SightSense: A Smart Haptic Alert Obstacle Detection System for the Visually Impaired

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***Abstract* — SightSense is an innovative wearable shin guard designed to enhance accessibility and safety for visually impaired individuals. The system integrates an ESP32-CAM microcontroller, an ESP32-S3-WROOM microcontroller, ultrasonic sensors, a liquid crystal display (LCD), a laser based optical module with lenses, a diffractive optical element (DOE), a PAM8302 audio amplifier, and a vibration motor driver to provide real-time haptic and auditory feedback. The optical subsystem projects structured light to improve obstacle detection accuracy and depth estimation. The device measures obstacle distance and delivers alerts through vibration and voice prompts, allowing safer guidance in both indoor and outdoor environments. Custom PCBs were developed to optimize portability and functionality. SightSense was tested across various obstacle types to evaluate detection accuracy, response time, and reliability. This project presents a cost-effective assistive solution that meets defined engineering requirements and demonstrates how our overall system will help improve mobility and independence for the visually impaired.**

***Index Terms* — Assistive Technology, ESP32-CAM, ESP32-S3-WROOM, machine learning, obstacle detection, PAM8302 amplifier, ultrasonic sensors, vibration motor, wearable device.**

I. Introduction

The motivation behind this project stems from the daily challenges faced by individuals who suffer from visual impairments and blindness. One of our team members has a family member with a visual impairment and every day for her is a challenge, especially when in different environments. Although tools like the white cane can provide essential assistance, they have their restrictions. While advanced assistive devices do exist, many are very expensive and out of reach for those who need them the most. As technology advances, we have an opportunity to design an innovative device that will address these challenges through an affordable, compact, and user-friendly shin guard for everyday use.

The SightSense system combines both sensor based and optical technologies to enhance obstacle detection and environmental awareness. The device uses two ESP32 microcontrollers, an ESP32-CAM [1] and an ESP32-S3-WROOM, along with two ultrasonic sensors, an LCD screen [2], a PAM8302 audio amplifier [3], and a Vybronics VG0840001D motor [4] to deliver real time feedback. For the optical side of our overall system, we will use a 650nm laser diode [5], two lens, and a diffractive optical element to project and analyze a structured light pattern. This subsystem will improve detection precision by distinguishing between distorted and undistorted light reflections, allowing identification of object shape and distance. Together, these components allow the SightSense to provide reliable and multisensory enabling guidance for indoor and outdoor settings.

Previous research and already commercial devices often rely on single mode feedback or require complex setups and high costs, limiting accessibility for most users. SightSense aims to bridge this gap by incorporating low cost and compact size to fit the shin guard with custom PCBs that will help with making integration easier.

Through iterative design and testing, SightSense provides an overall system that can be applied to improve mobility, safety, and independence for the visually impaired. The remainder of the paper presents the system design, implementation, and evaluation of the SightSense prototype.

II. Engineering Requirements

To ensure successful performance, the team established a set of engineering requirements to ensure that SightSense meets the intended functionality, safety, and reliability standards. The full list of requirements can be found in the detailed project documentation, but the major demonstrable requirements are summarized below.

Table 1 – Major Engineering Requirements

Engineering Requirement	Specification
High detection accuracy for multiple forms of obstacles (i.e., people, walls, trees, curbs, ditches/drop-offs, cones, steps, tables, and chairs).	≥ 90%
Distance of obstacle detection in front of the user should be significant.	≤ 2 meters
Immediate response time between obstacle detection	≤ 250 milliseconds

systems (i.e., structured light and ultrasonic) for real-time alerts.	

The team is working to ensure that each of these requirements is achieved through iterative testing and refinement of both hardware and software components. The final prototype demonstration will focus on validating obstacle detection accuracy, feedback timing, and overall usability in real world environments.

III. SYSTEM CONCEPT

Detailing the concept behind the operation of the SightSense system is essential to understanding its functionality. The device continuously monitors the user's surroundings using both the ultrasonic sensors and optical subsystem to detect obstacles and provide real-time feedback. A system flowchart, shown in Fig. 1, illustrates the major operational stages and decision logic of the device.

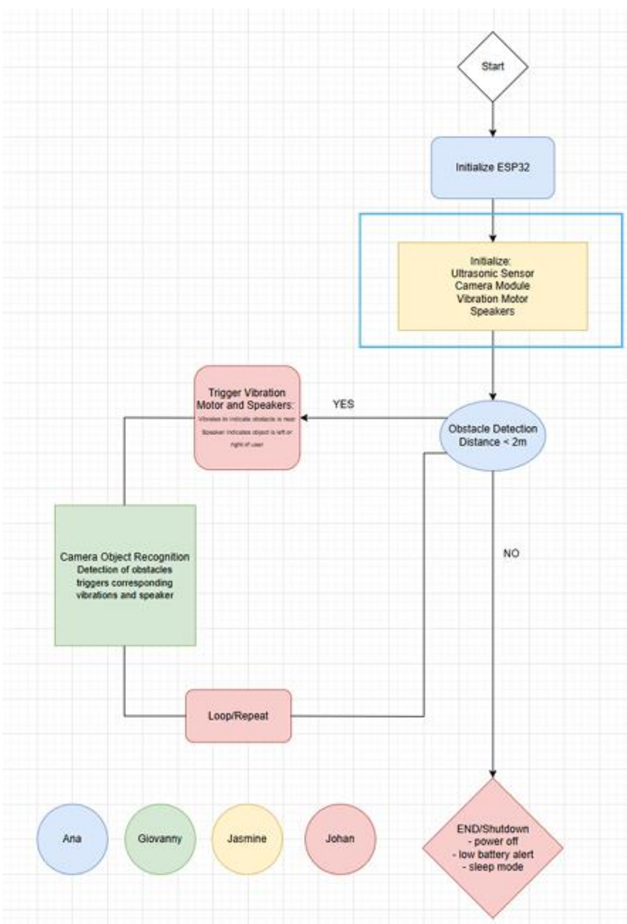

Fig 1. System Flowchart

After system startup, the ESP32-S3 initializes all hardware components, which include the ultrasonic sensors [6], laser module, LCD, and both vibration driver motor and audio amplifier. The system then enters its continuous detection cycle, where the ultrasonic sensors measure the distance of nearby obstacles. The LCD display provides users and developers with real-time system information, such as distance readings, device status, and error indicators during debugging. At the same time, the optical system projects a structured light pattern to improve obstacle shape. If an object is detected within a two-meter range, the device then activates the vibration motor and triggers audio alerts through the speaker. The vibration intensity and audio voice alerts vary based on the obstacle's distance, providing directional guidance to the user.

When no obstacles are detected, the SightSense will automatically enter low power mode or idle state to conserve energy. Power is supplied by a rechargeable lithium-ion battery and distributed through 3.3 V and 5.0 V regulators to ensure stable operation across digital and analog components. The modular system architecture allows each subsystem sensing, processing, power, and feedback to be tested independently. This not only improves reliability but also simplifies troubleshooting during integration. The figure below illustrates the system block diagram, highlighting the signal flow from sensors through the ESP32-S3 units to the haptic, audio, and visual feedback modules.

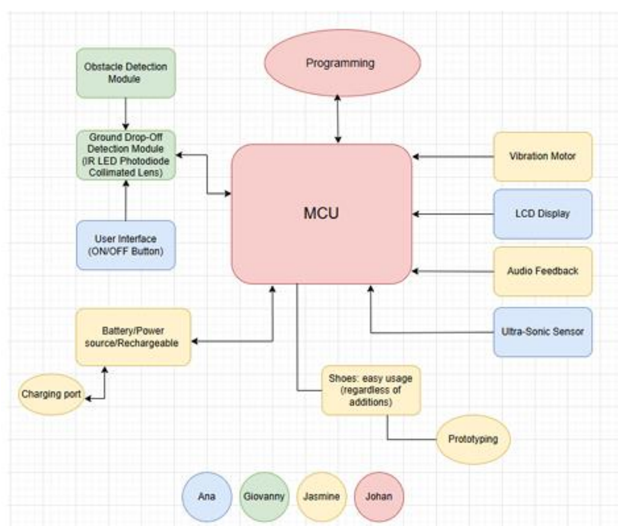

Fig. 2 Hardware Block Diagram

IV. PCB DESIGN & OVERALL SCHEMATIC

To implement the system hardware, multiple PCBs were developed using Fusion 360 Electronics. The design consists of six custom boards: a main interface board, the ESP32-S3-WROOM microcontroller board, a 3.3 V regulator board, a 5.0 V regulator board, an audio amplifier board, and a vibration motor driver board. Each board was designed to perform a specific function and connect through a modular wiring interface, allowing isolated testing and simplified system upgrades.

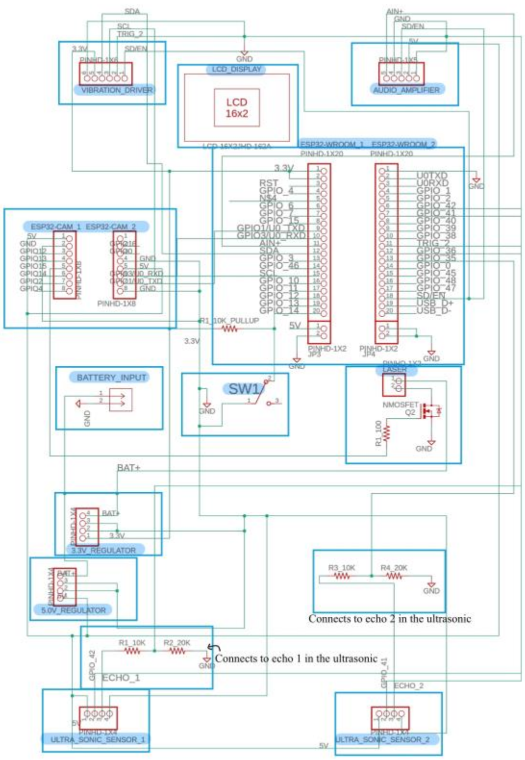

Fig. 3. Overall Schematic

The main board, which is shown in Fig. 3, serves as the central hub, routing power and communication lines between all subsystems. It includes input headers for the ultrasonic sensors, LCD, and speaker, as well as outputs to the haptic driver and battery management circuitry. Careful attention was given to trace routing, ensuring minimal signal interference between high-current and logic-level paths. Ground planes were strategically placed to reduce electromagnetic interference and ensure stable reference voltages for the analog sensors.

The ESP32-S3 board was designed with compactness and heat dissipation in mind, allowing the microcontroller to directly manage both communication and peripheral control. Additionally, protection diodes were implemented on the ESP32-S3 for power input terminals to prevent reverse polarity damage.

The 3.3 V and 5.0 V regulator boards provide isolated and filtered power rails to their respective components. These boards employ low dropout voltage regulators (LDOs) for efficiency and stability under varying loads.

For signal amplification, the audio amplifier board houses a PAM8302A-based Class D amplifier that drives the PUI AS02708CO-WR-R speaker. Decoupling capacitors were added close to the amplifier's power pins to reduce ripple and prevent audible noise artifacts.

The vibration driver board uses a SparkFun DRV2605L haptic driver paired with a Vybronics VG0840001D vibration motor, chosen for its low startup current and compact size. The board includes a MOSFET-based current control circuit to ensure stable operation and protect the driver from overload conditions.

Throughout the design process, schematic capture and electrical rule checks were performed repeatedly to minimize errors before fabrication. Each schematic includes labeled test points for verification and debugging. Post-fabrication validation involved continuity testing, voltage measurements, and oscilloscope verification of regulator output stability. This modular PCB approach improved fault isolation and allowed each circuit to be validated individually before full system assembly.

The complete hardware design provides a robust foundation for integrating sensing, processing, and feedback in a compact, wearable system.

V. POWER

Table 2 – System Hardware Power Requirements

Component	Voltage Requirement	Current Requirement
Battery	Supply None: Delivers 3.7V	1-2A
3.3V Regulator	3.7V	1.2A
5.0V Regulator	3.7V	1.8A
Ultrasonic Sensors: Right and Left	5V	15mA
LCD	5V	15-30mA
Laser	3.3V	25mA max current draw
ESP32-CAM	5V	~500mA
ESP32-S3-WROOM	3.3V	~500mA
Vibration Driver	3.3V	70-90mA
Vibration Motor	3.3V	90mA
Audio Amplifier	5V	Low current draw: 4ma quiescent and

		1uA in shutdown mode
Speaker	5V	-

Power for the SightSense system is supplied by a 3.7V 2500mAh rechargeable lithium-ion battery. The PCB includes a connector that connects directly to the battery pack, allowing the system to deliver power through the voltage regulators. These regulators convert the input voltage to both 3.3V and 5.0V, which will power the ESP32-S3-WROOM, ESP32-CAM, ultrasonic sensors, PAM8302 audio amplifier, LCD display, and vibration driver motor. The regulated outputs ensure stable operation. The table above, (Table. 2), shows the required voltage and current supplies for each of our components. Overall, the power consumption must operate continuously while remaining lightweight and portable.

VI. Object Detection Concept & Design

The optical system integrated into the Sight Sense project uses a structure light sensing system where an optical pattern is projected, and distortion is measured to detect different forms of obstacles. A baseline measurement is taken from the projector unit to the camera sensor unit which will allow for a depth mapping of the obstacles detected. This data will be processed on chip to get a "real time" response to the main MCU to alert the user and give directional output by speaker and vibration pattern. The system employs a 650 nm laser with output from 200MW to 250MW, collimating optics, and a diffractive optical element to project a light pattern on the environment. For the camera unit used, an optical band pass filter will be used to pass 650nm wavelength only. The band pass filter will allow the camera to identify deformations more easily in the projected pattern and infer depth information as well as spatial location of the obstacle within the user's path.

1) Optical Design Overview

The optical setup consists of two main subsystems, which are the projection module and the imaging module. The projection module includes a 650nm laser diode module, two lenses for collimation which are 6mm and 68mm focal lengths, and a diffractive optical element. The imaging system consists of an ESP32-CAM with a wide field of view camera lens and a 650 nm band pass filter. The band pass filter will make the pattern more visible to the camera, and the field of view must be fixed with the pattern visible to be able to get a depth mapping for triangulation calculation.

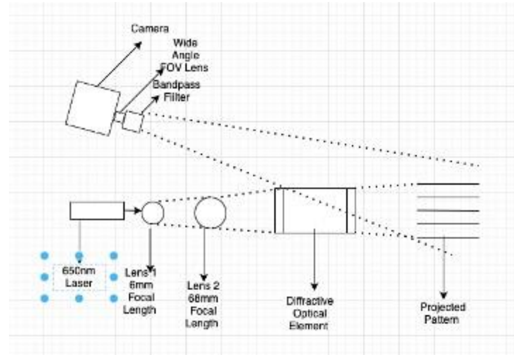

Fig. 4 The figure above gives a schematic view of the optical setup.

2) Projection Subsystem

The projection subsystem begins with a laser diode module that emits at 650 nm. To collimate and expand the beam we will be designing a two-lens system.

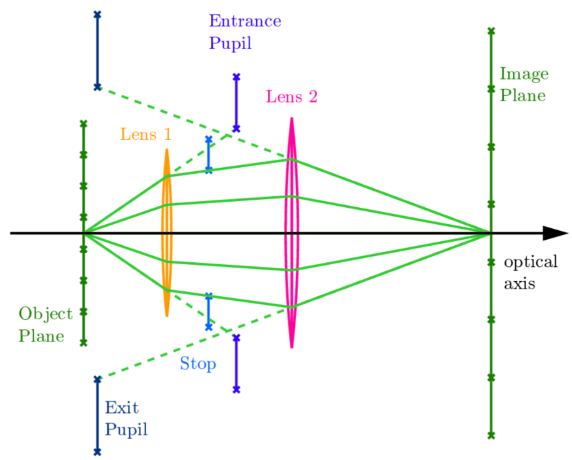

Fig. 5 Shows diagram of rays passing through two-lens system. [7]

The beam emitted from the laser passes sequentially through a first lens with a 6mm focal length to initially expand and collimate the beam and then a second lens with a 68mm focal length create a diameter that will fully illuminate the diffractive optical element's (DOE) input aperture. The equations used to verify these focal lengths are derived from two equations used in two-lens systems are shown below:

$$\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{f}$$

$$-\frac{s_1}{s_2} = M$$

Where s_1 and s_2 are the distances from the object to the lens and from the lens to the image plane. The magnification of the lens system is 11.33. Our DOE has dimensions of 10cm x 10cm. The measured expanded beam diameter can be calculated by multiplying our 9mm beam diameter with the system magnification of 11.33 which gives 10.2cm diameter, comfortably illuminating the DOE. Once the beam passes through the DOE a 7 horizontal line pattern is projected across the projected surface.

The projected pattern gives a balance between uniformity and contrast to be more visible to the camera module under various lighting conditions. The projected pattern covers an approximate area of 1 ft x 1.5 ft at 2 meters distance from the user, sufficient for short range obstacle detection.

3) Imaging subsystem

The imaging system used is based around the OV2640 camera unit, that is integrated onto an ESP32-CAM MCU. A wide-angle lens gives a field of view of 120°, which enables the camera to capture both near and far portions of the projected pattern. A 650nm band-pass filter is mounted in front of the lens to block out ambient light and isolate the structured light pattern from the environment, which will improve signal to noise ratio in the daylight settings.

The optical axis of the camera unit will be positioned slightly above and parallel to the projection axis from the laser. This will create a baseline necessary for depth detection. With the known fixed position of the baseline geometry, triangulation calculations can be done without the need for two cameras.

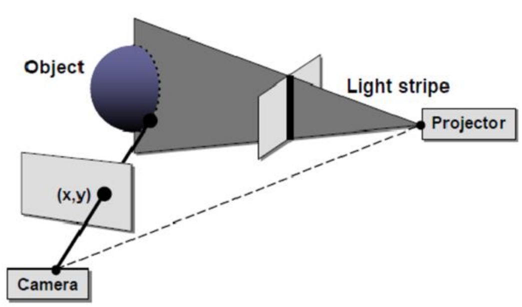

Fig. 6 Shows layout for triangulation in single camera system. [8]

4) System Applications

This optical design shows robust obstacle detection for the visually impaired. The structured light approach will help with depth perception and areas with poor lighting. By detecting distortion, the system will accurately detect objects and let the user know through immediate haptic feedback. This compact low power system will offer a non-intrusive alternative to lidar and stereo vision systems.

VII. SHIN GUARD DESIGN

The wearable obstacle detection system SightSense was developed as a shin mounted platform to provide real time spatial awareness for visually impaired users without obstructing movement. The shin guard design enables a combination stability, sensor spacing and alignment, and user comfort. By mounting the system on the lower leg, the optical projection path remains parallel to the walking direction. This enables depth mapping along the user's path along for detecting sudden drop offs or "ditches". The ultrasonic sensor will successfully detect objects directly in front of the user, successfully demonstrating sensor fusion. The mechanical housing of the system was designed to be lightweight, low power, and ergonomically secure. The housing box was modeled using CAD software and will be later 3D printed using PLA material to minimize weight while maintaining structural stability. A lightweight design is key to not fatigue the user or impede walking gait. The shin guard integrates several functioning subsystems which include the optical sensing module, ultrasonic sensors, processors, and battery. The upper part of the design houses the camera which will be tilted downward as well as the projector subsystem. Depth information of the path directly in front of user will be taken. Dual ultrasonic sensors are positioned laterally to extend obstacle detection beyond the structured light systems field of view. These sensors increase redundancy and capture low texture obstacles that might not be able to be captured by optical methods. The housing must hold multiple PCB designs incorporating the ESP-S3-WROOM and ESP32-CAM wireless data processing and communication, with power supplied by compact lithium-ion battery. Adjustable elastic straps enable the device to fit securely on users of various leg sizes while maintaining consistent optical alignment. The shin guard design achieves a low profile and efficient integration optical and electronic components with a wearable final user-friendly design in mind. This allows for hands free operation with real time obstacle detection with directional haptic feedback, making it a practical solution for assisting mobility in the visually impaired.

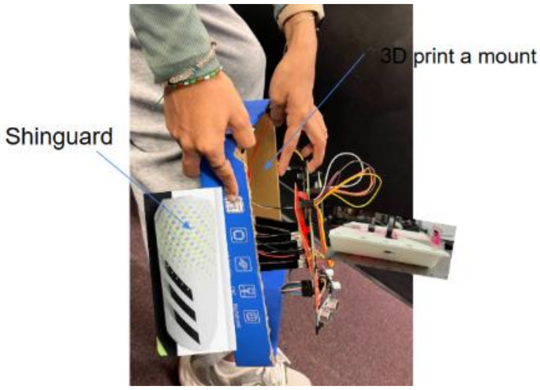

Fig. 7. SightSense Design

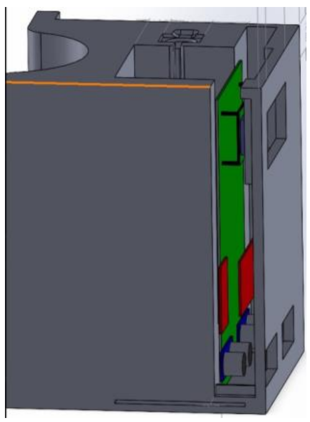

Fig. 8. SightSense CAD Prototype

VIII. SOFTWARE DESIGN VIA ESP32-CAM AND EDGE IMPULSE

This project runs on an ESP32-S3-WROOM that will control most of the components on the electrical side and an ESP32-CAM that uses an Edge Impulse (EI) model to find distortions in a projected line grid for the optical subsystem.

A. Compute & Tasks (ESP32-CAM).

We use the ESP32-CAM with the OV2640 sensor and PSRAM, capturing 160×120 grayscale (QQVGA) images. The system cycles through four tasks: a camera task captures each frame and scales/normalizes it. An EI inference task runs the model on that frame. An event/alert task confirms real detections. And a telemetry task prints simple status lines over USB/serial (UART) so we can monitor the device in a terminal. Tasks run on a steady schedule, and simple inter-task signals ensure they don't interfere with each other when sharing data.

B. Vision / ML (Edge Impulse)

The EI pipeline takes the image through EI preprocessing (Edge Impulse is an embedded machine-learning platform for training and deploying tiny models to microcontrollers), then a small Convolutional Neural Network (a compact convolutional neural network. A ML model specialized for images), and finally a FOMO-style head (Edge Impulse's "Faster Objects, More Objects," is a lightweight detector that highlights which grid cells likely contain an object/distortion rather than computing full bounding boxes. This is ideal for low-power devices that marks which small cells in the image look like a distortion. Only the distorted spots are labeled during training, so everything else is learned as background. To increase the model's versatility, we collected and trained images across varied lighting and environmental conditions. This includes bright outdoor areas, dim indoor areas, and reflective flooring so glare doesn't cause false positives. After the model runs, we smooth results by requiring the detection to persist for N frames in a row, and if several nearby cells fire together, we merge them into one detection.

C. Camera, Memory, and Speed.

The small frame size keeps things fast: a QQVGA grayscale frame is about 19 kB and easy to handle. Frames and the model reside in PSRAM, while tight inner loops keep small pieces in faster internal RAM. Our speed target is 15–20 frames per second and at most 200 ms from camera to model to alert. If processing gets slower than this, we first reduce the EI input size (96×96) before changing the model itself.

D. Alerts, Data, and Safety.

Over UART we print periodic status lines, showing uptime, FPS, and average confidence, and detection event lines whenever a detection occurs, including the timestamp, their (x,y) cell positions, and average confidence. No images are stored or transmitted; only simple numeric summaries are used. Configuration writings are range-checked, and output intensities are clamped for safety.

E. Calibration & Testing.

We perform a one-time checkerboard procedure to learn a clean "map" of the grid for quality checks. On each boot, a short (~1s) auto-baseline recenters brightness assumptions for the current lighting, and a small gain setting is stored in non-volatile memory, so it persists across reboots. To quantify generalization, the dataset is partitioned 80/20 into training and validation sets within Edge Impulse. The split is balanced by various scenes and lighting conditions to preserve the ratio of distortion vs. non-distortions across environments. Only the training 80% is used to update model weights. The testing 20% is used for creating quantifiable accuracy, checkpoint selection, and model/training choices. No frames from the validation set are used for augmentation or threshold tuning, ensuring an unbiased estimate of performance prior to on-device testing.

F. Application Design.

The system is designed for stand-alone operation. No mobile or desktop application is required to achieve full functionality. For configuration, status monitoring, and log collection, the device exposes a USB/serial (UART) console that is compatible with standard terminal programs (Arduino Serial Monitor). At startup, the console presents a concise status header and thereafter emits periodic status summaries and event records in a line-oriented, CSV-friendly format to facilitate real-time observation and post testing analysis. This console-based approach minimizes integration overhead, enables platform-agnostic use across Windows/macOS/Linux, and supports dependable field work where wireless links may be unreliable or unavailable.

G. Operator Console (UART).

The console shows simple status lines every 1–2 seconds reporting FPS, and recent confidence. On each detection, it prints a single detection even line with the time and the cell coordinates where the distortion was seen.

H. How It Runs (Data Flow).

When powered, the device immediately starts capturing frames and running the EI model. If a distortion is confirmed, the device vibrates and beeps and prints a detection event line, while status lines continue so you can see it's alive and how fast it is running.

I. Testing in the Lab.

We adopt an iterative collect, validate, and deploy workflow spanning Edge Impulse and the ESP32-CAM. Using Edge Impulse's phone to web upload, we first acquire short sequences of the projected grid under diverse conditions: bright and dim interiors, matte and glossy floors, and with/without obstacles. In Edge Impulse Studio, we perform Live Classification on the phone to verify that model activations occur only when true grid distortions are present. When false positives arose, we immediately supplement the dataset with targeted "hard negatives" from that scene, retrain, and re-evaluate until the false positives are suppressed.

Once phone-based validation is satisfactory, we deploy the model as an Arduino library from Edge Impulse, integrate it into the ESP32-CAM firmware, and flash the device. On-device evaluation focuses on two outcomes: (1) timely, consistent alerts when obstacles disrupt the grid; and (2) stable behaviors in the absence of obstacles, even under challenging lightning and environments. Any missed, delayed, or false alerts trigger a targeted data capture of the offending scenario, followed by rapid retraining and redeployment. This continuous loop, collect, phone validate, retrain, deploy, and device validate loop continues until performance is stable across the expected operating environments.

IX. Software Design and integration via ESP32-S3-WROOM

The ESP32-S3-WROOM software design is responsible for processing distance measurements, generating feedback, and updating the display in real time. The program continuously reads input from two ultrasonic sensors positioned on the left and right sides of the main board. Having both sensors will help in determining the proximity and direction of nearby obstacles. Based on the defined distance range and when an obstacle comes in contact with the user, the microcontroller activates both the vibration motor and the audio feedback module. The vibration intensity and the audio alerts will correspond to the obstacle's position, providing directional awareness for the user. Simultaneously, the LCD screen displays the left and right distance readings. When the obstacle is close to the user the audio alert will let the user know when to turn left or right as well as let the user also know when an obstacle is detected a certain distance away. When an object is getting closer the vibration motor will also go off, this will allow individuals who have a hard time hearing as well to feel the vibration and help them guide them around obstacles. This coordinated operation allows the SightSense to deliver intuitive real-time feedback, enhancing special awareness and guidance to safety for the visually impaired.

Future updates to the software will include adding and idle state to the device when a user is inactive for more than five-ten minutes, optimized timing control, and fix the interrupts of the ultrasonic sensors to allow the readings to reduce latency and ensure smoother performance. These improvements will further enhance the reliability and responsiveness of the SightSense final prototype.

X. CONCLUSION

The development of the SightSense wearable system successfully demonstrated an effective, low-cost solution to enhance obstacle detection and guidance for visually impaired individuals. By integrating all our components into one final prototype the device achieved reliable real time guidance in both indoor and outdoor environments. Testing confirmed that the SightSense prototype met its key engineering requirements for detection accuracy, response time, and usability.

Looking ahead, future improvements will focus on refining the optical subsystem for higher precision by training the machine learning algorithms for more environmental classification of objects. Through continued development, the SightSense project demonstrates how the overall device can be applied to create accessible and affordable solutions that will assist the visually impaired.

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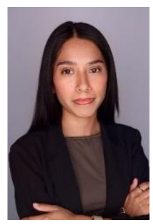
BIOGRAPHY



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