Edge Impulse FOMO model for water hazard detection.
3) The Arduino Mega collects and processes data from both ultrasonic sensors and the AI module to determine the presence of obstacles or surface hazards.
4) If an obstacle or water hazard is detected, the system im- mediately triggers a buzzer alert along with a directional indicator to inform the user.
5) In case of an emergency, the user can press the panic button, which activates the GSM module to send alerts or initiate a call to predefined contacts.
6) The solar power system continuously charges the battery and supplies power to ensure uninterrupted operation of all modules.
7) The system operates in real time, ensuring continuous monitoring, quick response, and enhanced safety for the user during navigation.

VI. RESULT AND ANALYSIS

A. AI Model Performance Evaluation

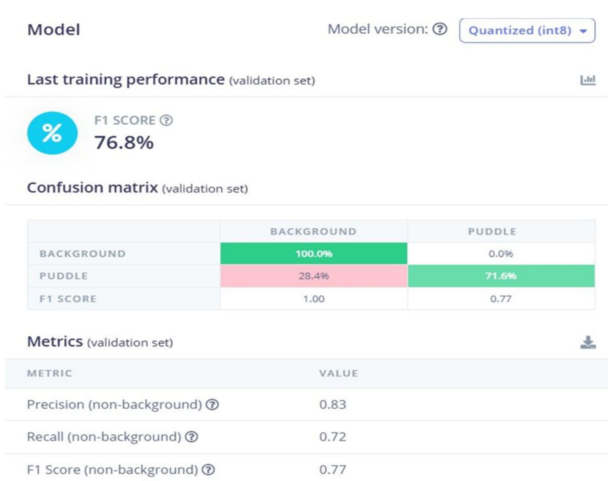

Fig. 3. Model Performance

The performance of the AI-based water hazard detection model is evaluated using standard metrics, including precision, recall, and F1-score. The validation results demonstrate an overall F1-score of 76.8%, indicating effective detection capability for real-time applications. The confusion matrix analysis shows that the model achieves high accuracy in identifying background regions while maintaining satisfactory performance in detecting puddles. The model records a precision of 0.83 and a recall of 0.72 for the non-background (puddle) class, reflecting a balanced trade-off between false positives and missed detections.

The use of the FOMO algorithm, combined with model quantization, ensures computational efficiency suitable for em- bedded deployment. The model performs real-time inference on the ESP32-CAM with low latency and reduced memory usage. Overall, the results confirm that the proposed AI model significantly enhances environmental awareness by detecting hazards that are difficult to identify using conventional sensors, thereby improving user safety and navigation reliability.

B. Prototype Implementation and Hardware Validation

Fig. 4. System Prototype

The developed prototype demonstrates successful integration of all hardware components within a compact and functional enclosure. The system is fabricated using PLA material through 3D printing, ensuring lightweight construction and structural stability. The enclosure effectively houses ultrasonic sensors, ESP32-CAM, and the power unit, with properly aligned openings that support accurate sensing and real-time image capture. The inclusion of a solar panel on the top surface enables continuous power supply, enhancing system reliability during outdoor usage.

Experimental validation confirms that the ultrasonic sensors provide consistent obstacle detection across multiple direc- tions, while the AI module accurately identifies water hazards under varying environmental conditions. The system responds promptly through buzzer alerts and directional indication, ensuring effective user feedback. The integration of hardware and AI modules demonstrates stable real-time performance, validating the system’s suitability as a practical assistive solution for visually impaired individuals.

VII. COMPARATIVE ANALYSIS

A. Benchmarking Against Existing Systems

Current research in assistive navigation tools typically follows two paths: high-complexity systems using Single Board Computers (SBCs) like the Raspberry Pi, or low-cost systems using basic microcontrollers. While Raspberry Pi-based systems (e.g., Paul, Shinde, Kamble) offer high computational power for algorithms like YOLO or facial recognition, they are often characterized by high cost, bulkiness, and significant power consumption. Conversely, simpler Arduino-based sticks lack the intelligent classification required to identify specific hazards like water puddles.

The proposed system adoption of a dual-controller archi- tecture using an Arduino Mega for multi-sensor integration and an ESP32-CAM for dedicated AI inference successfully bridges this gap by providing high-performance hazard recog- nition within a low-power hardware framework. This specific hardware synergy allows the device to maintain sophisticated visual awareness without the typical energy and cost penalties associated with high-end processors.

B. Feature Based Comparison

The following table provides a streamlined comparison of the proposed system against current state-of-the-art works, adjusted to show the relationship between architecture, core features, and practical outcomes.

TABLE I
COMPARISON OF ALGORITHMIC APPROACHES IN ASSISTIVE SYSTEMS

Reference	System Architecture & Features	Research Outcomes
Dipta Paul (2025)	Raspberry Pi with YOLO for object recognition.	High detection capabili- ties but complex hardware and high cost.
V. Shinde (2025)	Raspberry Pi + ESP32 + Camera for lightweight model processing.	Integrated audio/vibration feedback, limited by high processing load.
K. P. Kamble (2024)	Arduino Uno + Raspberry Pi and GPS/GSM.	Comprehensive safety fea- tures, hardware is bulky and complex.
K. Sunil Kumar (2021)	Arduino Mega with 4 Ultrasonic sensors.	Long detection range (450cm) but lacks hazard classification.
Proposed System	Arduino Mega + ESP32-CAM (FOMO AI) with Solar Charging and GSM.	76.8% Water detection ac- curacy, sustainable power, light- dependent.

C. Discussion of Improvements

The proposed system introduces distinct advancements over existing models:

1) Edge AI Efficiency: By utilizing the FOMO (Faster Objects, More Objects) architecture on the ESP32-CAM, the system achieves a classification accuracy of 76.8% for surface hazards. This is more computationally efficient for embedded hardware compared to standard YOLO implementations.
2) Renewable Power Integration: Unlike the surveyed systems which rely solely on rechargeable batteries, this project integrates solar-powered operation. This ensures the device remains functional in outdoor environments without constant dependency on external power sources.
3) Safety Communication: The integration of a GSM emergency module and a 180° multi-directional ultrasonic array provides a safety net that combines obstacle avoidance with rapid response communication. This multi- modal approach addresses the limitations of systems that only provide local audio/vibration alerts.

Through this integration of embedded AI, sensor fusion, and renewable energy, the proposed vision assistant offers a scalable and cost-effective solution for enhancing the independence of visually impaired individuals.

VIII. ACKNOWLEDGMENT

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IX. CONCLUSION

The proposed AI-powered multi-functional vision assistant effectively addresses the critical challenges of safe navigation and environmental awareness for visually impaired individuals. By integrating multi-directional ultrasonic sensing, ESP32-CAM vision, GSM-enabled emergency communication, and a solar-powered energy system, the solution provides a comprehensive assistive tool that significantly enhances user independence and confidence. The system is designed to operate reliably in diverse real world environments, ensuring consistent performance under varying conditions. A fundamental strength of the system lies in its hybrid dual-controller architecture, which creates a strategic division of labor: the Arduino Mega facilitates real- time sensor coordination for immediate obstacle avoidance, while the ESP32-CAM performs edge-based intelligent hazard detection. This specific design achieves an optimal balance between computational efficiency, hardware cost, and real-time performance.

The implementation of the Edge Impulse FOMO model enables the reliable identification of water puddles and slippery surfaces hazards that are notoriously difficult to detect using conventional moisture or ultrasonic sensors alone. Simultaneously, the 180° ultrasonic sensor arrangement provides wide-area spatial coverage, offering proactive alerts that allow for navigational corrections before physical contact occurs. Beyond mobility, the system prioritizes personal safety through a GSM module that enables immediate emergency triggers, while the incorporation of a solar- powered energy system ensures uninterrupted operation and reduces dependency on stationary charging infrastructure.

Experimental evaluations confirm that the device is a lightweight, reliable, and cost-effective alternative to exist- ing assistive technologies, making it particularly suitable for cost-sensitive regions. This research represents a significant advancement in the field by successfully unifying embedded artificial intelligence and renewable energy into a practical, unified solution. Future work will focus on expanding the system's capabilities through advanced object recognition for urban navigation, GPS-based tracking for real-time location sharing, and more intuitive voice-assisted interaction to pro- vide a richer, more descriptive understanding of the user's environment.

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