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

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EEL4915 – Senior Design 2
Group 5

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# Chapter 1 Executive Summary

The Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) project is an innovative wearable shin guard designed to enhance the accessibility, safety, and independence of individuals who are visually impaired or blind. In order to offer real-time environmental awareness and obstacle detection, this smart shin guard combines several sensor systems, two microprocessors, haptic feedback via a vibration motor and audio alerts via a speaker, and wireless communication technologies into a durable and user-friendly design.

The need for this device stems from the daily challenges faced by individuals who suffer from a visual impairment. One of our team members has a family member with a visual impairment and every day for her is a challenge, especially to navigate in different environments. Although tools like the white cane can provide essential assistance, they have their restrictions. In today's rapidly evolving world of technology there is a strong opportunity to create something more effective. While advanced assistive devices do exist, many are very expensive and out of reach for those who need them the most. Our goal is to design a solution that is not only innovative and functional but also affordable and accessible to the visually impaired community.

With the SightSense shin guard, it will include multiple hardware components such as two microcontrollers which will be the ESP32-CAM for images and to send messages to the ESP32-S3-WROOM-1 for data processing and control, 3D light structure that will map a grid out of the environment detected, haptic motors for directional vibration feedback, ultrasonic sensors to measure distance when an obstacle is detected, and audio feedback to alert the user also when an obstacle is detected by giving direction movement. This system will be powered by a 3.7V rechargeable battery, and with the camera module that comes with the ESP32-CAM, it will provide image processing that will work with lasers and the 3D structure to detect the environment for distortions. We will also include an LCD screen display that will show distance readings to make sure that the ultrasonic sensors are working. All these features will be able to detect up to two meters of range and will work with a 90% accuracy to ensure the safety of the user. Furthermore, the shin guard's durable and modular design is further enhanced by including a custom PCB board for power management as well as making wiring less and easier to implement.

A comprehensive review of existing products along with user feedback helped shape our design process. This research was very important as this guided us to establish different types of achievable goals to ensure that accurate obstacle detection and dependable feedback systems were in place. Measurable performance objectives, including detection range, battery life, response time, and overall durability were outlined in a detailed engineering specification table. This table will be used at the end to make sure that we met our goals and that the final design worked as intended during final testing. The team also developed block diagrams that show our task distribution, and status for both hardware and software design steps. All the main components and systems are then combined into a prototype that will create the SightSense wearable shin guard.

In summary, the Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) shin guard project shows a great dedication to practical problem solving. Our approach offers a clear path to the development of a fully functional prototype for our final product that will also balance innovation, cost, and make it user centered.

# Chapter 2 Project Description

In this chapter, we will discuss the Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) shin guard project. This smart shin guard is designed to assist individuals with visual impairments by identifying obstacles and giving turn left turn right directions. This will make navigation more secure. We will discuss the project's background, objectives, and features. In addition to system requirements, important engineering parameters and detailed hardware and software designs are provided. This chapter will also highlight the proposed prototype of how our final shin guard will look.

## 2.1 Project Background and Motivation

Navigating daily life independently can present considerable challenges for people who are blind or visually impaired individuals. Traditional white canes provide tactile feedback, meaning they allow users to detect obstacles by touching them. While the white cane can be helpful and is a standard tool for navigation, it limits the user to only sense what is in front of them. This can lead to accidents with changes in the ground or dangerous conditions like busy streets. In a rapidly increasing world with advanced technologies, we have an opportunity to rethink and improve this important mobility device through wearable innovations.

The goal of the Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) is to move beyond the limitations of the traditional white cane by introducing a smart shin guard designed for enhanced safety, guidance, and user independence. SightSense offers a wearable solution that has essential features like obstacle detection, vibration and audio haptic feedback, and a rechargeable battery, making it suitable for everyday use.

According to the World Health Organization, approximately 2.2 billion people worldwide experience vision impairment or blindness [1] . Many individuals could benefit from assistive devices designed for modern needs. Individuals with blindness and visual impairments of all ages who aspire for greater independence and enhanced safety on their daily travels will be among our target audience.

Real-world experiences and user feedback reveal the drawbacks of the conventional mobility aids which inspired this project. Users express that they need better obstacle awareness, more information about their surroundings, and guidance tools that do not interfere with the ease of comfort. This project also carries personal significance. A close relative of one of our team members has a visual impairment and uses a traditional white cane to get around daily. Seeing the difficulties she encounters, especially in new or crowded settings, stressed the flaws of the cane and inspired our commitment to this project. The Smart Haptic Alert Obstacle Detection System for the Visually Impaired shin guard aims to close those gaps and provide improved independence, safety, and guidance by combining modern technologies into a wearable alternative aid.

## 2.2 Goals and Objectives

The primary goal of the SightSense shin guard project is to create a wearable assistive shin guard that will improve mobility and obstacle awareness. The team has established goals that will adhere to the SMART acronym, Specific, Measurable, Achievable, Relevant, and Time Bound, this will guarantee significant development as well as place a strong emphasis on timelines, performance standards, and well-defined targets for both hardware and software.

### 2.2.1 Goals

The Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) shin guard project will aim to overcome the challenges that the cane faces by incorporating emerging technologies to enhance user awareness, safety, and independence into a wearable shin guard.

Shown in Table 1 are the following goals that are organized into three tiers, basic, advanced, and stretch. Each level builds on the previous, leading to a final prototype of the SightSense shin guard, that not only satisfies practical needs but also demonstrates the potential of technology-driven mobility solutions.

Table 1: Project Goals Overview for the SightSense Shin Guard

| Goal Type | Description |
|---|---|
| **Basic** | • Design a smart shin guard system that detects obstacles within a 2-meter range with 90% accuracy.<br>• Operating continuously for a minimum of 6 hours on a single charge using a rechargeable battery that will guide visually impaired users.<br>• Implement one 3D light structure sensor and two ultrasonic sensors to enable multi-directional detection, providing real time guidance alerts with ≤250ms latency to the user.<br>• Develop the SightSense system as a strap on attachment that houses all core components, allowing users to easily wear it within 30 seconds. |
| **Advanced** | • Enhance the user experience by incorporating a forward-facing camera module capable of capturing real time environment mapping and identifying at least four object categories (wall, ditch, person, and tree, table, and chair) using lightweight materials.<br>• Implement haptic feedback using a vibrational motor and a speaker, providing directional alerts with a 250ms delay, allowing visually impaired users to receive clear guidance alerts in real time.<br>• Incorporate a voice guidance system that delivers clear, spoken alert instructions (e.g., Turn left, right, Obstacle detected) using audio output, with latency under <1 second.<br>• Optimize system performance for both indoor and outdoor use by calibrating sensors and audio output to adapt to different lighting |

| | |
|---|---|
| | and ambient noise levels (up to 60dB), ensuring consistent detection for indoor, outdoor, and low light with background noise. |
| **Stretch** | • Expand shin guard accessibility by supporting voice feedback in at least two languages (English and Spanish), with a language selection menu available through an app.<br>• Implement fall detection using an accelerometer, with the system triggering emergency alerts via Bluetooth or SMS within 10 seconds of detecting a fall.<br>• Integrate GPS based navigation support using a GPS module, enabling users to navigate to five saved destinations with the user's preference, with audio guidance and <5-meter location accuracy.<br>• Design and implement an SOS alert feature activated by a double tap pressure sensor within the insole, to allow visually impaired users to quickly signal for help by sending their location to an emergency contact in <15 seconds. |

A successful design of the SightSense shin guard will result in a fully working prototype that detects obstacles within a 2-meter range and notifies the user in real time with less than 250 milliseconds of latency. The final prototype will operate continuously for 6 to 10 hours on a single charge. Key success criteria include reliable performance by doing multiple tests, ease of use and comfort by completing guidance tasks, and measurable improvement in avoiding obstacles over walking without assistance. Overall project success will be measured by these specifications and completing prototype testing by the end of the development timeline.

### 2.2.2 Objectives

The objective of the A Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) shin guard aims to provide functional and user-friendly mobility assistance for those with visual impairments.

The system's main function from the basic level will be to use two ultrasonic sensors to measure and detect obstacles within a 2-meter range. An LCD screen to display distance measured to make sure that the ultrasonic sensors are working properly. This will help identify the object's detected distance and provide real time feedback in the form of vibration and audio alerts within 250 milliseconds of detection. We will also use a structured light system to detect obstacles in a frame. The shin guard also needs to run continuously for six to ten hours to support daily use from the rechargeable battery powered in a single use. System performance will be evaluated through indoor and outdoor testing. The device will be designed as a strap on module that can be put on or taken off, of various shin guard kinds in less than 30 seconds, making it easy to use every day without requiring the user to change their footwear.

For the advanced level, the shin guard's enhanced capabilities will include a speaker and vibrational motors that will both provide multidirectional haptic feedback. Voice guidance will also be implemented, allowing the system to provide spoken commands like "Turn left” or “Obstacle ahead” with less than one second delay allowing users to receive clear navigation information. The system will also be adjusted to work well indoors, outdoors, and at low light levels, with ambient noise levels of up to 60dB, to guarantee dependable use in a range of settings. The system will also be able to differentiate between at least four obstacles, wall, person, tree, and ditch/pothole with at least 90% or higher detection. This will be possible because the camera module will enable object detection showing the distortion versus undistorted. All hardware will be enclosed in a water-resistant box.

As part of the stretch objectives, if time permits, the team will want to expand the shin guard safety and accessibility features. These include an accelerometer for detection of fall. If a fall is detected, an emergency GPS alert will trigger within 10 seconds. Another feature we want to incorporate is a GPS navigation system that will allow the user to pre-define five destinations using audio-based directions. In addition, a double tap pressure sensor built into the insole will trigger the SOS alarm system, which is an extra safety feature that enables users to call for help in an emergency. Additionally, the system will offer voice feedback in at least two languages (English and Spanish), with the ability to select a language through a mobile app. These features are explained more in section 2.8 Prototype Illustration.

Below are a few figures showing the components of the optical design aspect of the project. Included are the laser module, a collimating lens, and a diffractive optical element.

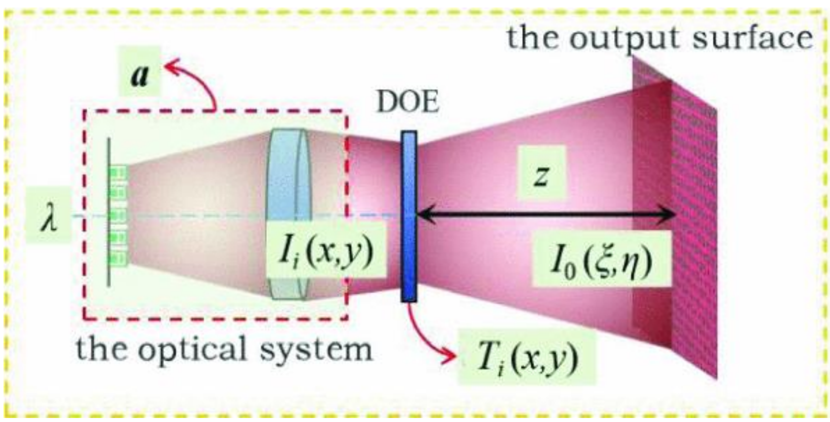



Figure 1: Shows optical system used by SightSense project

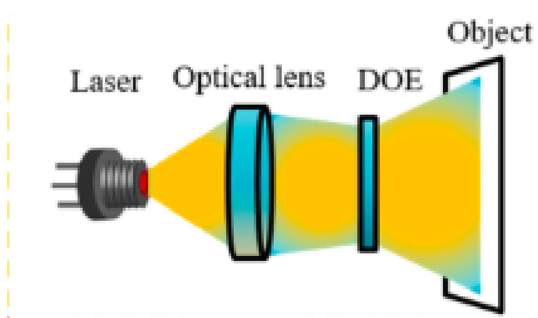
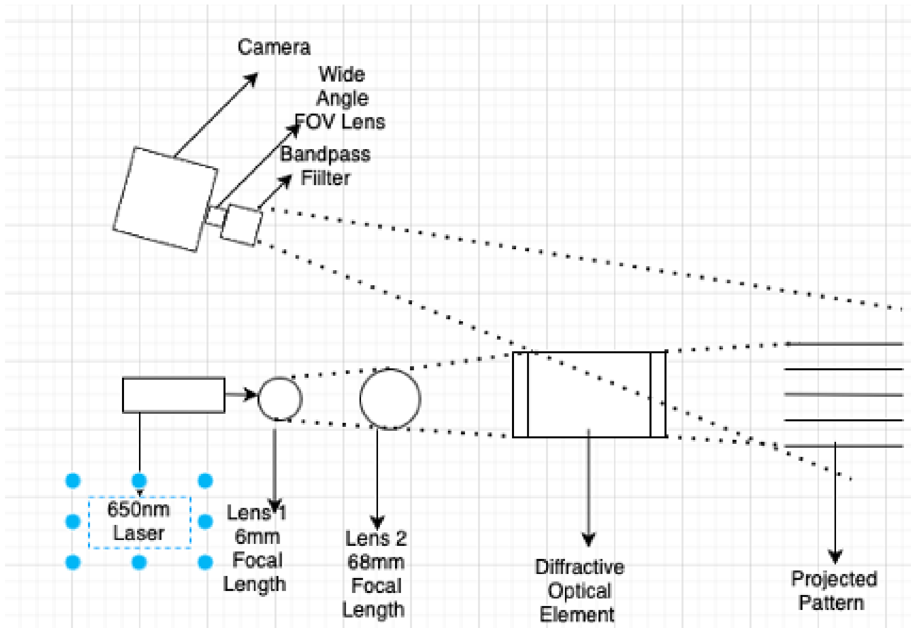



Figure 2: Another illustration of laser diode module, collimating lens, and DOE.

An overview of the structured light system that will be used in the final design of the SightSense is presented in the figure below. The system includes the projector that is explained in the prior figures, while also including the camera module that will be used to capture the images needed to calculate the distortion of the projected pattern.



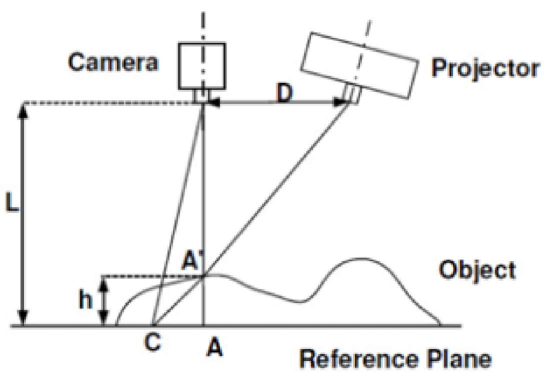




Figure 3: Structured light system that is used with projector, camera, and the baseline used for depth mapping

## 2.3 Features and Functionality of Final Product

The features of our SightSense system are its wearable and compact design, a fusion of a structured light projection system and ultrasonic sensor for reliable obstacle detection, onboard processing, low power consumption, and environmentally robust use in ambient and low light settings. The system will be small enough in design to mount on a shin guard and allow for hands free operation. The final design will enable a comfortable, low profile, and unobtrusive ease of use in everyday life. The user to test the final product will be visually impaired, so ease of use is very important for the final product. The structured light projection system will enable reliable obstacle detection through pattern distortion measurements. This distortion will enable a depth mapping as well as the shape of the object or obstacle. Any distortion in the stripe pattern will be observed and the signal will be given that an object is in the way of the user. When the path is clear, we will not have any distortion pattern. An ultrasonic sensor system will also be implemented in the design. Distance will be detected using time of flight of an ultrasonic source. This is another sensor for the SightSense that will detect obstacles and objects in the path of the user. The combination of different sensors will allow for overlap in detection zones, which ultimately lead to the same goal of reliable obstacle detection for the user. There will be onboard processing done using the microcontroller for the system, which will be done on an ESP32-CAM. The SightSense system will be able to have low power consumption as a feature as well. All the components used are optimized for low current, low power, and an all-day use. This is important in case the user of the product needs to use the SightSense all day. This project needs to be environmentally robust in the way that it can be used and operated indoors and outdoors. The laser projection pattern will be visible in all light settings, which include both ambient and low light.

The SightSense functionalities include obstacle detection in real time, 3D depth estimation from the ground level, enhanced spatial awareness for visually impaired users, hands free and passive operation, and haptic feedback. The key function of the SightSense will detect objects and elevation changes such as curbs, and potholes. Through this object detection, trips, falls, and collisions will be avoided by the user. 3D depth estimation through the structured light system will be available from the ground level. Object distance will be calculated from deformations of the projected stripe patterns on the object. This will work on textured and nontextured surfaces. The use of our SightSense project will enhance spatial awareness for the visually impaired. This project is intended to supplement the use of a cane or other mobility aids used by visually impaired individuals. This device will also be hands free and used passively by the user. This project should be able to be used with no user interaction and fully automated once the system is turned on and engaged. The use of haptic feedback will warn the user of an obstacle. This can be done through a speaker giving instructions or a series of buzzers and beeps. The use of the ultrasonic sensor will give distance detection for obstacles and inform the user of changes in the distances of obstacles.

## 2.4 Existing Products / Past Projects /Prior Work

In researching for our SightSense project, we did not find anything like this but did find similar products that involve using shoes. Several existing smart shoe products and wearable mobility aids were analyzed to guide the design process. These prior efforts illustrate the potential and limitations of integrating sensing and feedback technology directly into footwear to assist the visually impaired.

One notable example is the Le Chal smart shoe, developed in India [2]. This product embeds vibration motors in the shoe soles, which respond to GPS navigation directions and obstacle proximity. The shoe is paired with a smartphone app, allowing users to set destinations and receive turn-by-turn haptic cues. While the Le Chal shoe demonstrates the viability of combining location-based services with wearable feedback, its reliance on GPS alone limits its effectiveness for real-time obstacle avoidance in dynamic environments.

Another example is the Shoe Integrated Navigation System (SINS), a prototype system developed for real-time guidance [3]. This design uses ultrasonic sensors mounted at the front of the shoe to detect nearby obstacles and trigger vibration feedback at varying intensities based on proximity. The sensors detect obstacles within a range of 0.5 to 2 meters, while microcontrollers process input and control the vibration patterns. The system is effective for low-level obstacle avoidance but lacks extended features like object classification or indoor mapping.

Research presented in a 2023 review by Joseph et al. in Sensors outlines several additional smart shoe prototypes [4]. These systems typically integrate low-power microcontrollers (e.g., NodeMCU or ESP32), ultrasonic or infrared sensors, and vibration motors. In some designs, sensors are placed on the toe or sides of the shoe to increase coverage for ground-level hazards, curbs, or stairs. Feedback is delivered either through vibration actuators in the insole or via wireless connection to a smartphone. A few models even incorporate piezoelectric energy harvesters that generate power from foot movement to extend battery life.

Some smart shoe systems go beyond obstacle detection. For example, a prototype cited in the review includes moisture sensors to detect wet or slippery surfaces, while another tracks foot pressure distribution to detect falls. Although most of these systems remain in prototype stages, they highlight the growing interest in wearable assistive technology as a supplement or enhancement to the traditional white cane.

These existing products and research studies provide a strong foundation for the SightSense project. Our smart shin guard aims to combine the strengths of previous designs such as reliable low level obstacle detection and intuitive haptic feedback while addressing their limitations. Key goals include extending sensing range, improving environmental adaptability (e.g., operation in bright light or wet conditions), increasing power efficiency, and ensuring comfort and ease of use in everyday wear.

## 2.5 Engineering Specifications Table

This project requires the design and realization of SightSense, which will detect obstacles and give real time feedback for blind/visually impaired people. For this project to be successful, certain specifications will need to be met. These can be found on the table below.

Table 2: Requirement Specifications for the Final Product

| **Engineering Requirement** | **Specification** |
|---|---|
| Accuracy of detection of multiple forms of obstacles (i.e., people, walls, bushes, benches, ditches or drop-offs, steps) must be reliable. | >90% |
| Range of the distance of obstacle detection in front of the user should be significant. | Up to 2 meters |
| Detection response time between sensors (i.e., structured light, ultrasonic) and MCU for user notification should be fast. | < 250milliseconds |

| | |
|---|---|
| Battery life for user should last a certain amount of time. | 6-10 hours |
| Device needs to be able to run on a low power battery source. | 5 V |
| Device needs to be wearable and light weight. | < 8 lbs |

## 2.6 Hardware Block Diagram

The diagram below outlines the design and functional flow of the obstacle detection system for visually impaired users, with individual responsibilities color-coded by each team member. At the core of our system is the Microcontroller Unit (MCU), which interacts with all major modules and components. The programming of the MCU is handled by Ana (blue), ensuring that data from input devices like the Ultrasonic Sensor and Obstacle Detection Module are processed efficiently. Ana (blue) is responsible for the User Interface, including an LCD Display and the ultrasonic sensors. Giovanny (green) oversees the obstacle detection done by the structured light system where a laser emitter sends a beam through an expansion lens, then collimating lens and finally diffractive optical element where a camera with a 650nm band pass filter identifies ground-level hazards. Jasmine (yellow) handles the power system, including the Battery/Rechargeable power source and the Vibration Motor, as well as ensuring the system can be recharged via a Charging Port. She also manages the Audio Feedback component. The team jointly contributes to the prototyping phase and focuses on maintaining shin guard usability regardless of the integrated modules. Together, this system enhances situational awareness for users through multiple sensory feedback mechanisms.

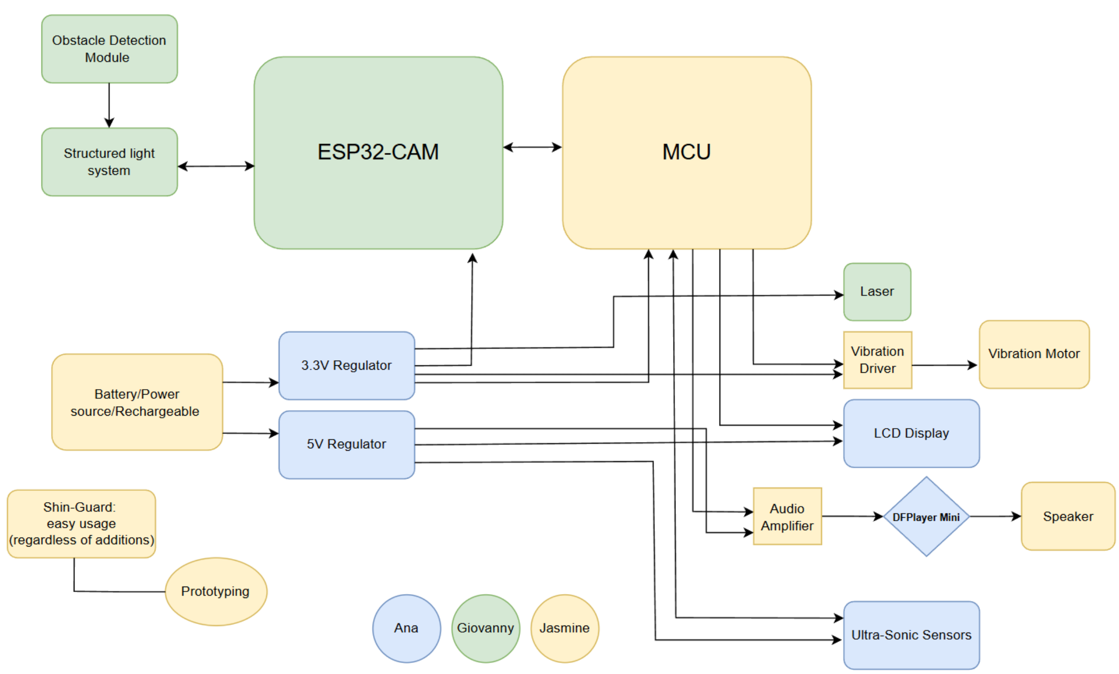



Figure 4: Hardware Block Diagram for Project

## 2.7 Software Diagram / Flowchart

This software diagram illustrates the operational logic of the wearable obstacle detection system around an ESP32 microcontroller and an ESP32-S3-WROOM-1 microcontroller. The process begins with Ana initializing the ESP32-CAM, she uses Edge Impulse and the Arduino IDE to capture laser-grid images, for both distorted objects and undistorted. Followed by uploading the images to the cloud, to training the distortion-detection model, and finally deploying the model on the board. When the deployed model runs on the ESP32-CAM board, a detected distorted pattern turns on the ESP32-CAM's onboard flash LED and drives a signal output bit to high. This bit is read by the ESP32S3 which will then blink its own LED when distortion is detected and keeps it off when no distortion is present. Simultaneously, the ESP32-S3 reads the ultrasonic sensors to measure distance up to 2m. If an obstacle is detected, the system triggers the vibration motor and speaker to alert the user. The vibrations indicate proximity, while audio feedback specifies whether the object is to the left or right. The system loops continuously until either a shutdown is triggered, due to low battery, or no obstacles are detected. This software architecture ensures real-time responsiveness and layered sensory alerts for improved navigation and safety.

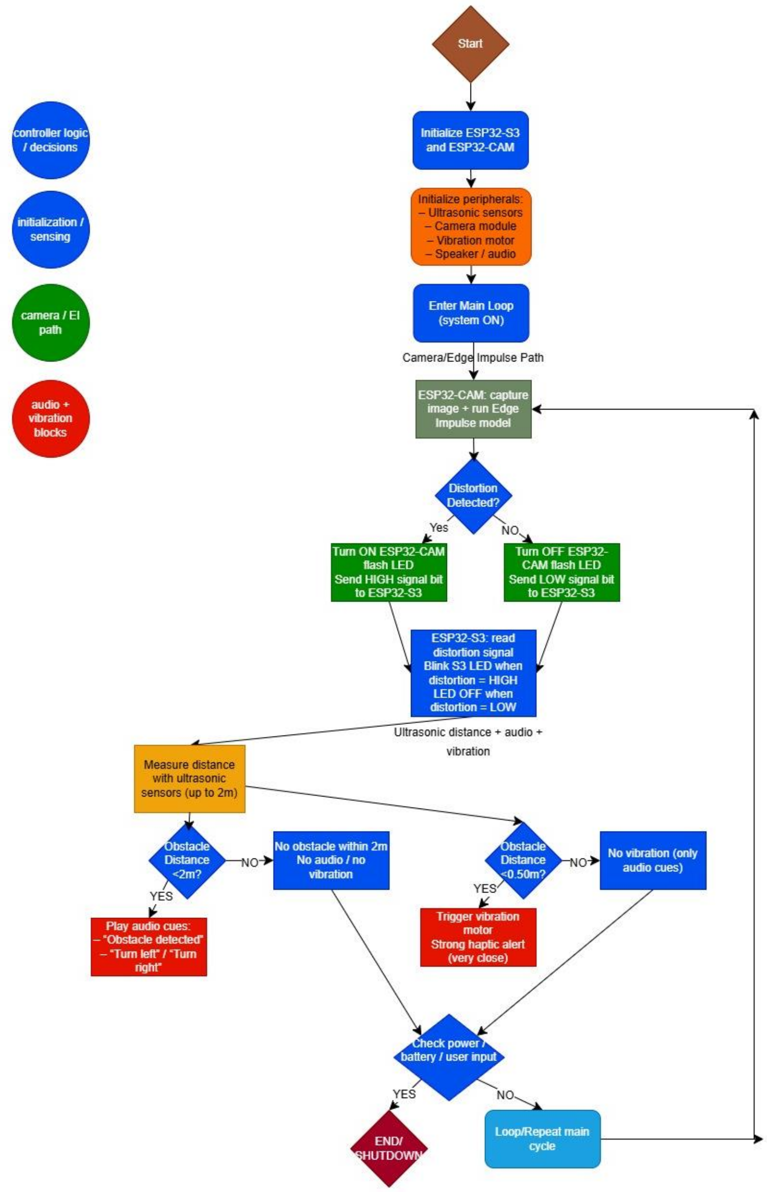
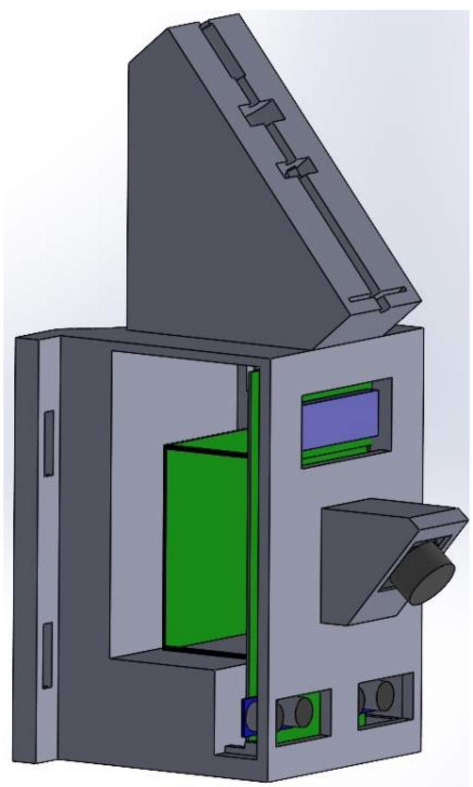



Figure 5: Software Flow Chart

## 2.8 Prototype Illustration / Blueprint

The following illustration demonstrates a visual representation of the SightSense design, highlighting the integration of key hardware components. It also illustrates the placement of our key features.


Figure 6: Initial Prototype Design with all components



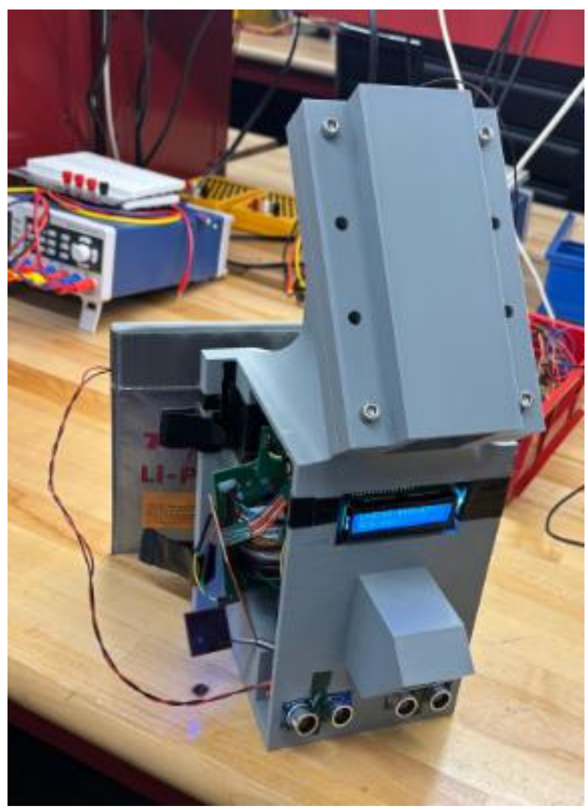


Figure 7: Final Prototype Design with all final components inside

Below is a breakdown of each component shown in the first illustration above and its function:

**Basic:**

- Rechargeable battery: This will power the entire shin guard, it needs to last between 6-10 hours on a single charge, ensuring the shin guard remains reliable and convenient for extended daily use.
- Laser Projector: Will emit a laser beam that will be shaped into known pattern for structured light system.
- Camera Sensor: Will act as systems "eyes" sensing for distortion of projected pattern.
- Ultrasonic sensors and LCD screen: Will help the laser measure and display the distance from an obstacle.

**Advanced:**

- Camera: Camera will act as a sensor for object detection and be able to classify objects.
- Vibration and audio feedback: Will provide cues to the user through vibration patterns and audio support in the shin guard. These vibrations and audio will signal objects, direction, and or proximity of obstacles and guide the user.
- Durable protective electronic housing design: Ensure that all electronic components, including sensors and wiring, are protected against water, making the shin guard durable and able to use the shin guard in various outdoor conditions.

**Stretch:**

- SOS alert system/ button: Activated by a discreet pressure sensor or tap pattern to allow visually impaired users to quickly signal for help in emergencies
- GPS tracking to notify emergency contacts: This requires the use of cellular which could send an alert to contacts if the user runs into trouble.
- GPS navigation: The addition of GPS will help the user by giving real-time directions from the speaker provided.

## 2.9 House of Quality

The house of quality diagram which is shown below illustrates the relationship between the users' needs and the engineering specifications of the Smart Haptic Alert Obstacle Detection System for the Visually Impaired shin guard. The HOQ also includes the marketing requirements.

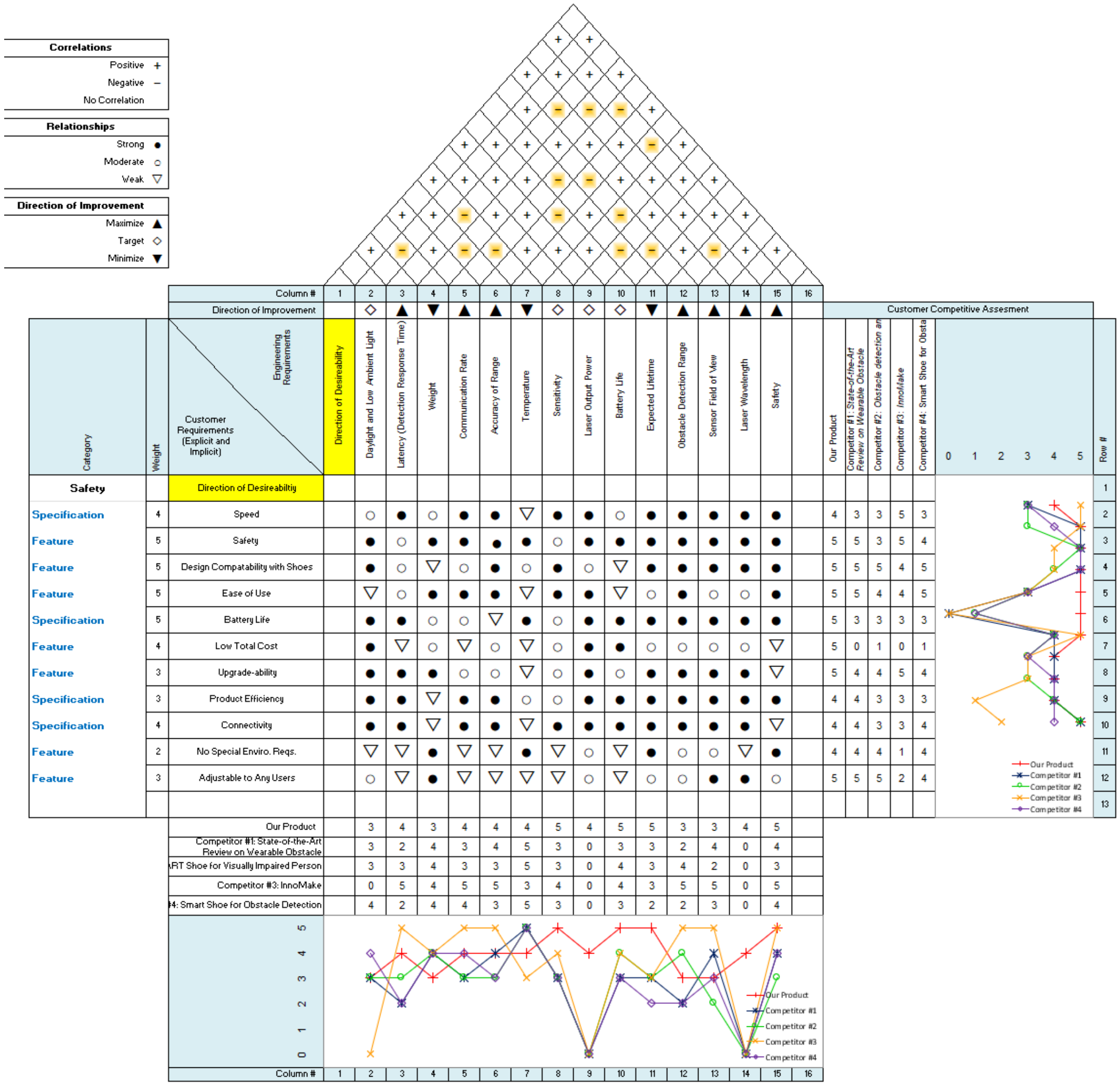



Figure 8: House of Quality Illustration

# Chapter 3 Research and Investigation

This chapter presents the detailed investigation and analysis conducted to select the most suitable components and technologies for the SightSense smart shin guard. Each subsystem, ranging from sensing, processing, power, and feedback, was studied against multiple alternatives to balance performance, cost, and integration ease. The research also explores algorithms, structured light sensing techniques, and prior literature to provide foundational knowledge that supports design decisions.

## 3.1 Part Selection and Relevant Technologies

To make the SightSense project a working functional and reliable shin guard for the visually impaired, we put a lot of thought into choosing the right components and technologies for developing a working product.

The primary function of the SightSense shin guard is to detect obstacles in the user's path and provide real time haptic and audio feedback. We will need to ensure that accurate distance measurement through sensors, real time processing with a microcontroller, and feedback via vibration and the speaker all must work together to finalize our final product to help the visual impaired community.

We first started off with, defining requirements and constraints. Figuring out what our prototype system needed to do, things like sensing, processing data, communicating, and providing real time feedback. Then this is where we looked at and researched different components that could handle each of these jobs. When picking parts, we focused on what mattered the most, factors such as power efficiency, ease of programming, whether the components would work well together, and overall cost efficiency. Our team compared our options in each area to make sure we ended up with a design that would work and wouldn't be too expensive or complicated to build and if we wanted to scale it up this could also be done in the future.

Each subsystem in this chapter also has specific performance criteria that needs to pass in order for our final design to be able to work and be safe for the users. For more information, please visit chapter 9.

This section is divided into two main categories, the hardware components and software selection. For the hardware portion we will discuss and compare two to three of the same part and compare them to choose the best option out of the two or three that will work best for our project. On the software side we will cover our programming setup, why we chose the program, and how it will be implemented onto the board for this project. All of these choices will work together to create the foundation for our final prototype.

## 3.2 Hardware Selection

In this section, we will walk through the hardware selection process. We will explain why we chose each component, their role within the overall system, and how they all connect together. We will also pay close attention to power efficiency, size and weight constraints and if the shin guard will be functional and comfortable for the visually impaired users to use.

### 3.2.1 Shin Guard Selection

The SightSense shin guard system is built around a wearable platform that integrates electronics into everyday footwear to make walking for the visually impaired easy and reliable. The person who will be testing our shin guard prototype will be the relative of one of our team members who has a visual impairment, so this became our first step in the hardware selection process. Since she is also diabetic, we had to carefully assess various shin guard types, such as sneakers, Crocs, and shin guards, to determine the most suitable base for embedding our components.

When choosing our shin guards, as mentioned above, there are multiple factors that we need to consider. The first being what type of shin guard can hold the most weight without worrying about components falling apart due improper spacing. This means we need something sturdy to hold everything together. The next factor would be weight, which shin guard can hold the most weight without it being too heavy on the user. Another factor to consider is wiring, what shin guard can be easy to wire to install all our components.

Looking at shoes, we see that they are a good option. We can add our necessary camera to the top of the shin guard as well as the ultrasonic sensors. All other components will be placed on the sides or at the bottom of the shin guard. The bad thing about sneakers would be the lack of space that will be needed to implement the rest of our components, thus having no room or, in other words, being too compact. Overall, the sneakers will be sturdy and not heavy, but the wiring will be difficult to work with.

Looking at our second option, Crocs, the camera and ultrasonic sensors will be at the top, and everything else will be on the sides and bottom of the shin guard, like the first option. Right away we see that the Crocs will not be sturdy enough to hold our components in place like we wanted. The weight will be a bit heavy on the Crocs because the shin guard overall is light, so adding the weight of the components will be a little too much. For the wiring portion, these shin guards will be the best to wire because of the holes already in the shin guards, so wiring and the implementation of the rest of the components will be so much easier than the sneakers.

For our final design we decided to use a shin guard as a base for a 3D print that will house all the pcb’s, entire optical system, as well as ultrasonic sensor. The decision to change to a shin guard design came from wanting an original product that seems practical as well as useful for a visually impaired user.

Table 3: Comparison of Shoe Types

| Parameters | Sneakers | Crocs | Shin Guard |
|---|---|---|---|
| **Sturdy** | Moderate | Low | High |

| | | | |
|---|---|---|---|
| **Weight** | Moderate | Moderate | High |
| **Implementation** | Low | Moderate | High |

Key: Low = Weak/Less Suitable – difficult to work with, Moderate = Average/Acceptable – in the middle, High = Strong/Ideal – highly suitable for this project

#### 3.2.1.1 Shin Guard and Socks

In the initial design phase of the A Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) shin guard, our team explored a variety of footwear platforms to accommodate and support our electrical components which include the microcontroller, ultrasonic sensors, LCD display, vibration and audio haptic feedback, and the battery. As we mentioned in the sections above, we researched and evaluated the following footwear, sneakers, crocs, and shin guards before deciding on the shing guard as it will allow to have a 3D built housing that holds all components.

The goal with this new idea is to maintain the same functional capability which is obstacle detection with haptic and audio feedback while improving wearability. Once everything is working, we will mount the electronics directly onto the sides of the shin guard and will be worn on the lower leg with Velcro straps. This will make taking off the final product easier to take off and put on. To provide comfort and stability and to prevent the guard from slipping or irritating the skin, a soft, breathable compression sock will be worn below. Overall, with this new concept we introduced we improved ergonomics, easy to use, and comfortable to wear. Our goal is to develop a final product that seamlessly integrates into users' lives without placing any restrictions.

### 3.2.2 Microcontroller Unit (MCU) Selection

The most important component for the SightSense shin guard is the selection of the microcontroller unit (MCU), which will serve as the central processor that will manage and control all inputs, outputs, sensors, communications tasks and our other key features. When picking the right MCU, we looked for things like processing power, easy for us to work with, whether it can connect wirelessly, size, low cost, and power efficiency. In this section, we will discuss our top choices and the option we went for at the end.

The first option we researched was the Raspberry Pi 4 Model B [5]. This board is a complete desktop computer designed for desktop-class computing. Some of the features this board has to offer are its quad-core 1.5GHz processor, memory up to 8GB, dual displays, multiple USB ports, and gigabit ethernet. Other things are its 40-pin GPIO pins, Bluetooth, and high-power supply. While this is an excellent choice for image processing, which will be good for this project, it consumes significantly more power, it will be harder to code as the group lacks python expertise, its large size, and a bit expensive which is around $40, which makes the Raspberry Pi not an ideal candidate.

The second option we looked at was the commonly known MSP430FR6989 board [6]. This board was mostly used in our classes at UCF, especially for the embedded systems class, making this board an easy option to use. The MSP430FR6989 is a low-power MCU that is developed by Texas Instruments, known for its 128KB FRAM memory and minimal energy consumption. This board includes a 16MHz processor, 83 GPIO pins, advanced sensing, a real-time clock, and a 12-bit ADC, and optimized for sensing. On the other hand, this board lacks wireless connectivity, camera support, and processing power needed for the shin guard project. While very good for low-power environments, and a price of $24 which is lower than the Raspberry Pi, coding for this project will take more time since we will need more lines of code to do one task. This makes the MCU also not an ideal candidate.

Our last option was the ESP32-S3-Wroom Development Board [7]. This board is compact and cost-effective at $15. This microcontroller has key features such as Wi-Fi, Bluetooth, and a built-in camera option. It has a dual-core processor that goes up to 240MHz, plus it supports various communication protocols like UART, SPI, PWM. This board is ideal for our SightSense shin guard because of its small size, wireless connectivity, and low current drain to save power. This board also makes it easy to code and implement in Arduino as the team has a background in it.. All in all, the size and efficiency of the ESP32-S3_Wroom makes it a great match for what we need.

The table below summarizes the options we have researched for our needed microcontroller board that will make our shin guard project for visually impaired individuals possible.

Table 4: Microcontroller Comparisons

| **Specifications** | **Raspberry Pi 4 Model B** | **MSP430FR6989** | **ESP32-S3-Wroom** |
|---|---|---|---|
| Processor | Quad-core 1.5 GHz | 16MHz | Dual core up to 240MHz |
| Memory | Up to 8 GB RAM | 128KB FRAM | 16MB PSRAM + 16 MB Flash |
| Wireless Connectivity | Wi-Fi + Bluetooth | Not Included | Built in Wi-Fi and Bluetooth |
| Camera Support | Optional | Not supported | Built in camera |
| GPIO Pins Available | 40 | 83 | 36 |
| Power Consumption | High | Very Low | Low |
| Ease of Coding | Low | Moderate | High |
| Size | Large | Compact | Very Compact |

| | | | |
|---|---|---|---|
| Cost | ~$40 | ~$24 | ~$15 |

After evaluating all of our options for the three microcontrollers, we decided to go with the ESP32-S3-Wroom for the SightSense shin guard project as it made the most practical and efficient choice for our wearable design.

### 3.2.3 Laser Selection

For our Sightsense project, the laser diode module is one of the key components needed for the structured light system used for depth mapping and object detection. The ideal laser would have a stable output, with a narrow beam capable of being used with a diffractive optical element for beam shaping to create a stripe pattern. The laser must also be compatible with the embedded system used to control the system. To find out which laser would be best to use for our project, the laser diode modules were evaluated based off the wavelength needed to match the D.O.E. needed which is at 650nm, the output optical power needs to be high enough for projection pattern to be visible to camera sensor. Beam profile and intensity are compared, as well as uniform beam is essential for projection of the stripe profile. The use of a built-in driver circuit is also essential in this project because of the space constraints of the design being on a shin guard and not wanting to give unnecessary work to our electrical engineers as the summer semester shortens development time. Because this student funded project, the price of materials and ease of sourcing were prioritized. Because of the low power requirements in the design, all components need to be able to be powered off a 3.7V battery. Based off these criteria, three laser diode modules were compared from trusted distributors such as Amazon, Thorlabs, and Lasermate. The following table compares laser diode modules.

Table 5: Comparison of Laser Modules

| Part Name | Wavelength ( nm) | Output Power | Beam Shape | Driver Included | Price |
|---|---|---|---|---|---|
| **Lasermate LDM-655-04** | 650nm | 4mw | Elliptical | Yes (TTL Modulated) | $42.00 |
| **Hobbyant Red Dot Laser** | 650nm | 200-250mw | Circular | Yes | $30.98 |
| **Thorlabs CPS635R** | 635nm | 0.6mw | Circular | Yes | $78.00 |

For prototyping, the hobbyant laser will be used for its low cost and ease of shipping. Eventually, the hobbyant laser was selected for its stronger beam output as well as similar beam shape and built in driver circuits compared to the more expensive lasers. All the information found in the charts was taken from data sheets from the respective websites and sellers [9] [10] [11].

### 3.2.4 Lens Selection

The optical lens is a crucial component in the structured light system used for our project. This lens is responsible for focusing light rays onto the sensor. The lens will refract the light rays from the scene and converges onto the sensor for a clear image. Choosing the correct lens to incorporate to achieve necessary resolution, field of view, and minimal aberration is crucial. To choose the proper lens compatibility with the existing laser diode module and D.O.E. is necessary. The lens needs to have a short focal length to achieve a wider field of view needed for short range object detection. The lens needs to have proper aperture and lens diameter with minimal distortion and other aberration. The size and mounting are important as standard sizes can use an m12 or m9 mount. The preferences for the lens are affordability and that they are readily available.

Table 6: Comparison of the Lens

| Lens | Focal Length | Field of View | Mount Type | Lens Type | Distortion | Cost |
|---|---|---|---|---|---|---|
| **2.1 mm Wide angle M12** | 3.6nmm | 140 degree | M2 | Wide angle glass | moderate barrel distortion | $12.00 |
| **6 mm M12 Standard** | 6.0 mm | 60 degree | M12 | Glass, multi element | moderate | $10 |
| **Plano Convex** | 8.0 mm | na | Lab mount | Single element pcx | minimal | $18 |

Option 1 is the best for the space constraint of the shin guard design. The wide field of view comes with barrel distortion, which is an issue for object detection, as this could impact the image of the striped output projection. The second lens is good for testing in a controlled environment with better image quality and sharpness, which will improve the imaging of the striped design. Lens 3 is used for ensuring the laser path remains collimated through the D.O.E. and the information from the chart was provided by the websites and distributors and can be found in the reference section [12] [13] [14].

## 3.2.5 Structured Light Camera Selection

After testing with the ESP32-CAM initially the team had issues deploying the ML algorithm needed to detect distortion from objects not caught by the ultrasonic sensors. Upgrading to ESP32S3CAM was considered, but late in the process of development we were able to successfully deploy the ML algorithm on the ESP32-CAM. The low power and onboard real time processing made the ESP32-CAM the final camera selection for the structured light system.

### 3.2.5.1 Grid Distortion Algorithm Design

With the camera selected, the next step was to evaluate how to analyze the projected light grid for signs of environmental obstruction. The approach consists of three key stages:

spacing, line bending, or gaps in the grid pattern to infer physical obstacles.

We considered more complex algorithms like stereo vision or depth-from-focus, but they were deemed unnecessary and computationally heavy. The grid-warp detection algorithm, by contrast, runs efficiently and requires only a single image. It also works under partial occlusion since line deformation is usually visible even when only a portion of the pattern is blocked.

Threshold tuning was key to reducing false positives. Through trial and error, we established optimal spacing and angle variation tolerances, reducing misfires from textured floors or shadows. This image-based module acts as a supplement to the ultrasonic sensor, allowing for richer spatial awareness and improved user safety.

3.*2.5.2* Environmental Tuning & False Positive Reduction

A common issue with embedded sensors is misinterpretation of environmental data, leading to false alerts or missed obstacles. This was particularly relevant for our project, where uneven terrain, wet surfaces, or bright sunlight could affect sensor input.

For the structured light module, we addressed this by capturing image datasets under different lighting conditions: indoor fluorescent, outdoor sunlight, and dim hallway settings. Our algorithm was refined to adapt thresholds dynamically based on local contrast and grid density, significantly reducing error rates.

For ultrasonic sensors, averaging filters and redundancy checks helped to validate object presence before feedback was triggered. We also introduced logic to ignore objects that appear for less than 100ms, preventing misfires from thin poles, leaves, or surface reflections. These refinements were the result of careful field testing and iterative firmware improvements.

3.2.5.3 Event Patterns

As part of our structured light distortion analysis, we documented and categorized the most common types of grid deformation patterns encountered during environmental testing. Each distortion type provides specific visual cues that can be mapped to likely real-world obstacles or terrain changes. This mapping enables the system to trigger different feedback intensities tailored to the urgency of the hazard. The table below summarizes the most frequently observed distortion events, their likely causes, and the corresponding system responses designed to alert the user effectively.

During our preliminary distortion classification tests, we observed recurring visual anomalies in the gridded light pattern that could be systematically linked to common environmental obstacles. By defining these visual signatures and their likely causes, we established an early decision framework for the system's real-time response logic. The table below summarizes four of the most distinct distortion types we recorded, along with their expected triggers and the system responses programmed to alert the user accordingly. These classifications will serve as the foundation for future refinement and expanded detection accuracy.

Table 7: Comparison Pattern Type

| Pattern Type | Visual Signature | Likely Cause | System Response Triggered |
|---|---|---|---|
| **Bent Lines** | Curved horizontal or vertical segments | Wall, leg, or pole | Short pulse + audio alert |

| | | | |
|---|---|---|---|
| **Gaps/Broken Lines** | Missing sections in the grid | Edge of step, object in path | Stronger vibration |
| **Blurred Grid** | Soft, smeared edges | Water, fog, transparent barrier | Audio only (non-urgent) |
| **Angled Skew** | Tilted or diagonal line deformation | Slope or hill | Mild haptic warning |

Test examples:
To validate system performance, we will conduct multiple trials simulating real-world walking paths with embedded obstacles. Currently, we have saved two reference images from the gridded light system. One showed an undistorted pattern projected onto a flat surface and another displaying visible distortion caused by an obstacle. Our detection algorithm was able to accurately distinguish between the distorted and undistorted images, confirming the basic functionality of the structured light analysis module. This distinction then allowed the code to output "Distorted" and "Undistorted" depending on whether the gridded light system was distorted or not respectively.

The figure below illustrates the gridded light system projected onto a flat, unobstructed surface. This undistorted pattern serves as a visual baseline for our structured light detection algorithm. Because the lines remain evenly spaced, parallel, and symmetrical, the system can use this reference to detect any deviation or distortion caused by nearby obstacles. Establishing this clean grid projection is critical for calibration and allows our code to reliably differentiate between normal terrain and potential hazards during real-time operation.

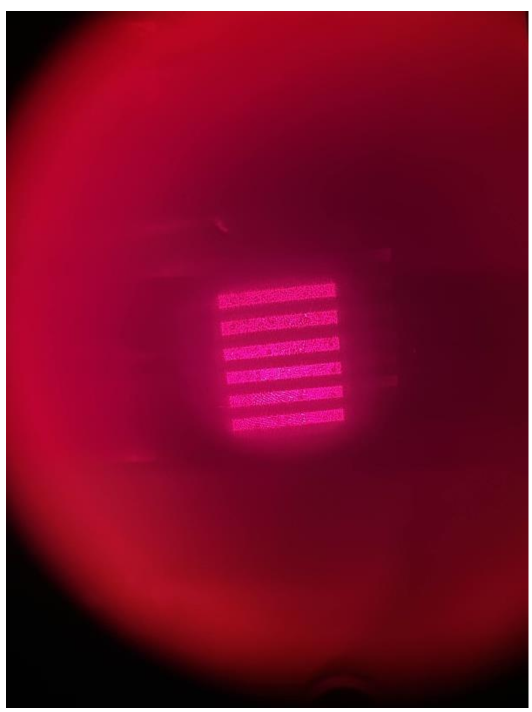


Figure 9: Undistorted gridded light system

The image below displays a distorted version of the gridded light system caused by the presence of an object within the projected area. Unlike the uniform pattern seen on flat surfaces, this image shows gaps in the lines that indicate a disruption in the light path. These distortions provide essential visual cues for our obstacle detection algorithm, allowing the system to identify the presence, shape, and approximate location of nearby hazards. This type of deformation is what triggers the feedback mechanisms in the SightSense smart shin guard, such as vibration or audio alerts.

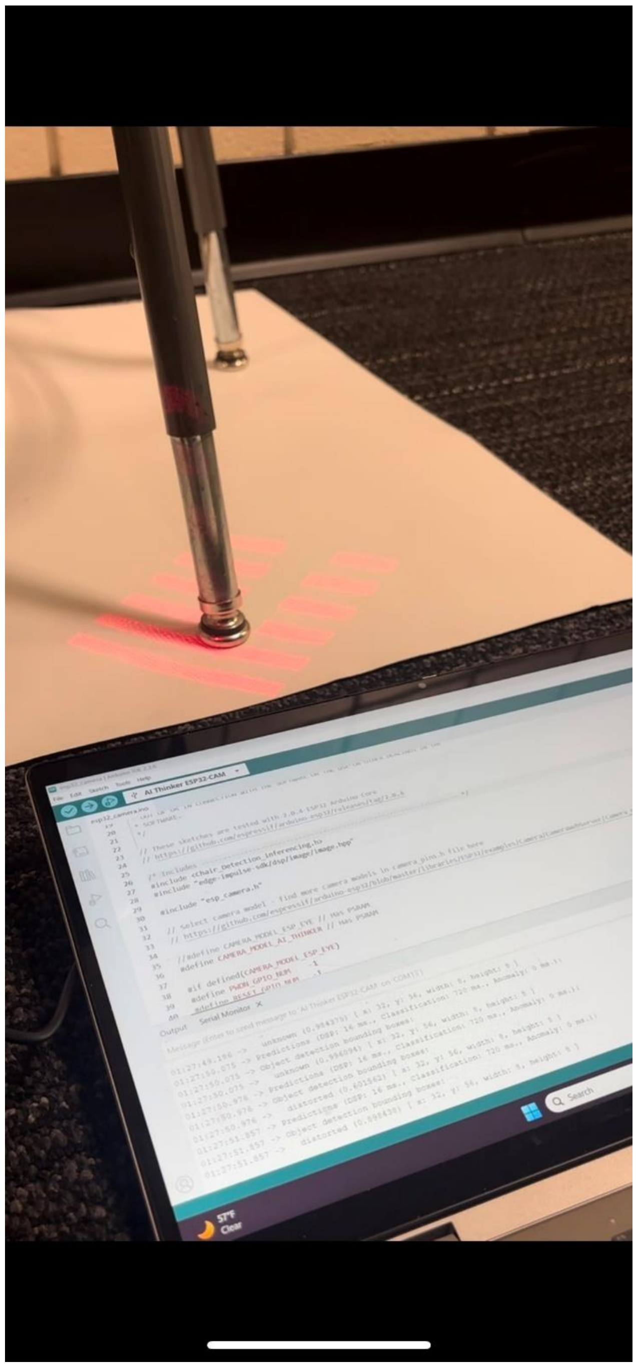


Figure 10: Distorted gridded light system

The image below shows the current output of our distortion detection algorithm. The output prints "Object detection bounding boxes" while detecting. Later the output prints "Distorted" to show that it sees a distortion in the gridded light system as shown in Figure 12. This algorithm is a current baseline for our distortion detection algorithm. As we move forward in Senior Design 2, we plan to work towards allowing the code, camera, and gridded system to be able to work effortlessly to signal audio and vibrational cues to show an objects distance from user and direction so that users with visual impairment can navigate effortlessly through various environments.

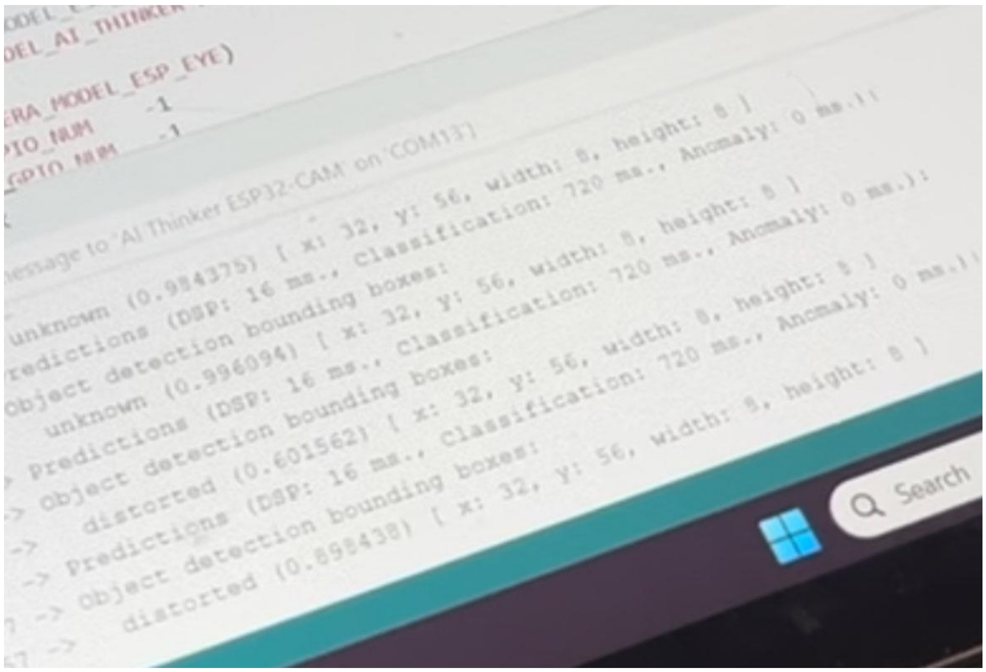



Figure 11: Distortion Detection Output distortion

In one planned scenario, the user will walk toward a recycling bin positioned approximately 1.2 meters ahead on a flat sidewalk. We anticipate the projected grid will show a horizontal compression pattern upon approach, which should trigger a high-priority alert. The system is expected to activate the vibration motor at full intensity for 500 ms, followed by a distinct audio tone to notify the user.

Benefits of Structured Light Pattern Analysis:
By translating optical distortion into categorized alerts, we enable the shin guard to function not just as a binary obstacle detector, but as a spatial awareness tool. Over time, we plan to expand the pattern database and train the system to auto-calibrate thresholds based on user walking style, environmental lighting, and grid projection angle. These insights will support improvements in both reliability and user trust, especially in outdoor environments where unexpected terrain can pose serious hazards to visually impaired individuals.

3.2.5.4 Comparison to Other Wearable Vision Systems

Wearable computer vision systems typically fall into two categories: obstacle avoidance aids and navigation aids. Our SightSense shin guard aligns more with the former but introduces a unique structured light approach, unlike conventional camera or LiDAR setups.

Most available systems rely on cameras mounted on glasses or belts, which can be invasive or require directional orientation. In contrast, SightSense projects light downward from the foot, avoiding the need for directional calibration. The depth feedback is locally processed and fed back to the user in real time without requiring internet or cloud services.

Some vision-based smart canes rely on infrared structured light or stereoscopic lenses, but these are bulky, expensive, and often unreliable in bright light. Our laser grid design is compact and can be tuned to visible red light, which performs well under various ambient conditions. While not as advanced as full 3D reconstruction, our implementation balances simplicity and real-world usability. We expect future iterations to improve even further with the integration of lightweight processors and more adaptive vision algorithms.

### 3.2.6 Camera Selection

The camera sensor is an integral part of the structured light system because it captures the distortion and deformation in the projected pattern, which is used to generate a depth mapping using spatial geometry. The system used for our SightSense project needs to be low power, and small in spacing, but able to identify distortions in the projected pattern in real time. To choose the best camera module for our project, the key characteristics to be considered include resolution as adequate pixel density is needed to capture the stripe patterns. The frame rate needs to be high enough that objects can be detected, and the user can be notified in real time. Without this feature, the product would not be useful. The selected camera module must also be compatible with the microcontroller used for the project. Again, the form factor is key, because the SightSense is a shin guard design with limited space for components. The lens mount should support customizable lenses, and the system is designed to run on low power. Cost and availability are crucial because this is a self-funded student project. The camera comparison will be shown in the table below.

Table 8: Comparison of the Camera Types

| Camera | Resolution | Interface | Lens Mount | Operating Current | Cost |
|---|---|---|---|---|---|
| **ESP32_CAM** | 1600x1200 | Wi-Fi, UART | Fixed M12 | 160mA | $7.00 |
| **Arducam Mini 2mp** | 1600x1200 | SPI | M12 swappable | 140mA | $15.00 |
| **Raspberry Pi Camera Module 3** | 4608x2592 | CSI | M12 or CS mount | 250mA | $25-$35 |

The ESP32-CAM was selected as the primary imaging sensor used for the imaging system for several reasons. The low power consumption and native Wi-Fi capability enable easy programming integration. The camera unit we chose has sufficient resolution to be able to detect the distortion in the striped patterns for the structured light system, which will detect objects at a short range of less than 2 meters. The low cost and affordability make it ideal for a student-led project like our own. The camera module is easily integrated with the microcontroller and supports basic image processing where a machine learning convolutional neural network can be run on chip. The raspberry pi camera module offers higher resolution but was not chosen due to the need for a dedicated pi host board. The Arducam offers flexibility but falls short in real time object detection and the information found in the table can be found in the reference section [15] [16] [17].

### 3.2.7 Ultrasonic Sensor Selection

For our SightSense shin guard we will work with ultrasonic sensors for part of our obstacle detection and distance measurement feature. To determine the best sensor for our design, we compared three commonly used ultrasonic sensors based on range, accuracy, and ease of integration with the ESP32-CAM.

The HC-SR04 is the first option we examined since it is a very popular sensor, and we also used this component as part of our Junior Design course at UCF. This ultrasonic sensor is low-cost with a detection range of 2cm to 400 cm and accuracy that can reach 3mm. It uses it's I/O pins to produce accurate distance measurements and runs as 5V. However, the ESP32-CAM uses 3.3V, but this can be fixed through using a simple boost converter. All things considered, this is the best choice due to its small size and reliable performance, which make it a good fit for obstacle detection for our shin guard project.

The next ultrasonic sensor we looked at was the JSN-SR04T-3.0 [18]. This sensor ranges from 21cm to 600cm. It has a precision that can reach as high as 3mm and even though this is a longer distance from the HC-SR04, [19] this sensor has a slower response time. It is also a waterproof version of the ultrasonic sensor, which is a good feature, especially to have for outdoor use like what is needed for our shin guard. This sensor also operates at 5V and requires more space and power making it less ideal for what we need.

The last option was the RCWL-1601 ultrasonic sensor which is a smaller sensor compared to the rest. It is compatible with 3.3V and 5V and the 3.3V can work with the ESP32-CAM. It offers a shorter range and only goes up to 2-400cm for 3.3V and 2-450cm for 5V [20]. This sensor results in less accuracy. This ultrasonic sensor has some difficulty in troubleshooting and integration thus making this ultrasonic sensor also not a reliable option. The table below summarizes our comparisons between the three ultrasonic sensors modules based on key performance, compatibility, and integration for the S.I.G.H.T shin guard.

Table 9: Sensor Comparison Table

| Feature | HC-SR04 | JSN-SR04T-3.0 | RCWL-1601 |
|---|---|---|---|
| **Voltage Operation** | 5V | 5V | **3.3V** – 5V |

| | | | |
|---|---|---|---|
| **Range** | 2-400cm | 20-400cm | 2-440cm |
| **Accuracy** | ~3mm | ~5mm | ~5-10mm |
| **Waterproof** | No | Yes | No |
| **Size** | Compact | Heavy and Large | Small |
| **ESP32-CAM Compatibility** | Needs boost converter | Needs boost converter | Yes |
| **Cost** | ~$3 | ~$8 | ~$3 |
| **Best Fit for Shoe Project** | Yes | No | Maybe |

After comparing our three options, the HC-SR04 ultrasonic sensor was selected for our SightSense shin guard due to its reliable performance, range, compact, and cost-effective design. While it requires 5V, we will implement a boost converter to allow smooth integration with the ESP32-CAM.

### 3.2.8 LCD Screen Display Selection

Another hardware component we plan to add to the SightSense shin guard is the liquid crystal display or LCD. This component is a flat panel display screen that is used in embedded systems and is known for its low power consumption, compact size, and cost efficiency as well as they come in different dimensions. For the Sightsense A Smart Haptic Alert Obstacle Detection System for the Visually Impaired shin guard, the LCD screen will help us as engineers to verify outputs, calibrate sensors, and to make sure that the final product is functioning as expected. This feature can provide critical information to caretakers or users on obstacle detection alerts, this will work alongside the vibration and speaker components, give the battery level of the shin guard, and for the future to possibly give status during new software updates. But for now, the LCD screen will help us make sure that the SightSense shin guard is working during prototyping by working with the ultrasonic sensors and displaying distance readings. Below we will discuss three different types of LCD displays and compare each one to find the right fit for the final design of our product.

The first option we investigated was the OLED 0.96” I2C Display. This screen comes in a compact design that supports a 128x64 pixel grid [21]. It also does not need any backlight, and it uses less power than the classic LCD screens. It operates at 5V and comes with its own voltage regulator, which is good because it can be compatible with a 3.3V. It uses the SSD1306 driver and works with via the I2C communication. This makes integration easier to work with. The issue with this board is that it is more complex to program rather than the text only LCDSs. This option is not ideal for our wearable shin guard product as it will be harder to read and work in bright outdoor settings.

The next option is the LCD1602 display screen. This LCD display screen is the most widely used in embedded systems. This one is the one that the team is most comfortable with because we have used this screen in the Junior Design course offered at UCF. This blue screen offers two rows of 16 characters each with a parallel interface that is controlled by the MCU [22]. This screen operates at 5V and is composed of a 5x8 dot matrix for good character representation [22]. This screen also has the option of a backlight that can connect with a potentiometer that can help with adjusting the contrast of the display for best viewing. This LCD display is cost effective, easy to use with any microcontroller but will be best with the ESP32-CAM that we are using. However, this screen only works with text and no graphics, but it works since that is not what we intended to use.

The last and final option we researched was the 1.44" TFT Color Display. This LCD screen is a full graphical 128x128 pixel resolution [23]. It uses the DT7735 driver and connects via the SP1 to offer a vibrant color display. However, because of these advanced features it requires higher power consumption, will require more GPIO pins and programming is more complex than the other two options above.

After analyzing the three options, the LCD1602 is chosen as the ideal LCD screen display for the SightSense shin guard, due to its simplicity, low power needs, and ease of use. While the OLED and TFT displays offer enhanced capabilities, they create more complex problems with their advanced features. The table below shows the comparison of each option and their features they have to offer as well as a summary of which LCD screen display we chose.

Table 10: Comparison of LCD Displays

| **Feature** | **OLED 0.96" (SSD1306** | **LCD1602 (16x2)** | **TFT 1.44" Color (ST7735)** |
|---|---|---|---|
| Display Type | Monochrome Graphics | Text only 2 lines | Full Color Graphics |
| Interface | I2C | I2C or Parallel | SPI |
| Resolution | 128x64 pixels | 16x2 characters | 128x128 pixels |
| Cost | ~$8 | $3.50 | ~$8-$12 |
| Power Consumption | Low | Low | High |
| Ease of Use | Moderate | Low/Easy | High |

### 3.2.9 Vibration Motor Selection

The SightSense shin guard system is designed to make every day walking a more comfortable and easy experience for the visually impaired. This means that any features we add to the shin guard need to be safe for human interaction on an everyday basis. A key feature for this system is the vibration motor that will assist the user by vibrating when an obstacle is detected in its path. When selecting a vibration motor there were many to choose from that would be considered adequate for this system, but ultimately, we can only choose one. Below are three potential vibration motors and an explanation into why one is selected.

Seeed 316040001:

The Seeed 316040001 is a brushed DC eccentric mass (ERM). It has a voltage of 2.5-3.5V and an expected current is <80mA typically. It is ideal for compact DIT electronics and the coreless DC allows bidirectional mounting. These features could make this motor ideal for our project. However, all ERM's have a coarse vibration (buzziness) which means it will have an uncontrolled frequency. This is not ideal since we would like the vibration motor to be strong and have a clear frequency level that skin-to-skin contact will allow. This motor does, however, run on a classic DC voltage input which is an important factor to consider when choosing a motor. This means that there will not need to be any other additions to the PCB. This product is meant to be worn daily and needs to be the most stable and have a strong vibration, we will not be choosing this device for our product.

DFRobot FIT0774:
The DFRobot FIT0774 is a brushed DC eccentric mass (ERM). It has a voltage of 1.5-4.2V DC(3V rated) and a typical 50mA at 3V current. It has a RPM of 11,00 ± 2,500 and is an ideal small form factor for wearables. As stated above in the Seeed vibration motor, ERM's have a buzziness to their vibration, which is not ideal when we would like a very clear sensation when letting the user know there is an obstacle in its path. However, this motor runs directly from a DC voltage source which is easier and can be then run on a battery of our choosing rather than needing any other additional inputs to the PCB. Similar to the Seeed above, we need to have the safety of the motor against the skin and although this can be done with this device, we would like to be able to have control over the frequency and precision on the motor which is not applicable when it comes to this motor.

Vybronics VG0840001D:
The Vybronics VG0840001D is a Linear Resonant Actuator (LAR) AC type. It has a voltage of about 2VAC sine drive at 170Hz but does require a LRA drive circuit. This vibration motor has a crisp haptic response and has a low latency, but it will require a dedicated driver IC. The downside to this device is that it does require an AC sine wave driver. This is a downside since it will mean adding this component to the PCB. An AC sine wave driver (like the DRV2605) is meant to help the LRA with waveform library and auto-resonance tracking. As per its description from Texas Instruments "The DRV2605 device is designed to provide extremely flexible haptic control of ERM and LRA actuators over a shared I2C-compatible bus. This control relieves the host processor from ever generating pulse-width modulated (PWM) drive signals, saving both costly timer interrupts and hardware pins". This is a vital part of the design of our board but it will be necessary when initializing this motor. This motor provides the most accurate and clear vibrations

and is optimized for skin contact and because of the consistent resonant frequency it is easier to feel on the skin and should be quieter. The life span is also significantly longer than the ERM devices and will benefit our product.
Ultimately, for this product we will be choosing the Vybronics VG0840001D for our vibration motor. It provided the best capabilities out of the chosen vibration motors regardless of the additional features needed to be added to the PCB design.

Table 11: Comparison of Vibration Motors

| **Parameters** | **Seeed 316040001** | **DFRobot FIT0774** | **Vybronics VG0840001D** |
|---|---|---|---|
| **Size** | D: 9.91mm, Thick: 2mm | D: 10mm, Thick: 2.7mm | D: 8mm. Thick: 4.05mm |
| **Weight** | 0.9g | 1.82g | 1.27g |
| **Freq.& Sensitivity** | Uncontrolled frequency | Uncontrolled frequency | ~170Hz (consistent resonant frequency) Optimized for skin contact, commonly used in wearables |
| **Price** | $1.20 (in bulk) | $0.99 (each) | $5.39 (each) |
| **Durability** | N/A | ~100k cycles | Excellent longevity/consistent response |
| **Requirements** | None | None | Requires a LRA driver circuit |

### 3.2.10 Vibration Motor Driver Selection

For the SightSense shin guard, we will need a vibration motor driver that will control the vibration required for this project. This driver will need to produce minimal vibrating sensations that will not affect the user through skin interaction. It will need to provide tactile feedback so it can allow users to feel alerts when an obstacle is detected 2 meters away. It also needs to use less power, so it doesn't drain the battery right away. Below we will discuss three types of vibration motor drivers and then choose the best fit that will work for our final product.

The first option we researched was the DRV2605L by Texas Instruments. For this vibration motor driver, we see that it is both a Linear Resonance Actuator (LRA) and an Eccentric Rotating Mass (ERM) motors [24]. This means that both are capable of producing complex and subtle vibration effects. This driver supports a voltage range of 2V to 5.2V, and it communicates with the microcontroller via I2C interface. This will help with enabling control over motor operation. This driver also includes over 100 licensed effects, six ERM and one LRA library as well as audio-to-vibe features [24]. The DRV2605L vibration motor driver is a strong choice because of its drive capability and integrated feedback loop. This will give accurate vibration strength. However, the cons of this device are that it is too complex when it comes to programming, the I2C feature will require more wiring, and its advanced features can cause problems for simple vibration needs.

The next option we looked at was the SparkFun Electronics 14538 Vibration Motor Driver. This is very similar to the DRV2605L, this is because the DRV2605L is the actual motor driver chip, and the SparkFun 14538 is a breakout board that includes this chip and all necessary components. It is simple compared to the first option, and it specializes in Eccentric Rotating Mass (ERM) [25]. It also functions at 2V to 5.2V and uses a pulse width modulation input with a 0-100% duty cycle to regulate vibration intensity [26]. This vibration motor is easy to use and has basic speed control, compact size, and affordable. This is an ideal choice as this fits the criteria that we are looking for in a vibration motor driver.

The last option we looked at was the Adafruit DRV8833 Dual Motor Driver. This driver is a general-purpose dual motor driver that is capable of controlling two DC motors. It supports a wide power supply voltage range of 2.7V to 10.8V [27]. It can also deliver current up to 1.5A per channel. This also can be controlled via PWM to signal for speed and direction. While this is good, this causes more complex programming because it has the power to control multiple motors instead of one, if we only stick to vibration motors. The DRV8833 does not have the features of haptic effects or any specific vibration types. This driver is considered larger than the SparkFun 14538, it also may cause an overkill for simple vibration. Thus, not making this a good option.

After comparing these three vibration motor drivers, the SparkFun 14538 is the best choice to go with as it prioritizes simplicity, cost efficiency, and reliable control. While the DRV2605L is the runner up because of its advanced features we did not go with this option as its complexity and higher cost make this driver less suitable. The Adafruit DRV8833 is also great for dual motor setups but lacks specialized vibration motor control and it is also larger than the rest. The table below summaries all three vibration motor drivers.

Table 12: Comparison of Vibration Motor Drivers

| **Feature** | **SparkFun 14538** | **DRV2605L Texas Instruments** | **Adafruit DRV8833 Dual Motor Driver** |
|---|---|---|---|
| Motor Type Standard | ERM vibration motors | ERM and LRA vibration motors | DC motors and vibration motors |
| Control Interface | Simple PWM control (1 pin) | I2C communication | PWM speed and direction control |
| Voltage Range | ~2V – 5.2V | ~2V - 5.2V | 2.7V – 10.8V |
| Current Capability | Works well with small vibration motors | Integrated current feedback control | Up to 1.5A per channel |
| Built-in Vibration Effects | No | Yes, over 100 pre-programmed effects | No |
| Ease of Use | High | Low | Moderate |

| | | | |
|---|---|---|---|
| Size | Compact | Small but still needs extra components | Larger |
| Cost | Cost effective | Higher cost | Cost effective |
| Best For | Simple vibration | Advanced vibration | Dual motor control |

### 3.2.11 Rechargeable Battery Selection

The core value of this product for the SightSense shin guard is to be an easy and helpful guide for anyone who is visually impaired. One of the key features for this project will need to be the rechargeable battery. The rechargeable battery is arguably one of the most important parts of this project since it will provide power to all components. Without a perfectly working battery this project will not be able to run at the desired efficiency that the product is looking for. This includes easy recharging and a long battery life. After researching rechargeable batteries, three have stood out as potential options for our device. We will break these down and explain our selection.

Before we begin our explanation of the three possible batteries, there is one battery that met almost all product requirements and would have been chosen for our product had it been in production or sold in the United States during the time of our project. This rechargeable battery is the Panasonic NCR18650B. This would be the ideal battery simply due to its capacity capabilities which are far greater than any of the other batteries listed. In the table below, I have added this as a comparison to the other batteries, since this would have been the ideal choice.

Adafruit 2011 Li-Ion:

The Adafruit 3.7V 6600 mAh LiPo battery is an excellent choice for this project due to its high capacity, built-in protection, and compatibility with typical wearable electronics. It has a large 6600 mAh capacity which provides longer runtime, making it ideal for our project, which will need to operate continuously for many hours without recharging. To be precise, if we assume our product consumes 200mAh, we can use the formula 6600mAh/200mAh = 33 hours before the battery needs to be charged. this would exceed our goal by 23-27 hours, which is a significant upgrade. The integrated protection circuit ensures safe operation by guarding against overcharging, over-discharging, and short circuits, which is especially important in portable applications. Additionally, its standard JST-PH 2.0mm connector makes it easy to integrate with power management boards and is compact and lightweight. This battery strikes a great balance between performance, safety, and ease of use—making it a reliable power source for embedded and wearable systems.

Adafruit 150 mAh:

The Adafruit 150 mAh is a Li-Po Pouch or Lithium Polymer. This type of battery is flexible and lightweight and comes in customizable sizes. It is ideal for small wearable products. But the battery is more fragile and is sensitive to overcharge (discharge). This battery has a voltage of ~3.7V and a capacity of 150mAh. This is a significantly lower capacity compared to the other two batteries listed. As stated in the Dantona L37A26 battery example, to find the duration of a battery, we will divide the given 150mAh by an estimated consumption (using the same from above 200mAh), 150mAh/200mAh = 45 minutes. This means the user would need to charge the shin guards every 45 minutes and therefore it is not practical. A benefit to this battery, however, is the flat pouch form and the easy to use plug in wires and is incredibly lightweight. This makes the battery easy to install. A significant downside is that this type of battery is typically made for small low-power devices and not typically used in large main power systems. This is not an ideal candidate for our battery options.

SparkFun 2.6 Ah:
The SparkFun 2.6 Ah is a 18650 Li-Ion or Lithium-Ion Cylindrical Cell. Lithium-ion cylindrical cells (as stated in the Dantona L37A26 battery) are widely available, have a high energy density, have a robust casing, and thermal stability. But they are ridged and are heavier than pouch cells. This battery has a voltage of ~3.7V and has a capacity of 2,600mAh. This battery does not have simple easy to use wires but rather requires a holder and protection for battery stability. Without circuit protection this could be very dangerous, which will mean another part will need to be installed. This battery does have the same capacity as the Dantona L37A26, which means it should have a similar runtime. Which means it should reach our duration goal of 6 - 10 hours of power. This battery does meet the specifications we are looking for but we will need to add protection, which would provide overcharge, over-discharge, and short-circuit protection to ensure safe charging (and discharging) for the battery, as well as a battery holder. This is not an ideal candidate for our battery options.

After careful consideration of the parameters of all three batteries, the best fit for the SightSense shin guard will be the meshnology Li-Ion. Due to its popularity, stability, simplicity, and its capacity which will help us reach our longevity of daily use.

Table 13: Comparison of the Rechargeable Batteries

| **Parameters** | ****Panasonic NCR18650B** | **Meshnology 3000mAh 3.7V Li-Ion** | **Adafruit 150 mAh** | **SparkFun 2.6 Ah** |
|---|---|---|---|---|
| **Battery Type** | 18650 Li-Ion Cylindrical Cell | Lithium Ion **rechargeable** | Li-Po Pouch Cell | 18650 Li-Ion |
| **Voltage** | 3.7V | 3.7V | 3.7V | 3.7 V |
| **Capacity** | 3,400 mAh | 3000 mAh | 150 mAh | 2,600 mAh |
| **Current** | ~2-3 A (continuously) | Up to ~1-2 A (continuously) | ~200 mA | ~2–3 A |
| **Protection Circuit** | No: would need to add separately | Yes: built-in | No | No |
| **Connector** | No | Bare leads | JST-PH 2-pin | Bare terminals |
| **Price** | ~$11.00 | ~$14 | ~$5.95 | ~$11 |

### 3.2.12 Battery Charger Selection

For this selection we will need a battery charger that charges the battery we chose from above in the Rechargeable Battery Selection. The specifications for this part are to safely and efficiently replenish the energy stored in a rechargeable battery. It will also need to control the voltage and current delivered to the battery, to ensure that charging is done within safe limits to prevent overheating, overcharging, or damage. This is important to research due to the wearable device of our SightSense shin guard, since it will need to be safe for the user and have battery longevity. Below we will discuss and compare three battery charging modules to determine which is the best suited for the smart shin guard. Each option will be evaluated on features such as size, safety, current, and compatibility with the shin guard.

The first option we will look at is the SparkFun LiPo Charger Basic (PTH08080) Micro USB. This charger is based on single cell lithium, it uses the MCP73831 chip but has fewer integrated features. It provides charge current from 15mA to 500mA [28] and comes in a small breakout form. The pros for this charger is that it is compact and micro-USB input. On the other hand, this charger lacks advanced protection circuity and has no onboard status indicators. This charger is a good option but not ideal choice for the SightSense shin guard.

The second option for the battery charger we looked at was the TP4056 charging module. This module is a low-cost lithium battery charger, it can provide 1000mA of charge current over micro-USB and includes protection circuitry [29]. While this battery charger has high charging current the TP4056 board is often heavier, lacks quality assurance, and may be too much for small batteries. Thus, this is also not a great choice for the SightSense shin guard.

The last option we researched was the Adafruit Industries LLC 4410. This battery charger is a compact and efficient lithium-ion/polymer battery charging module that is based on the MCP73831 chip. This charger is also designed for single cell batteries and is ideal for low power systems which would work greatly for this project. This device offers minimal external components making this battery charger lightweight and easy to use. It also provides automatic charge termination and status indication. The Adafruit 4410 is perfectly suited for the final design that works for safety, reliable, and efficient charging.

The table shown below shows the three different types of battery chargers and compares each feature to find the right one. The team went with the Adafruit 4410 battery charger selection because of it of its compact size, safety, current, and compatibility with the SightSense shin guard.

Table 14: Comparison of Battery Charger

| **Feature** | **SparkFun LiPo Charger Basic (PTH08080) Micro USB** | **TP4056 charging module** | **Adafruit Industries LLC 4410** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Charging chip | MCP73831 | TP4056 | MCP7381 |
| Charging current | 500mA | 1A | 500mA |
| Input interface | Micro-USB | Micro-USB | Micro-USB |
| Protection circuitry | None | Built in | Built in |
| LED indicators | No | Yes | Yes |
| Board Size | Compact | Large | compact |
| Ease of use | Low | Moderate | High |
| Cost | $4.95 | $3 | $5.95 |

### 3.2.13 Speaker Selection

To make absolutely certain the SightSense shin guard will function at the highest level, installing another obstacle alert sensor is imperative. Similar to how the vibration motor will vibrate when an obstacle is within a certain distance from the shin guard, the speaker will alert the user whether an object is on the left- or right-hand side of the user. This gives the user double the amount of coverage (Vibration motor and Audio speaker) and makes sure that the user has as much time to avoid possible collisions. This project will only require one type of speaker. Below we have listed three possible speakers and reasons as to why or why not the item was chosen.

Same Sky CDS-15158-SMT-TR:
The Same Sky CDS-15158-SMT-TR speaker has a Sound Pressure Level (SPL) of 87dB, a power of 0.3W, a size of 15x15mm, and a frequency range of 800 Hz - 20 kHz. Breaking this down, the SPL is at 87dB which although is not bad at all and in reality is a very good volume level, it is not as loud as the other speakers selected. The power is 0.3W which is a lower power and although suitable for small rooms or lower volume listening, this is not an ideal choice when it comes to this product. This shin guard will require to be worn in all types of settings, meaning a speaker best at low volumes will not be applicable to the daily life of the user. Another issue with this potential speaker is its size. This speaker is on the smaller size compared to the other two speakers and it may not produce sound loud enough for outdoor usage. And lastly, the frequency range is perfectly acceptable for outdoor usage, other speakers have a wider range. Another small but important factor about this speaker is the fact it is not weather resistant. This is a very good speaker but arguably not the right fit for this project.

Same Sky CDS-20144:
The Same Sky CDS-20144 speaker has an SPL of 92dB, a power of 1W, a size of 20x14.4mm, and a frequency of 800 Hz - 20 kHz. Breaking this down, the SPL is at 92 dB and when compared to the other speakers listed is the loudest. This is a very important feature since it will allow for us to input a much louder sound and make sure the user can hear the alert in a noisy area. The power is 1W, which is again a very good characteristic since the more power the speaker has the more the user can hear it in noisy areas. This is yet another benefit to choosing this speaker. The size, however, is not as good as other

speakers. Although the size of this device is 20x14.4 mm and is decent in a general sense it would have been more beneficial to have a larger speaker that could generate sound to higher places (the users' ears above). Lastly, this device has a frequency of 800 Hz - 20 kHz. This is not a huge loss in terms of outdoor use; however it is not as wide a range compared to other speakers in this comparison. For a few side comments about this device, it is not weather resistant and the mounting aspect of this could be a particular challenge for the shin guard itself. For this project device is a high contender in terms of valuable characteristics for this project.

PUI Audio AS02708CO-WR-R:
Lastly, the PUI Audio AS02708CO-WR-R, has an SPL of 88 dB, a power of 0.5W, a diameter 27mm, and a frequency of 300 Hz - 20 kHz. What does this mean? With an SPL or Sound Pressure Level of 88 dB we can say that this speaker can produce a decent level of noise - although comparing it to the Same Sky CDS-20144 it is not as loud and therefore loses some credibility in the selection. Nevertheless, the speaker should be loud enough to produce loud sounds or alerts. The power is 0.5W and although not bad, the more power the object has, the louder the speaker can produce noise. A key feature is the actual size of the device. The diameter is 27mm and therefore is the largest speaker in this list. This is arguably the best speaker to choose from given this characteristic since it will be able to project farther. Lastly, the frequency being from 300 Hz - 20 kHz is a huge advantage. This is the widest frequency range in this list and therefore produces a better low-end response - which means it will produce more perceptible tones outdoors. An added bonus to this speaker is the easy mounting capabilities and the weather resistance. Easy mounting makes for less issues in the installation process and less mistakes. The weather resistance is a huge bonus. This could be the determining factor in choosing this speaker since this is to be placed on a shin guard and needs to withstand the outside world for the user's everyday use.
After comparing the speakers selected in this list. We ultimately ended up going with the PUI Audio AS02708CO-WR-R for its weather resistance, frequency range, size, and easy mounting capabilities.

Table 15: Comparison of Speakers

| **Parameters** | **Same Sky CDS-15158-SMT-TR** | **Same Sky CDS-20144** | **PUI Audio AS02708CO-WR-R** |
|---|---|---|---|
| **Size & Weight** | 15x15mm (rectangle)<br>2.1g | 20x14.4mm (rectangle)<br>1.3g | 27mm (circular)<br>4.5g |
| **SPL** | 87dB @10cm | 92dB @ 10cm | 88dB @ 10m |
| **Mount Type** | Surface | Surface | Through-hole |
| **Frequency** | 800 Hz - 20 kHz | 800 Hz - 20 kHz | 300 Hz - 20 kHz |
| **Weather Resistant** | No | No | Yes |

| | | | |
|---|---|---|---|
| **Power** | 300mW | 1W | 0.5W |
| **Impedance** | 8 Ω | 4 Ω | 8 Ω |

### 3.2.14 Speaker Amplifier Selection

Now that we have our speaker chosen, we will need to decide which amplifier is needed to fit this speaker so that it can boost low power audio signals from the microcontroller to a higher power level that can work with the speaker and produce sound that is not too loud but loud enough for the user to hear the alerts. Below we will discuss three choices to see which amplifier will fit best with the PUI Audio AS02708CO-WR-R speaker.

We will begin with the Adafruit 2130, also known as the PAM8302A Mono Class D Audio Amplifier. This device is super small and capable of delivering 2.5W into a 4-8 ohm impedance speakers [30]. Looking at the chip inside of this amplifier we can observe that it runs on 2.0V-5.5V DC voltage supply. With the class D chip, the Adafruit 2130 is very efficient which can go over 90% efficient when using an 8ohm speaker [30]. This device also is ideal for low voltage battery powered systems, which is perfect when working with the SightSense shin guard. This module counts on a fixed gain of 24dB making this amplifier a great choice for its clean audio output with minimal distortion, small size feature, and easy to implement. It also generates low electromagnetic interference (EMI). Even with its mono output only and fixed gain this speaker amplifier makes a great choice for our final design.

The next option we researched was the PAM8403 Stereo Class D Amplifier. For this amplifier it is a very popular choice for speaker amplifiers. It provides two 3W channels into a 4-ohm load and 5V power supply [31]. This module also falls into class D which means that its efficiency can go up to 90% making this amplifier efficient. Another feature that this module has is that it can also produce low EMI as the first option as well, it has very low noise and is easy to control volume with its two-channel stereo output which makes controlling the volume easier for the user to adjust in different environments. On the other hand, this amplifier is larger compared to the Adafruit 2130 and it requires extra wiring thus not making it user-friendly. This option is great but not for what we need for our final design.

The last option is the LM386 Analog Audio Amplifier, which is another option that everyone uses. This amplifier operates at a voltage range from 4V to 12V or 5V – 18V [32]. It outputs around 0.5W of power which is lower than the two options above. The LM386 requires external components like resistors and capacitors to set gain and filter the output, which makes implementation more complex. When we consider the pros and cons for this amplifier the pros of this device are its simple analog design but for the cons we see that it has poor efficiency compared to the first two choices, requires more components, distortion, on the bigger side and does it generates more heat and is less power efficient which is not good for the wearable shin guard.

After comparing all three speaker amplifiers, the Adafruit 2130, also known as the PAM8302, was selected as the most suitable amplifier for the SightSense shin guard. The table below summarizes these three options and demonstrates why we chose the Adafruit 2130 for its performance, simplicity, and reliability.

Table 16: Comparison of Speaker Amplifiers

| Feature | Adafruit 2130 PAM8302A Mono Class D Amplifier | PAM8403 Stereo Class D Amplifier | LM386 Analog Audio Amplifier |
|---|---|---|---|
| Type | Class D Mono | Class D Stereo | Analog |
| Output Channels | 1 | 2 | 1 |
| Max. Output Power | 2.5W at 4-8 Ω | 3W at 4 Ω | ~0.5W |
| Voltage Range | 2-5.5V | 5V | 4-12V or 5-18V |
| Size | Compact | Big | Larger |
| Efficiency | High | High | Low |

For the battery we selected, Adafruit Industries LLC 2011, we need to regulate the voltage to different components that require different voltage levels. Since the battery we have chosen has a nominal voltage of 3.7V, we will need to use a voltage booster and a buck-converter to help regulate the voltage from 3.7 volts to 3.3 volts or 5 volts respectively. In the next two sections we will be giving a detailed explanation into which booster or buck-converter we selected, other options we considered, and why or why not we choose our specific component.

### 3.2.15 Battery Buck Converter Selection

In this section we will be discussing which buck-converter we selected for our battery. Like we stated earlier, our battery produces a nominal voltage of 3.7V but some components require a lower voltage. Below we will compare 3 different buck converters and select one for our final product.

SparkFun 5V to 3.3V 2A Synchronous Buck Converter (AP63203):
The SparkFun buck converter is a high-efficient and compact module. It is designed to step down voltages from a broad range of 3.8-3.2 volts to a stable 3.3-volt output. It uses a synchronous switching regulator - AP63203, which will allow it to reach high efficiency and can support up to 2A of continuous current. It is a key feature that this converter is able to deliver a high maximum current (up to 2A) while maintaining a steady output of 3.3V. This converter was typically built for small portable systems since it leads high on both reliability and compact size. It includes very essential features like the thermal shutdown and short-circuit protection. It also has an enable pin (EN) for power control from the microcontroller, like the ESP32-CAM. For our project which has multiple components - the camera, ESP32, ultrasonic sensor, laser module, speaker, amplifier, and vibration motor - having more space to move around in terms of current is essential. This ensures that we

avoid voltage drops and power instability. This converter is a reliable and robust power delivery system for a multi-load product.

Pololu 3.3V Step-Up/Step-Down Regulator (S8V9F3):
The Pololu S8V9F3 is a buck-boost converter which is capable of stepping up and stepping down the input voltage to a regulated 3.3V. It can adjust a wide range of inputs from 1.4V to 16V, which makes it an ideal candidate for our battery of choice since our battery could drop below the output voltage during discharge. The regulator supports up to 1A of output current and produces a high efficiency of about 90%. It includes a thermal shutdown and overcurrent protection. This is a key feature since thermal shutdown prevents overheating, extends product lifespan, reduces risk of fires, and ensures safe operation. Overcurrent protection protects against short circuits and overloads, prevents equipment damage, reduces fire risks, and ensures electrical safety. These are both extremely important factors to consider when selecting a buck converter. Another feature of the Pololu converter is its compact design, its size makes it extremely appealing in terms of PCB compatibility in comparison to other products. Since it has a large versatility in handling its low input voltages for battery systems, its maximum output current is less ideal. Our power system is demanding and with low current flexibility, devices such as the camera and audio amplifier can typically create spikes in the current. This 1A converter might not be able to handle this load under a sustained load. Since our system will be using a stable 5V input from a regulated booster we will no longer need the step-up capability. This means that although this is a useful regulator for our product it is too complex and does not provide enough benefits compared to other converters.

Pololu 3.3V 500mA Step-Down Regulator (D24V5F3):
This step-down regulator is highly compact and efficient for converting voltages down to 3.3V. It supports 500mA of current and has an input range of ~6.6-36V. Due to its input range it is typically suited for high-voltage sources and because its efficiency lies between 80%-93%. Similar to the other two converters, it includes protections like thermal shutdown and over-current limits. Its size is ideal since this will need to be easily adapted onto a PCB. However, regardless of its efficiency it is underpowered for our product. The 500mA current limit could work for one or two components but it will not be sufficient for the entire system we are running simultaneously (ultrasonic sensor, camera, speaker, vibration motor, ex.). Even if certain components can operate at low power, the simultaneous operation may easily exceed the converter's capabilities. This will lead to undervoltage and system resets. Comparing this to other converters which have four-times the current, this is not an ideal choice for our product.

Table 17: Comparison of Battery Buck Converters

| **Parameters** | **SparkFun AP63203** | **Pololu S8V9F3** | **Pololu D24V5F3** |
|---|---|---|---|
| **Input Range** | 3.8-32V | 1.4-16V | ~6.6-36V |
| **Output Voltage** | 3.3V (fixed) | 3.3V (fixed) | 3.3V (fixed) |

| | | | |
|---|---|---|---|
| **Maximum Output Current** | 2A | ~1A | 0.5A |
| **Efficiency** | High | ~90% | 80-93% |
| **Prot6ctions** | Thermal, Short Circuit | Thermal, Over-current | Thermal, Over-current |
| **Size** | ~1” x 1” | 0.4” x 0.65” | 0.5” x 0.4” x 0.1” |

For our product we have selected the SparkFun AP63203, which offers a reliable and strong power delivery solution for our system which has dynamic load demands. This converter is the best choice for ensuring a consistent performance across all systems in our design.

### 3.2.16 Battery Boost Converter Selection

Adafruit PowerBoost 500 basic:
The Adafruit PowerBoost 500 basic is a 5V boost converter module built from the TI TPS61090 IC. It was designed for LiPo batteries and can convert 3.7V(our battery voltage) to a regulated 5V output at 500mA. It has a synchronous design, this helps reduce energy waste and heat generation, which helps with wearable electronics for safety. The board has an enable pin functionality and a low battery indicator pin which will be incredibly helpful for the user to determine if the battery needs to be charged. It is a compact layout and for the PCB offers clean solder pads to make for easy integration on our PCB customs. Although it doesn’t offer the highest current capacity, 500mA is sufficient for many 5V components (LCD display, ultrasonic sensor, audio amplifier). A bonus is the Fusion/Eagle files that are available for the Adafruit products. Overall, this module is ideal for our 5V power demands due to its reliability, safety features, and ease of integration.

QWinOut Synchronous 1S LiPo Booster:
The QWinOut 1S LiPo Boost Converter is a cost-efficient, compact module designed specifically for converting 3.7V LiPo battery to 5V. It is a synchronous step-up design which enhances efficiency and reduces heat. This is extremely beneficial in wearable application since both space and thermal buildup are major concerns. The module supports up to ~1A of current output which makes it suitable for moderate loads (sensors, LED indicators, speakers). Its design is simplistic, making it ideal for beginners. Another advantage is its easy PCB integration. The module includes through-hole solder pads that make it organized and clean to attach to a custom board. It is also low cost and suited to a LiPo battery. Although it does lack the enable pins and low-battery detection it is still an excellent choice for powering a 5V system and can typically be paired with a buck-boost converter for 3.3V.

Readytosky 5V UBEC (3A):
The Readytosky UBEC (Universal Battery Elimination Circuit) is a strong voltage converter that can step-up from LiPo inputs (as low as 3.7V) to a solid 5V output at up to 3A. It was designed initially for applications that require higher current loads. However, this includes so many components that the UBEC can provide enough power to all of these without being phased. The output is clean and consistent, which is ideal for digital devices and control. It is slightly larger than the other options, however, is still compact enough for

small portable projects, such as ours. It includes convenient through-hole solder pads which make it adjustable and adaptable for PCBs. An added bonus is its tolerance for field use, which means our system will have a greater tolerance against voltage spikes and thermal variation. For multiple 5V applications this is the ideal choice.

Table 18: Comparison of Battery Boost Convertors

| **Parameters** | **Adafruit PowerBoost 500** | **QWinOut Booster** | **Readytosky UBEC** |
|---|---|---|---|
| **Max Output** | 500mA @ 5V | ~1A @ 5V | 3A @ 5V |
| **Size** | 50 x 22 mm | ~30 x 15 mm | RC |
| **Efficiency** | Synchronous with low noise | Synchronous - good for wearables | RC style |
| **Ease of Use** | Easy | Through-hole | Good |
| **Footprint** | PCB available | Compact | Moderate |

For our project the Adafruit PowerBoost 500 is the easiest option with good documentation, ideal for small to moderate loads (under 500mA), a clean 5V output and safety features like an enable pin and low-battery indicator.

Once all hardware components are bought, we will start prototyping by using a breadboard, wires, and other components to make sure that all hardware parts are working properly before implementing on a printed circuit board (PCB) and onto the final design. The PCB board will serve as the central platform that connects all electronic components that are apart of the SightSense shin guard. This will help the shin guard by minimizing weight and size that are crucial to maintaining user comfort. It will also facilitate stable connections to each hardware component to make sure everything looks clean and not crowded. Careful consideration will be given to make sure that power distribution and signal routing are done correctly. Further technical details can be found in chapter 8.

## 3.3 Software Selection

The software platforms and tools selected for the SightSense shin guard were chosen based on their compatibility with the hardware, ease of development, support for real-time processing, and low memory usage. Since the development is embedded in a wearable device and operates autonomously, all software components need to be lightweight, efficient, and compatible with the ESP32S3 WROOM microcontroller.

Arduino IDE:

The Arduino Integrated Development Environment (IDE) was selected as the primary development environment for firmware programming. The IDE provides extensive support for ESP32-based devices and simplifies integration with sensors, actuators, and Wi-Fi/Bluetooth communication modules. Its large ecosystem and open-source libraries accelerated development, particularly for prototyping sensor logic, motor control, and state machine implementation. This software was used to program both mcu's, as well as the haptic feedback response system, and able to make communication between esp's a more straightforward process.

ESP32 Board Support Package (BSP):
To support the specific hardware features of the ESP32-CAM, such as dual-core processing and built in Wi-Fi, the ESP32 BSP for Arduino was installed. This allowed developers to use GPIO pins, timers, camera functions, and wireless communication protocols seamlessly. This dev board was used to stream images from the camera module installed in the final position in its 3D print position.

Graphing and Simulation Tools:
To design and simulate software behavior, canva.com was used for flowcharts, state diagrams, and use case diagrams.

### 3.3.1 Software Challenges and Mitigations

**UART Overflows**: Caused intermittent freezing; resolved via `Serial.flush()` and reduced output frequency.
**Stack Overflow in Recursion**: Sensor polling routines restructured to iterative loops.
**Camera Buffer Crashes**: Limited image resolution to avoid heap fragmentation.
**PWM Distortion**: Fixed by adjusting timer resolution and switching speaker mounting position.
These refinements helped stabilize the system, especially under continuous runtime testing.

By creating a ML learning algorithm through Edge Impulse, the baseline of undistorted 6 stripe pattern was used. Through trial and error, the algorithm was successfully deployed and tested on the ESP32-CAM to accuracy as high as 83%. By creating a real time operating system that was not holding images on chip, just processing them in real time, most of the issues above were overcome.

To ensure efficient development, integration, and visualization throughout the SightSense project, a variety of software tools were selected based on their compatibility with the ESP32-CAM microcontroller and their ability to support real-time processing and embedded system design. Table 21 provides a summary of the primary software platforms used in this project, outlining each tool's role and the reasoning behind its selection. These tools enabled streamlined firmware development, hardware interfacing, system debugging, and the creation of visual representations essential for documenting and communicating software logic.

Table 19: Summary of Software Tools

| Software Tool | Purpose | Reason for Selection |
|---|---|---|
| **ThorCam** | Image capture for testing | Calibrating distortion patterns with DOE projection |

| | | |
|---|---|---|
| **Arduino IDE** | Firmware development | ESP32 compatible, easily documented |
| **ESP32 BSP** | GPIO, camera, and network support | Hardware abstraction |
| **Visual Studio Code** | Advanced code editing and debugging | Debugging support |
| **Canva.com** | Diagram generation | Flowcharts, State diagram, Use Case Diagram |
| **GitHub** | Version control | History tracking, feature branching |
| **PlatformIO** | Advanced build system | Supports multiple targets and CI/CD-like builds |

To enable efficient hardware-software interaction within the SightSense smart shin guard, our development leveraged a variety of embedded software libraries. These libraries provided essential functionality for handling sensor inputs, managing actuators, processing serial communication, and maintaining real-time responsiveness. By integrating well-supported and lightweight libraries, we were able to reduce development time, improve code stability, and ensure seamless compatibility with the ESP32-CAM platform. The table below outlines the core libraries used, their purposes, and the specific features they enabled within our firmware.

Table 20: Core Software Libraries Used in Embedded Development

| Library Name | Purpose | Relevance to Project |
|---|---|---|
| **NewPing.h** | Ultrasonic distance reading | Reads and averages data from HC-SR04 |
| **ESP32CAM.h** | Camera management | Accesses frames from Thorlabs module |
| **Wire.h** | I2C communication | Interfaces with DRV2605L motor driver |
| **Adafruit_DRV2605.h** | Vibration motor control | Controls haptic feedback vibrations |
| **tone()** | Built-in function for audio feedback | Generate alerts using speaker |

## 3.4 Requirements and Specifications for Optical Components

For our project the A Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense), which is a wearable smart shin guard for the visually impaired, a structured light sensing system will be used to detect objects and obstacles. For this system to be accurate and reliable, the optical components chosen need to be able to achieve certain specifications and requirements. In the following section, the optical components chosen specifications will be written in table format. Calculations will be done with the chosen components and will be compared to see if they fall within the chosen parameters. This is an important aspect of the research done for this project to confirm that the chosen components will be able to successfully detect objects and obstacles through our structured light sensing system.

### 3.4.1 Component Specification

The optical components chosen for the structured light system used in our SightSense project include a diffractive optical element or DOE, two aspheric plano convex lens, camera lens, and laser diode module. The first lens expands the beam, and the second lens collimates the beam. The table below will give the specifications of the components chosen. All these are key components needed in the stripe projection process and taking measurements of the distortion in the stripes to get a reliable depth mapping and to identify potential obstacles and objects in the user's way.

Table 21: Optical Component Specification

| Component | Parameter | Specifications | Unit |
|---|---|---|---|
| **Aspheric Plano Convex Lens** | A) Focal Length<br>B) Diameter<br>C)Coating<br>D)F/# | A)3 to 15<br>B)2 to 6<br>C)650<br>D)F/2 to F/4 | A) mm<br>B) mm<br>C)Nm<br>D)- |
| **Diffractive Optical Elements** | A) Wavelength<br>B) Pattern Type<br>C)Field of View<br>D)Projection Distance | A)650<br>B) Linear Stripe<br>C)60 to 80<br>D)2 | A) Nm<br>B)7x7<br>C)Full angle<br>D)Meters |
| **Camera Lens** | A) Focal Length<br>B) Field of View<br>C)F/# | A)2 to 4<br>B)70 to 140<br>C)f/2 – f/3 | A) mm<br>B) Degree diagonal<br>C)- |
| **Laser Diode Module** | A) Wavelength<br>B) Output Power<br>C)Operating Voltage/Current | A)650-660<br>B)3-5<br>C)3.3 @ 25mA | A) nm<br>B)mW<br>C)V/A |

### 3.4.2 Chosen Engineering Requirements

For the A Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) to achieve the goals listed in chapter 2, certain system requirements must be met. This includes a fast, almost real-time response to objects detected. The distance that will be in the range of detection must go up to 2 meters. These are the basic requirements and more will be shown in the table below. These are the requirements chosen for our project and achieving these requirements will be the final goal of our sight project and ensure that the user has a successful and safe experience while using the product. User safety is the most important factor in our project, because ultimately the goal of the SightSense is to improve user independence.

Table 22:Chosen Engineering Requirements

| **Engineering Requirements** | **Requirements Specifications** | **Unit** |
|---|---|---|
| Latency (Camera to Vibration) ensures a fast response time. | ≤ 250 | ms |
| Obstacle Detection Range to give adequate distance to stop or redirect. | ≥2 | meters |
| Maximum power consumption enables multiple hours of use. | ≤1.5 | Watt |
| Depth accuracy to distinguish curbs, potholes or ditches, and steps. | ≤ 7 | cm |
| Minimum field of view required to capture sufficient scene width for SLS. | 70 | degrees |

### 3.4.3 Details of Design Calculation

Based off the specifications given by the data sheets of the chosen optical elements, calculations can be derived to express if these specifications fall within the chosen specifications for the SightSense This is a crucial step in component selection, because the calculation of the components should fall within the specified specifications of our project.

The first calculation shown will be for the “detection box” created by the diffractive optical element. Based off the height and width, and angle of the element, we can get the exact size of the “detection box” created by the DOE. This detection box will be the area of the fanned-out region of the laser beam where the projected horizontal lines will be visible. The area of this detection box will be for objects within 2 meters. Any object that is detected in this area will be seen as an obstacle and will let the user know, and when the path is clear, the user will also be notified.

Equation 1: Detection Box of Diffractive Optical Element

$$Detection\ Box\ at\ 2\ meters$$

$$Width:\ 2\ x\ D\ x\ Tan\left(\frac{\theta_H}{2}\right)\ =\ 2\ x\ 2\ x\ \tan(20°)\ =\ 1.46\ meters$$

$$Height:\ 2\ x\ D\ x\ Tan\left(\frac{\theta_V}{2}\right)\ =\ 2\ x\ 2\ x\ \tan(10°)\ =\ 0.7\ meters$$

The calculated width for the detection box is 1.46 meters wide by 0.7 meters high. These calculations will be referred to later in the chapter to compare with the horizontal scene width of the camera module.

The laser diode module that will be used for the project is a 650nm “dot” laser beam. The overall power output with the operating current will be shown in the equation below.

Equation 2: Shows Output Power @ 3.3V and 25mA

$$Output\ Laser\ Power\ =\ V\ x\ I\ =\ 3.3\ x\ .025\ =\ 82.5\ mW$$

The optical power output of the laser used in the final SightSense project is between 200 and 250 output. The output power calculated above is taken from the operating current and voltage of the laser diode module. The laser diode module on the data sheet reads that it is a 250mW laser which is class 2 or 3R which with proper classification can be safe if it is not viewed directly. With the calculated output power of 82.5mW, the laser diode module falls into the category of low power components needed for the SightSense project.

The camera module that will be used for the structured light system will be used for object detection. By taking the pixel count and pitch, the field of view of the camera can be calculated. Having sufficient field of view to be able to capture the area where curbs or drop offs will be crucial to the success of the final design. The figure below will show the calculations for the field of view. The camera module used will be the OV2640 found on the ESP32-CAM. The camera module has an active pixel array of 1600 x 1200 pixels, and 2.2 µm pitch.

$$width\ 1600\ x\ 2.2\mu m = 3.52\ mm$$

$$height\ 1200x\ 2.2\mu m = 2.64mm$$

$$diagonal\ \sqrt{3.52^2 + 2.64^2} = 4.41mm$$

$$FOV = 2\arctan\left(\frac{sensor\ size}{2f}\right) = 2\arctan\left(\frac{4.41}{22.6}\right) = 81°$$

Figure 12: Field of View Calculation for OV2640 Camera module

The final calculated value of 81 degrees will fall within the necessary range for accuracy and success of the structured light system for the SightSense project and meets the 60 degrees field of view that is a minimum requirement for the project. With the field of view meeting the requirements, the next step is calculating if the camera module will be able to get a full image of the projected striped light pattern given by the diffractive optical element. The equation given below will give the measurement for the horizontal scene width.

Equation : Horizontal Scene Width of OV2460 Camera Module

$$2\ x\ \tan\left(\frac{62°}{2}\right) = 2\ x\ \tan\ (31°)\ x\ 2\ x\ 0.6018\ =\ 1.2\ meters$$

This horizonal scene width falls comfortably within the 1.4-meter detection box created by the diffractive optical element that was calculated earlier in the chapter. This detection box needs to be captured by the camera module to calculate distortions in the projected light pattern of stripes that will detect objects and obstacles. A table will be given below to tabulate the chosen engineering requirements and the calculated specifications.

Table 23: Engineering and Calculated Specifications

| Parameter | Chosen Specification | Calculated Specification | Meets Requirement |
|---|---|---|---|
| **Detection of Obstacles within "detection box" @ 2 meters** | ≤1.4m | 1.2m | yes |
| **FOV (Horizontal)** | ≥60° | 81° | yes |
| **Laser Power consumption** | ≤1.5W | 82.5mW | yes |
| **Frame Rate** | ≥15fps | 15-20fps | yes |

The camera module detection area falls within the "detection box" created by the diffractive optical element. This means that any object within that detection area that will cause distortion will be captured by the camera module. This will alert the user that an object or obstacle has been detected.

The field of view of the camera module was also calculated and has exceeded the required specifications needed for the structured light system used by the SightSense project.

Laser power consumption wanted to be kept below 1.5W as a specification chosen by the SightSense team to keep power consumption as low as possible. With an output power of 82.5mw while operating at 3.3 V and 250 mA, this falls below the 1.5W specified by the team. An engineering design constraint for this project includes using low power components to maximize power and battery life of the final product.

For real time object and obstacle detection to occur without the user having to adjust for gate and walk in a regular motion, the camera module should operate at least 15 frames per second, and off the spec sheet for the ESP32-CAM, the frames per second are from 15 to 20.

### 3.4.4 Optical Design Trade Offs

During the initial testing process, it was determined that improvements in certain design parameters could give drawbacks to other parameters. Examples of this include the field of view versus resolution, optical power versus eye safety, and resolution versus dynamic range. A higher degree field of view increases how much of the field that the camera sensor can see, but as it increases, distortion also increases. There is also a lower pixel density per degree. With increased distortion, this will negatively affect the performance of the obstacle detection system, because we want a clear projection of the vertical stripes. Any distortion from an increased field of view will negatively affect the distortion measurement of the projected stripes. For eye safety, the SightSense shin guard will use a laser diode module below 5mW optical output. It can be thought that perhaps by increasing the power of the optical output of the laser diode, the distance for obstacle detection can be increased. If a more powerful laser diode module were to be used, the increased power would make it not possible to use in public. The distance in mind for obstacle detection was 2 meters. This means that the angle of the projection fan out from the diffractive optical element must match with the focal distance and field of view of the camera module. If the projection does not match the camera distance and field of view, the structured light system will not be reliable and accurate. Finally, the biggest optical tradeoffs in our SightSense project include resolution versus dynamic range, for example, a low-cost sensor may miss low light projections in a brighter ambient light setting. One of the designs constraints we have is the overall cost of the project. There are cameras and lenses available that would cover the budget of the entire project for SightSense and the same can be said for other components on the project, but for structure light, the camera sensor is crucial in the success of 3D scanning.

## 3.5 User Interface Design Calculations

Designing an assistive device for visually impaired users demands a unique approach to user interface (UI) development. While typical graphical interfaces are not applicable, the SightSense smart shin guard leverages multimodal feedback mechanisms to communicate with the user. These mechanisms serve as the equivalent of a traditional interface, providing real-time alerts and intuitive guidance through vibration and audio cues.

The user interface is minimal by design but highly responsive. For instance, different vibration patterns correspond to specific distances detected by the ultrasonic sensor. A short pulse indicates a distant object, while continuous pulses suggest immediate danger. Similarly, audio tones differ in pitch and volume depending on proximity. These settings were chosen after internal testing among team members and reflect human-centered principles for accessibility.

## 3.6 Calibration and Tuning

To ensure accuracy and consistency across different environments and use cases, the SightSense shin guard undergoes a series of calibration and tuning procedures. These are essential to align sensor outputs, feedback thresholds, and detection logic with real-world use.

The calibration testing for the ultrasonic sensor system was tested at multiple distances expecting the haptic response to correspond to the distance from the user. As the user approaches the obstacle, the haptic response will alert the user. The DRV2605L motor is calibrated for three vibration levels using a linear ramp-up voltage pattern as the user approaches the obstacle.

## 3.7 Mechanical Mounting and Enclosure Design

The physical integration of electronic components within footwear presents mechanical challenges that impact sensor performance and user comfort. Our team selected the Dunlop Chesapeake shin guard for its wide toe area, water resistance, and interior mounting volume. Components are mounted using Velcro, zip ties, and foam padding to minimize vibration transfer and physical discomfort.

A PLA 3D print was created specifically for this project to house all PCB components, the LCD screen, camera, optical bandpass filter, and laser projection system. The system has space on the side for the speaker system, as well as ports to connect the vibration motor and move it into different positions based off user preference.

## 3.8 Structured Light Grid Testing Setup

In anticipation of future upgrades, the SightSense team explored structured light grid projection using a diffraction optical element (DOE) and ov2640 camera module. This setup allows us to visualize grid distortions caused by nearby objects. The baseline for this testing included gathering close to 1600 images from the ESP32-CAM from the position where the camera would be on the final design. Undistorted images were taken as a baseline and images were taken and classified for different forms of obstacles, such as chair legs, steps, and pot holes. As the images were classified and the algorithm was successfully deployed, test runs were done with confusion matrices built on the data to check for accuracy. For our tests we ran about 80% accuracy.

## 3.9 Maintenance and Replaceability Design

A wearable system like SightSense must be easy to repair and upgrade over time. We adopted a modular wiring scheme using JST connectors and socketed headers, allowing rapid replacement of defective components. Battery access is tool-free, and sensor modules are mounted in swappable compartments.

All components on the design will be easy to replace and or repair. The ultrasonic sensors can be unplugged and replaced in seconds. The optical system can have components replaced within minutes as well. The main PCB board disconnects from the ESP32-CAM with wires, which allow for easy and fast removal of the camera module from the main board.

## 3.10 Human Factors Engineering and Safety

Safety and usability for visually impaired users are paramount. All design choices were evaluated for potential user risk. For instance, the ultrasonic sensors are mounted to detect obstacles right in front of the user. For our testing processes, the specs for reliability of the system must be met before confidently letting a visually impaired user use the product. Once accuracy is 98% the product can safely be used by the public.

## 3.11 Sensor Selection Comparison:

To evaluate the most suitable sensors for obstacle detection and depth mapping in the SightSense smart shin guard, our team conducted a comparative analysis of various options based on range, accuracy, power consumption, ease of integration, and environmental reliability. The goal was to identify components that would meet the practical demands of a wearable assistive device, especially in terms of size, cost, and performance under real-world conditions. The table below presents a comparison of several sensor types considered during the research phase, highlighting the reasons behind the final selection of both the HC-SR04 ultrasonic sensor and the Thorlabs CS165CU camera.

Table 24: Sensor Comparison for Obstacle Detection and Visual Mapping

| Sensor Type | Pros | Cons | Used In Our Project |
|---|---|---|---|
| **HC-SR04 Ultrasonic** | Cheap, easy to integrate, accurate | Narrow beam, false positives | Yes |
| **VL53L0X ToF** | Compact, good short-range accuracy | Sensitive to reflectivity | No |
| **IR Sensors** | Low power, easy to use | Inaccurate in sunlight | No |
| **Thorlabs CS165CU** | High resolution, compatible with DOE | Expensive, requires processing power | Yes |

## 3.12 Summary Table: Design Constraints and Their Impact

The table below presents a concise overview of the various design constraints the SightSense team encountered and how these factors influenced decisions regarding hardware, layout, and feature implementation. This summary helps illustrate the engineering trade-offs necessary to create a functional and wearable device under practical limitations.

Table 25: Constraint Overview and Impact

| Constraint | Design Decision Impact | Example Component | Trade-Offs Made |
|---|---|---|---|
| **Power Limitation** | Required low voltage, efficient devices | 3.7V Li-ion Battery | Limited continuous runtime |
| **Ergonomic Fit** | Lightweight, balanced enclosures | ABS Housing | Reduced sensor range for comfort |
| **Cost Constraint** | Prioritized low-cost components with multi-use | ESP32-CAM | Avoided premium processors |
| **Environmental Protection** | Dust/water sealing necessary | IP44 Conformal Coating | Not submersible |
| **Safety/Comfort** | Adjusted vibration/audio levels | DRV2605L, Buzzer | Lower maximum intensity for safety |
| **Maintenance** | Tool-free access and modular swaps | JST Wiring, Velcro | Slight increase in shin guard footprint |

## 3.13 Design Constraints Comparison with Similar Products

Earlier in the design process in senior design 1, there were three similar products used in assisting the visually impaired. These three products were a $175 Tavkomo smart cane, a $1,150 WeWalk smart cane V2, and a $147 Phoenix smart cane. The design constraints that were compared between our SightSense project and the three comparable products mentioned above are economic, time, environmental, social, political, ethical, health and safety, manufacturability, and risk. The table below explaining the reasoning on the design constraints can be found below.

Table 26: Design constraints

| # | Constraint Category | SightSense Project | Tavkomco Smart Cane ($175) | WeWalk Smart Cane V2 ($1,150) | Phoenix Smart Cane ($147) | Comments |
|---|---|---|---|---|---|---|
| 1 | Economic | Low-cost components (ESP32- | Affordable but may have low | Very expensive and inaccessible | Moderately priced, with limited | Much lower cost with similar or better features |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Cam, laser) <$100 | sensor precision. | to many users. | value features. | and functionality. |
| 2 | Time | 1 summer semester and 1 fall semester timeline. | Off the shelf product. | Mass produced limited product updates. | Pre-built, limited adaptability/ custom use. | Custom built with rapid iteration flexibility. |
| 3 | Environmental | Designed for outdoor use. | Likely uses generic plastic. | Unknown recyclability, more power use from AI. | Uses basic detection, unclear weather proofing. | Purpose built for rugged outdoor use. |
| 4 | Social | Non-stigmatizing shin guard design. | Traditional cane form | High tech but bulky. | Follows traditional cane aesthetics. | Worn on foot so a lower profile design. |
| 5 | Political | Complies with low power laser regulations. | Unclear compliance with laser safety. | Uses AI may need to follow privacy policy. | Basic electrical compliance. | Explicitly follows laser safety from the start. |
| 6 | Ethical | Privacy respecting, user centered. | No clear info on privacy. | Cloud-based AI could bring up data concerns. | Minimal user feedback or control settings. | User retains full privacy. |
| 7 | Health and safety | Class 3R laser projection that points down only. | May lack thermal protection. | Includes feedback, but no laser safety classification. | May lack built-in protections for high current use. | Full safety assessment included in the design. |
| 8 | Manufacturability | 3D printable parts. Off the shelf components. | Aluminum tube, standard electronics. | Plastic moldings, complex internals. | Standard factory design. | Modular and field repairs available. |
| 9 | Sustainability | Rechargeable, reusability of modules. | Uses reflective tape. | Higher carbon footprint. | Unknown battery sustainability. | Energy efficient and upgradeable. |
| 10 | Risk | cannot have false positive results. | Alarm only. | AI failure or network issues will cause | Limited resolution or surface mapping. | Real word depth mapping will give more reliable results. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | detection breakdown | | |

In the comparison table above, the comment section explains how the design constraints for the SightSense project would be superior to the other similar products.

## 3.14 Safety Requirements for the Final Design

During the research process done for the SightSense project, information on safety requirements is crucial for following the correct protocol when attempting to design a product to help improve the everyday life and independence of the visually impaired. A table that goes over the safety requirements will be found below.

Table 27: Safety Requirements for Final Design

| # | Safety Requirement | Implementation in Final Design |
|---|---|---|
| **1** | Laser Safety | Laser power limited to Class 3R and mounted to only project downward |
| **2** | Electrical Safety | All wiring enclosed and insulated; components fixed in housing |
| **3** | Mechanical Safety | Components securely fastened to avoid detachment while walking |
| **4** | Thermal Safety | System tested to ensure no overheating during extended use |
| **5** | Eye Protection | Beam path designed to avoid accidental eye exposure |
| **6** | User Instruction | User guide provided with simple steps and warnings for proper use |
| **7** | Battery Safety | Rechargeable battery modules chosen with short-circuit protection |
| **8** | Environmental Safety | System designed to be resistant to dust and light water exposure |
| **9** | Feedback Clarity | Clear vibration or audio cues to ensure user knows when an object is detected |
| **10** | Public Interaction Safety | Device form is compact and low-profile to avoid interfering with others |

The table above gives a clear and concise breakdown of the safety requirements needed to be followed by SightSense as a final product. There are many considerations to keep in mind, especially that the user of the product will be a visually impaired person, that the product will need to be able to keep safe by avoiding objects and obstacles as well as following proper laser safety.

## 3.15 Optical Design Standards

Doing the investigation into the safety standards for our SightSense project, eight specific standards were found for the optical design portion of the project. These standards will be presented in the table below.

Table 28: Optical Design Standards

| # | Standard Regulation | Implementation in Design |
|---|---|---|
| **1** | IEC 60825-1 (Laser Safety) | Used Class 3R laser and aimed beam strictly at ground to ensure eye safety. |
| **2** | ISO 13482 (Robotics - Personal Care Safety) | Designed for non-contact obstacle detection and user comfort in wearable form. |
| **3** | ADA (Americans with Disabilities Act) Accessibility Guidelines | Project supports mobility for visually impaired users and encourages inclusivity. |
| **4** | FCC Part 15 (EMI Compliance for Electronics) | Selected low-frequency components and shielded wiring to minimize EMI. |
| **5** | RoHS Compliance (EU Restriction of Hazardous Substances) | Used RoHS-compliant components (e.g., ESP32-CAM modules, PCBs). |
| **6** | IEEE 802.11 (Wi-Fi standard used by ESP32-CAM) | ESP32-CAM follows IEEE 802.11b/g/n standards for wireless transmission (if used). |
| **7** | UL/CE Mark (Battery and power supply compliance) | Selected USB-rechargeable battery modules that meet UL/CE safety standards |
| **8** | ISO 9241-210 (Human-centered design) | User-centered iterative design and testing with emphasis on discretion and comfort |

The above-stated standards are to be followed by our SightSense project, especially because our final design will be used by a visually impaired person, making safety a top priority.

## 3.17 Conclusion

In this chapter, we thoroughly examined both the hardware and software components that were needed to implement our wearable A Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) shin guard. We investigated several options for every subsystem, which included sensors, microcontrollers, communication protocols, power solutions, and applicable software developments. This was done by carefully comparing various parts and technologies.

Another thing we covered briefly in this chapter was ensuring that we meet basic electrical safety standards. Making sure that no component overheats during operation, haptic motor should operate within human comfort limits, and sound levels must remain below thresholds that might risk too loud alerts.

Every comparison was supported by concise tables and justifications for every option that was discussed, guaranteeing that our decisions were based on user requirements, cost, availability, compatibility, and performance.

Critical choices about processing, power supply, haptic feedback, connectivity interfaces and sensing were all part of our hardware technology comparisons. To ensure smooth integration and adaptable code development, software comparisons were also conducted across several IDEs, libraries, and communication protocols.
Each table included at least three options for each hardware component. It also included our choices that were supported by the project's objectives, which included low power consumption, lightweight design, ease of programming, and accessibility for individuals with visual impairments.

To summarize, by making sure that each component was selected not just for its technical value but also for its effect on the user experience, this chapter established the framework for our system design. Our decisions demonstrate a balance between innovation and practicality. With this research being complete, we have a clear plan for testing, prototyping, and more importantly improvement which will enable us to move confidently into the project's development and integration stages.

# Chapter 4 Standards and Design Constraints

## 4.1 Relevant Standards

This chapter will outline the relevant standards and design constraints that influenced the development of the SightSense shin guard. These include rules pertaining to safety, wireless communication protocols, size and power restrictions, and user comfort. The goal is to guarantee that the final design is both functional and consistent with applicable rules.

### 4.1.1 Power and Battery Safety Standards

Any wearable system must include power management, especially for our SightSense shin guard project since it combines several components like microcontrollers, ultrasonic sensors, vibration motor, speaker, and camera as well as other components, that depend on either continuous or periodic power delivery. Ensuring safe, dependable, and effective energy utilization is crucial for long term durability and user safety as well as device performance. We will take a look at some of the following standards for power and battery safety.

**IEC 62133**

The most popular international standard for rechargeable lithium-ion battery safety is the IEC 62133. Some of its requirements include testing and ensuring lithium-ion batteries are dependable to use, especially with our wearable product since it will interact with a person [33]. The SightSense shin guard will rely on a compact lithium-ion battery that will be used to power the ESP32-CAM and ESP32-S3-WROOM-1 microcontrollers, ultrasonic sensors, and vibration and audio feedback. The design is guided by this standard which specifies the safety for rechargeable batteries used in portable applications to protect user safety and reduce hazards like overheating and short circuits or even in dangerous situations, like for example a fire. This standard is a great example of how to use these batteries, especially with our design because these shin guards will be used by a visually impaired individual. Making sure we follow these regulations will ensure that the SightSense device provides safe and reliable power while minimizing hazards.

### 4.1.2 Audio and Vibration Feedback Standards

For this section we will cover the audio and vibration safety standards that will be considered for our product. The SightSense shin guard is to be worn by an everyday user. This means that all standards set are needed to protect the user from any harm or damage.

**IEC 62368-1: Audio Standards**

The IEC is the International Electrotechnical Commission which helps create safety standards for electronics. The IEC 62368-1 is the safety standard for audio equipment and will be one of the standards we use to prevent pain, injury, or property damage due to hazards (e.g. electrical shock, fire, thermal burn). In the IEC 62368-1, the main topic of audio comes from the sound pressure levels or SPL section. SPL is a logarithmic measure of the effective pressure of a sound wave in relation to a reference value. The most commonly used unit of measure is decibels (dB). The standard requirements and testing methods that are necessary for protecting users from excessive acoustic energy emitted are in reference to components such as headphones and speakers. To begin, the acoustic energy source classification is the standard that classifies sound pressure levels as a type of energy source. These classes depend on the level and duration of exposure and if not properly controlled, the user could experience pain or injury. There are five classification levels ranging from A - E, with A being the highest rated class. An A-rated product has the highest rated sound absorption performance. This means it is extremely safe for the user. The requirements listed in the standard for personal listening devices are as follows: maximum A-rated sound pressure level is limited to 100dBA (Loud Street noise, noisy factory, police whistle) when measured with a 500mV input, devices must have volume control - they must not exceed 85dBA. To test these conditions, we can use the Head to Torso Simulator (although for our project we would need to measure more along the lines of a Head-to-Toe simulator) which should specify input signals and methods to determine compliance. The standard also includes warnings and information about audio equipment. That is if the audio equipment outputs above a safe threshold, it must have warning labels or instructions indicating the risks of hearing damage to the user.

**ISO 5349-1:2001: Vibration Standards**

The International Organization for Standardization is a nongovernmental worldwide federation of national standards. It comprises over 160 countries to help in the standardization process and ensures that all countries are informed of changes or additions to standards to improve the safety of life. That being said, one of the main safety standards for this project is the vibration motor that will be mounted on the shin guard. It should vibrate at a comfortable rate and should not cause any harm or damage to the user. The ISO 5349-1:2001, which is the mechanical vibration - measurement and evaluation of human exposure to hand-transmitted vibration, is the ideal safety standard we will be using for this product. Although our product will be worn on the users' leg, we will negate the "hand-transmitted" and rather use that as a general "all parts of the body vibration standard". The purpose of the standard is to provide guidance on measuring and evaluating hand-transmitted vibration to assess the risk of vibration-induced injuries (e.g. HAVS - Hand-Arm Vibration Syndrome). This is a very important tool for any small vibrating device. The standard applies to the vibration transmitted from a surface (tool or workpiece, in this case shin guard) into the hand of the user (in this case the calf of the user). It focuses on long-term daily exposure instead of short-term impulses. It uses frequency-weighted acceleration which is based on how harmful different frequencies are to human tissue and is typically measured in meters per second squared. The outcome of the standard showed that exposure in prolonged periods of time can cause circulatory, neurological, and musculoskeletal disorders. The higher the vibration levels or longer durations can increase the risk of damage. For this project we will need to ensure the duration of a vibration is not long enough so as to cause health risks to the user. There are ways and tools to reduce the risk of these factors, which are vibration-reducing gloves, posture, and temperature of the environment. After reviewing this standard our product design should meet the industry standards for human exposure to mechanical vibration.

### 4.1.3 Electrical Safety Standards

There are many standards for electrical safety. We will be focusing on a few of them and how they relate to this project. Beginning with the general standards on electrical safety and wearable electronics, the IEC/UL 62368-1 is a standard that covers safety of audio/video, in-circuit testing (ICT) and similar electronic equipment. This is a good standard we will follow since it is widely used for consumers and for wearable devices. The IEC 60601-1 applies to the product since some could say this is a medical device of some sort. Meaning since the product is for the visually impaired and is aimed at being an aid to help with sight. This provides the basic safety and performance we are looking for. In the same standard but different section, IEC 60601-1-2, this part refers to the electromagnetic compatibility (EMC) requirement for medical electrical equipment. In the IEC 60068 standard, this is in relation to environmental testing. Meaning when our product is in testing phases, we will need to follow these standards for vibration, shock, temperature, and humidity, which is incredibly important for the durability of the product. Another standard that fits under the general electrical safety standards is the IEC 61000-4-2, which is the electrostatic discharge (ESD) immunity which is the ability of a device to withstand the effects of ESD events without malfunctioning or being damaged. This stand is especially helpful for outdoor use.

Moving on to more specific electrical standards. The IEC 60364 standard covers general wiring and protection principles. Most of these standards are helpful for wiring harness/insulation, and although it is not very specific to small electrical components like our product. It does offer helpful information in terms of what general electrical standards look like in general wiring. Another standard for electrical safety is the IEC 61140, which focuses on the protection against electric shock. For battery safety standards, the IEC 62133-2 specifies safety for portable rechargeable cells (Li-ion/Li-polymer). This is an extremely beneficial standard since the battery we have chosen is a rechargeable Lithium-Ion Cylindrical Cell. The UL1642 and UL2054 are United States standards for battery safety in portable and consumer applications.

After researching an ample number of standards, there are plenty of electrical safety standards to consider when producing this project. Although this seems like a constraint to our project, this is extremely beneficial and will help our product in the long run and the safety of the user.

### 4.1.4 Camera and Image Quality

For a reliable structured light system to be able to detect objects, the camera system needs to be effective. This camera module needs to be able to measure image distortion in the projected stripes to be able to detect objects in real time through depth mapping of the area imaged. To ensure a quality imaging system, several constraints were followed when designing the SightSense project. The design constraints for the imaging system were resolution, as the resolution needs to be good enough to be able to capture the image of the projected stripes. Frame rates also need to be in the range where real time or semi real time detection is possible. The field of view is a very important constraint in that the field of view area needs to be able to detect obstacles but also drop offs and ditches. The module needs to function under low power and be able to operate under a current draw of 250mA to be able to be compatible with the ESP32 microcontroller. Size and weight constraints make the engineering design need small components and design. A swappable M12 mount enables easy switching between lenses during prototyping to optimize the design. The imaging acquisition system follows established standards for optical and digital performance. ISO 12233 is the standard that defines resolution test methods and includes the use of charts to be able to calculate the modulation transfer function. EMVA 1288 is the European machine vision association's standard for parameters such as signal to noise ratio, dynamic range and quantum efficiency as cited in the references in the appendix. The ESP32-CAM sensor was selected due to its low power design and capability of detecting visible light and using an M12 lens mount allows for swapping to lenses with better field of view. To confirm image quality tests were run to test sharpness, field of view, and contrast. The stripe contrast can be evaluated under ambient light to ensure pattern visibility.

### 4.1.5 Safety for Lasers

The use of laser diodes in structured light systems such as projectors requires careful consideration of the optical design and safety standards and regulations. For this structured light system to be designed and implemented, a red laser diode is chosen that operates at 655 nm and 4MW optical output. This laser diode module complies with international safety standards and meets the optical design specifications for the project. The main governing bodies that give the primary classification grades are the International Electromechanical Commission (IEC) and the American National Standards Institute (ANSI). IEC 60825-1 classifies lasers by power and wavelength, where our laser falls under class 2, which is considered safe for the eye due to the blinking response in the human eye [34]. ANSI Z136.1 provides detailed guidance on the safe use of laser diodes in different environments. Our design will have the necessary safety and regulation markings, which include beam direction control to minimize the risk of any accidental exposure. From an engineering perspective, several measures were taken to ensure safe integration of the laser system for the projector. The laser diode used is at 4MW and puts it well below the limits of stretching out of class 2. This eliminates the need for extra safety training or eye protection. The directional setup of the laser projector and camera is pointed down and away from the eyes of any oncoming pedestrian. The use of the DOE will also diffuse energy throughout the stripe pattern. The mechanical mounting of the laser diode module will be able to house the system and ensure that beams don't stray or reflect. The laser is powered by a 5V source and is optionally modulated, but software level controls enable use of the laser to be active only during operation. To validate the safety of the laser, the optical output power was measured, and thermal monitoring can be used to ensure no excess heat is causing integrity issues in the housing. This system has strict adherence to guidelines IEC 608251 and ANSI Z136.1 while also introducing electrical engineering concepts to mitigate laser hazards and citations can be found in the appendix.

### 4.1.6 Communication Protocols Standards

The SightSense shin guard integrates wireless communication to support modularity, real-time feedback, and potential future expansion such as mobile app pairing or sensor measurement. To ensure reliable and energy-efficient connectivity, the design follows standard communication protocols popularly adopted in embedded and wearable devices. These standards are used to help guarantee the device's compatibility, comparable signaling, and lower the amount of power drawn. These reasons are all strong necessities for battery-operated smart shin guards.

4.1.6.1 Bluetooth Standards

The SightSense shin guard has the option to deploy Bluetooth Low Energy to support wireless communication between the embedded controller and external devices. The design adheres to the Bluetooth Core Specification 4, developed by the Bluetooth Special Interest Group (SIG). This protocol was selected due to its strong balance between performance and efficiency in wearable technology. BLE 4.2 is ideal for the real time and low data rate needs of this system. This will ensure seamless integration with mobile platforms and potential accessories if we had more time. BLE 4.2 balances efficiency with real-time performance for wearable assistive technology.

Key Bluetooth Features:

- **Low Energy Operation:** Ideally used for battery-powered devices like smart shin guards.
- **Increased Data Throughput:** Allows faster communication compared to older BLE versions.
- **Extended Packet Lengths:** Reduces overhead by enabling larger data payloads per packet.
- **Enhanced Privacy and Security:** Incorporates LE Secure Connections and addresses randomization, preventing tracking and data leaks.
- **Interoperability:** Compatible with most modern smartphones and embedded platforms.
- **Data packet extension:** Increased packet size improves efficiency during short-range transfers, useful for test logging or firmware update pairing.
- **Secure Connections:** Enhanced pairing privacy reduces risk if integration with a mobile app or caregiver module is added in the future.
- **Widespread Adoption:** Ensures maximum interoperability with mobile and embedded ecosystems.

**Integration in SightSense**

**Hardware Layer:** The ESP32-CAM's onboard BLE module can handle pairing as well as other possible features.

**Current Role:** Primarily reserved for debug transmission and optional integration testing.

**Future Potential:** Possible expansion to include audio cues, GPS assistive data, or mobile app alert systems.

## 4.1.7 Ergonomics of Human System Interaction

**ISO 9241-210:2019**

This standard focuses on the ergonomics of the human system interaction. The ISO 9241 offers recommendations to better enhance interactive systems, ease of use, comfort, and accessibility [35]. These requirements allow for the SightSense shin guard, which is intended for those with visual impairments, to not only be useful but also comfortable for long term usage and easy to operate. Understanding user needs, designing with users in mind, and reducing physical and mental stress are important guidelines that the ISO 9241-210 follows [36]. These guidelines guide our decisions regarding component arrangements, making sure that the microcontroller and the sensors don't interfere with walking, lightweight design to prevent user fatigue, and clear, consistent audio and haptic feedback that is not overpowering but also easy to understand. By adhering to ISO 9241, we hope to prioritize the everyday use requirements of the visually impaired users while making the SightSense shin guard accessible, safe, and comfortable.

## 4.2 Design Constraints

A constraint is defined as a limitation or restriction. For the SightSense shin guard we have run into many constraints that have altered potential ideas for this project. We will cover various constraints and how we have found alternative solutions in order to make this product work as efficiently as possible.

### 4.2.1 Power Consumption & Battery Life

#### 4.2.1.1 Power Consumption

Our first constraint is power. In any electrical device or product, power is the most important feature. To operate an electrical device, power must be properly distributed safely and efficiently. For the SightSense shin guard, our team went through many ideas and options for determining what would be the ideal choice for a power supply. Since this device is meant for everyday walking, the battery could not remain plugged into an electrical source and would instead require a battery of some sort. The next issue was determining how long the battery life would last. This means we needed to find a battery that could power our device in a realistic way. We determined that the battery should last somewhere around 6 -10 hours as an initial goal and if possible 12 hours or more as a preferred goal. And since these shin guards are to be worn every day, the battery would also need to be rechargeable, to not create excess waste (throwing away drained batteries). Since power would be supplied to many components in the product, the battery itself would also need to last for an extended period of time without needing to recharge until the user was ready. This then put a constraint on the duration of time the power would need to last, and how much power the devices would require operating. Could a rechargeable battery do both? The answer is yes. After researching many different types of batteries, we determined that a rechargeable Lithium-Ion type battery would provide the best and safest power to our product without having to remove any of our desired devices.

#### 4.2.1.2 Battery Life

This product is aimed at those who are visually impaired to live a more comfortable life. This means that when an electrical component is introduced into the product it must not affect the user's everyday life. This means that a key feature must be the battery life and battery lifespan. According to the constraints we have set on the product, the battery needs to be as weightless as possible. This means that the battery cannot be incredibly heavy to hinder someone walking uncomfortably. Two constraints that go together are concealment from outside interference (weather damage, physical damage, etc.) and easily accessible rechargeability. This means that we needed a battery that is lightweight, stable, and rechargeable. There is also the main important constraint we need in a battery. It needs to be able to support all devices we are installing on the shin guard. These devices are the following: ESP32, boost converter, vibration motor, LRA driver IC, ultrasonic sensor, speaker, audio amplifier, laser, and camera. All of these devices will require the battery to run at peak performance. After researching we were able to find a battery that could supply enough power to all the constraints listed without removing required devices. Although constraints are typically meant to hinder a project's progress, in this case we were able to find a battery that can supply all the power we need to achieve our designs.

### 4.2.2 Size and Space Limitations

When creating and designing the SightSense shin guard, one of the biggest design limitations was the small amount of physical space that could be found in a typical shin guard form. In contrast to a portable or handheld device worn, for example on your wrist, a shin guard needs to maintain both comfort and structural support despite the several electrical components included on the shin guard. Some of the components we need to integrate onto the shin guard are the ESP32-S3-WROOM, ESP32-CAM, two ultrasonic sensors, a battery, an audio speaker, a vibration motor, and an LCD screen. Each of these components needs to be positioned carefully to avoid disturbing the user's comfort when walking.

Given that the user should not feel discomfort from these components, the electrical layout design, component dimensions, and mounting are directly impacted by this limitation. The ESP32-CAM needs to be oriented such that the shin guard material does not block its camera's ability to detect obstacles. The ultrasonic sensors are also going to be used to detect obstacles and give reading distance measurements, which will be placed at the sides of the shin guards.

Moving on to the battery, it needs to be small and strong enough to run the SightSense shin guard for extended periods of time. The battery cannot be overly large, as this would cause discomfort, and it could be too heavy for the user to carry. Another thing to watch out for is the vibration motor. We need to ensure that this motor is positioned somewhere where the user can feel the feedback but also need to make sure that the feedback isn't too strong, as this could cause shock or pain when walking. Design strategies to address space issues include choosing components with compact designs, choosing smaller wires to make wiring as clean as possible, and we will design and create a PCB board to reduce the electrical footprints.

All things considered, the user experience, structure layout, and component selection are greatly impacted by the size and space constraints. This limitation requires a careful balance between aesthetics and functionality, guaranteeing that all parts are safely incorporated without sacrificing the SightSense shin guard's use and comfort.

### 4.2.3 Cost Constraints

Another important design limitation that affects almost all parts of the SightSense shin guard is the overall cost. Since this project is a group effort and is a student-developed prototype, the shin guard has to be finished on a tight budget. The team's goal is not to go over $400-$500 but to stay under this amount. With this in mind, we have limitations that impact on the choice of components and materials we choose, so we can make sure that we stay within the parameters of the design.

The team gave priority to parts that provide multiple functions at a low cost in order to efficiently control expenses. For instance, the ESP32-CAM was chosen for our microcontroller since it was reasonably priced and also had features like Bluetooth and Wi-Fi, and a camera. We also chose a pack of two ultrasonic sensors as they were also at a low cost for two and had the features we were looking for. This was the case for all the components we used for this project. Overall, reliable object detection was made possible without going over budget, which gives us room to buy any other components we might need in the future.

Components were purchased from reasonably priced suppliers, which included Amazon, with time frames and delivery prices that were taken into account. We also used spare parts we had from previous projects that were not used to conserve money. Over time, cost limitations can affect our goal, since tariffs are in effect now, so we can save money where we can, so we can spend it on our PCB to order and deliver, plus the fee.

All in all, making strategic decisions and compromising some features and quality were necessary when working within a limited budget. The team overcame these limitations by creating a functional prototype that satisfies important performance goals while remaining financially feasible.

In the next phase of the project, cost constraints will continue to shape our design decisions. Particularly as we transition to printed circuit boards (PCBs) and more advanced enclosure materials. Unlike the prototyping stage, which allows for flexible use of jumper wires and breadboards, Senior Design 2 will require us to invest in permanent assembly methods. This will involve evaluating low-cost PCB fabrication services and possibly sourcing components from international suppliers to minimize unit cost. We also plan to revisit our component selection with a cost-per-feature mindset, identifying opportunities to consolidate functions or substitute parts with more cost-effective equivalents. Moreover, in anticipation of future scale-up or potential commercialization, we intend to document a full bill of materials (BOM) with current unit prices and projected bulk costs, giving us a clear view of manufacturing feasibility under cost-sensitive conditions. By continuing to treat affordability as a core design requirement, we aim to produce a final product that balances performance, reliability, and real-world accessibility for users who may not have access to expensive assistive devices.

### 4.2.4 Environmental Durability

Environmental durability is a crucial part in the design of the SightSense shin guard. Since the device is intended for use every day outdoors and indoors. The smart shin guard must operate reliably across varying weather conditions, terrains, and user behaviors. As such, mechanical housing, sensor placement, and electrical components are selected and configured to withstand environmental stress while ensuring consistent performance.

The table below summarizes the key environmental durability features integrated into the SightSense shin guard to ensure its reliable performance in a variety of real-world conditions. These considerations include protections against moisture, shock, dust, and continuous vibration during use. Each row outlines a specific environmental factor, the protective measure implemented, and its relevance to maintaining system functionality and user safety in diverse operating environments.

Table 29: Necessities considered for environmental durability

| | |
|---|---|
| **Shock and Impact Resistance** | The internal components will be cushioned with foam to absorb mechanical shock from walking or accidental falls from the user. |
| **Dust and Debris Protection** | Ultrasonic and optical sensors will be recess-mounted and shielded to prevent dirt buildup. Filter meshes may be implemented over sensor ports to reduce dust intrusion without interfering with the sensor's functionality. |
| **Vibration and Motion Durability** | Because the system is mounted in footwear, there is constant motion and vibration during usage. All internal wiring is routed through flexible conduit tubing. The components will also be fastened using low-profile backets. Vibration motors will be selected based on the life cycle and shock tolerance. |

The SightSense shin guard is engineered with practical and realistic environmental durability in mind. This was done so that we would be able to balance protection and performance without having to sacrifice the user's comfort and portability. By addressing challenges that could come from the environment, we were able to eliminate issues such as moisture, shock, and debris. This design strives to deliver a reliable and long-term solution for visually impaired users hoping to navigate in real-world conditions.

### 4.2.5 User Comfort and Safety

Designing a wearable structured light object detection system requires both adherence to user comfort but also must fall in line with safety standards. Since the user of the product will be using the SightSense directly for object detection for a visually impaired person, risk needs to be minimized; ease of use needs to be maximized, while still following all safety standards. Since this system will use laser projection and a camera module will be taking in images, standards for laser safety and unauthorized recording need to be followed [37]. Several constraints were followed during the process of designing the electrical and optical components. The form factor must be considered as components need to be compact and light weight to not impede the gait of the user. Weight distribution must be considered as well, to minimize fatigue or imbalance in the user. The material needed for the shin guard needs to be safe for the skin and non-abrasive to prevent any discomfort. Electronic components must not be in direct contact with the skin of the user to avoid irritating the skin. The safety standards for the optical system include the laser diode module used in the structured light system. The laser class of the laser used was within class 2 per IEC 60825-1. The laser system is well controlled as it is pointing down and away from the eyes of other pedestrians. The design of the class 2 laser includes warning labels in accordance with ANSI Z136.1 [37]. The system is running on low power between 3.3V and 5V which is relatively safe, and PCB's and exposed wires are enclosed to avoid electrical shock.

### 4.2.6 Ergonomic Constraints

Since the SightSense system is designed to be worn directly on the user's leg, ergonomics presented a major design constraint throughout the development of the prototype. The challenge was to integrate sensors, power systems, and feedback mechanisms without compromising comfort, balance, or natural gait. Early brainstorming sessions emphasized that any device worn over extended periods must be lightweight, non-intrusive, and well-distributed to avoid fatigue or physical strain.

Weight distribution was a key consideration when selecting both components and their placement. Heavy components such as the 3000mAh lithium-ion battery were strategically mounted near the ankle area rather than the toe or heel to avoid affecting walking dynamics. This placement also minimized the risk of the user accidentally damaging sensitive electronics while walking or navigating uneven surfaces. Additionally, socks will be used with our device so that there is a protective cover to prevent any damage to the skin.

Noise and haptic vibration levels were also tuned with ergonomics in mind. During testing, initial vibration settings were found to be too sharp and uncomfortable for prolonged use. As a result, the team adjusted both the intensity and duration of haptic pulses through the DRV2605L motor driver to deliver more subtle cues without sacrificing perceptibility. Similarly, speaker placement and volume levels were optimized to ensure that feedback remained audible in moderate outdoor environments without becoming disruptive or startling.

Lastly, because users with visual impairments may have unique footwear needs, we designed the system to be detachable and adaptable to multiple shin guard sizes and styles using Velcro and adjustable brackets, supporting a more inclusive and user-friendly experience.

### 4.2.7 Maintainability and Upgradeability Constraints

In addition to performance and affordability, the SightSense system was developed with long-term maintainability and upgradeability as guiding constraints. The device is intended to be used by individuals who may not have access to technical support or advanced repair services, making modularity essential. This influenced both hardware selection and firmware structure from the earliest design stages.

Each subsystem was designed to be independently replaceable. For example, the ultrasonic sensors are mounted using detachable JST connectors and socketed headers rather than soldered directly to the board, allowing for quick replacement in the event of damage. Similarly, the microcontroller can be swapped with another ESP32-CAM module using a pin-and-socket configuration without rewiring the entire circuit. This strategy reduces downtime and enables users or technicians to repair the system with minimal training or tools.

On the software side, modular functions were written to support plug-and-play behavior. Sensor readings, haptic feedback, and speaker tones are handled through individual interface functions, allowing additional sensors or actuators to be introduced with minimal changes to core logic.

By designing maintainability, we not only improved the system's reliability and longevity but also supported its real-world viability. In future phases of development, this modular framework will allow our team to add new capabilities such as structured light analysis without requiring a complete redesign of the shin guard electronics or codebase.

### 4.2.8 Summary of constraints and impact

Throughout the development of the SightSense smart shin guard, several engineering and real-world constraints influenced our design decisions. Each constraint required careful consideration to ensure that the final prototype remained functional, affordable, safe, and user-friendly. The table below summarizes these key constraints, how they shaped specific component choices, and the trade-offs we accepted to maintain system performance within realistic limits. This structured overview highlights the balance between ideal functionality and practical limitations inherent in embedded wearable systems.

Table 30: Summary of Design Constraints and Trade-Off Decisions

| Constraint | Design Decision Impact | Component | Trade-Offs Made |
|---|---|---|---|
| **Power Limitation** | Required low voltage, efficient devices | 3.7V Lithium ion | Limited continuous runtime, especially under high load |
| **Physical/Ergonomic Fit** | Enclosures must be lightweight, balanced, and unobtrusive | 3D Print Housing, Velcro Mounts | Reduced sensor coverage area in some orientations |
| **Coal Constraint** | Favored low-cost components with multiple features | | Avoided high-end sensors and limited onboard processing power |
| **Environmental Protection** | Design has to resist light water and dust exposure | Conformal Coating, IP44 Enclosure | Limited ability to submerge or operate in heavy rain |
| **User Safety and Comfort** | Requires safe vibration levels and non-disruptive sound cues | DRV2605L, PUI Audio Buzzer | Needed to tune intensity for perceptibility without discomfort |

| | | | |
|---|---|---|---|
| **Maintainability** | Modularity for component swaps and future upgrades | socketed headers, JST wiring | Increased physical footprint of electronics |

# Chapter 5 Application of ChatGPT and other Similar Platforms

## 5.1 ChatGPT

### 5.1.1 Overview

During the development of the Smart Haptic Alert Obstacle Detection System for the Visually Impaired or SightSense, which is a wearable smart shin guard for the visually impaired using Structured Light, ChatGPT was used to help brainstorm ideas for design decisions, component selection and evaluation as well as providing helpful information on concepts. Used correctly ChatGPT can be a very powerful tool, however limitations become more glaring during the prototyping and testing phases of the project. For example, for our design, physical optics testing and imaging with real time feedback are the basis of detecting objects and giving the signal to be able to avoid the obstacle. This would not be possible from a ChatGPT only prompt, or any other available AI. Modern LLM can be very helpful and provide useful information, and goes as far to possibly simulating a system, but cannot replace benchmark testing done with physical components in a lab where empirical data is collected. Many times, when using an LLM, responses are limited by the user prompt, regarding explicitly mentioning any and every system constraint. Our SightSense also requires significant optical design, which needs computer programs such as ZEMAX to be able to model lenses and their aberration. ChatGPT cannot model this lens performance, or beam profiles needed for the structured light deformations on surface needed to calculate light deformation in quantifiable way. Ultimately, relying only on ChatGPT for a project like this can be very risky, because of the high chance that the solution being given by the LLM will not hold up with hands on testing in a lab.

### 5.1.2 Pros and Cons in Our Project

Aside from being limited in a physical benchmark testing phase, the use of ChatGPT and other similar LLM are helpful and provided significant helpful features for our SightSense project. The use of LLM's allows for rapid research and clarification of ideas and concepts. In our project quick summaries were given for different forms of sensing such as LiDAR, Time of Flight, Structured Light, and Stereo Vision. Other key concepts which LLM's were convenient in recapping were optical such as collimation, divergence, and Seidel aberration. The use of LLM's are also helpful in search and procurement of components. They group components and give a good starting point of reputable sellers and match components from different subsections of the design to be able to match and be compatible. Ultimately, this is a time-saving feature of LLM's. Another benefit of the use of LLM's for our Senior Design project is its helpful recommendation of code and test logic needed, especially for the use of the ESP32 system. Support for prototyping is also given in the form of the support system needed to hold the projector and camera for the structured light sensing system.

Ultimately the biggest con of using ChatGPT and other LLM's for our project is that it can never "see" what is going on with testing and prototyping in real time. What is meant by this is that any LLM is dependent entirely on the manual description given by the user. For optical systems, ChatGPT cannot help with aligning a laser system or calibrating the camera component. Another con is lack of contextual awareness of our lab setup, unless remembered or brought up every time component recommendation can become generalized or even mismatched. Since LLM's have no direct optical simulation capability no numerical results can be given and cannot give simulation to improve aberration or beam path. From a standards and safety perspective ChatGPT might recommend a laser without accounting for the laser safety class, or regulatory compliance. This needs to be accounted for by all parties involved because of the inherent risk of eye damage by a laser. No LLM can create an original solution to solve a unique problem. This means that although existing databases can be searched, but an LLM cannot take the place of an engineer who can create an original solution.

### 5.1.3 Learning Impact with Examples

The use of LLM's such as ChatGPT can have both a positive and negative effect on the learning experience during senior design. A positive example of how ChatGPT has improved the learning experience has been through a combination of structured technical guidance. For the optical design portion of the project the LLM has helped provide a design workflow for lens design feedback, integration of the Diffractive optical element (DOE), and the principles of structured light according to instructor feedback. It has been helpful to have a tool that provides sourcing as well as justification for components and key theories needed for the success of the structured light system.

Recommendations that were given for the lens design were an aspheric lens for collimating the laser diode. The reason an aspheric lens is a good recommendation compared to the regular spherical lens is that they improve image quality through correction of spherical aberration which reduces blur. Distortion on the edges of the lens is reduced as well, which improves system performance for the structured light system which needs a wide field of view. This is crucial for getting a wide enough field of view to look for obstacles and drop-offs such as any possible ditches. Key details on the strategies needed to make a successful structured light system were provided and simple sketches and design blueprints were able to be generated.

One of the strongest aspects in the usefulness of the learning process in Senior Design and LLM's are the rapid prototyping support given. The microcontroller unit and camera system used for our project were able to be evaluated and enabled a quicker decision-making process. The ESP32 system used is an embedded system microcontroller, which both electrical engineers on the project were already familiar with. Through consultation of ChatGPT, these components can be ordered with a greater peace of mind of the design being successful and prototyping to begin to test feasibility for all models. The benefits given to justify the use of the ESP32 -CAM was the cost effectiveness and fact that it comes with a camera module already built in. Cost is one of the key factors for our project because we are entirely self-funded and do not count on any external sponsors or grants. Recommendations for this microcontroller were also given because of the compact size and low power consumption, which are also crucial components for the obstacle detecting shin guard to be successful. The structured light system which will be used for obstacle detection is made up of laser which will project stripes of light. The camera system used will take pictures of the stripes and any distortion in the stripes can be calculated and a depth map can be formed. The ESP32 has a dual core which can handle image data and processing. Finally, this microcontroller is compatible with an Arduino IDE, which the LLM used mentioned that it is relatively easy to program. With this information given by LLM, which matched the recommendations given by the electrical engineers on the team, the ESP32 was selected for prototyping.

In terms of the laser used for prototyping, ChatGPT did give a recommendation on why the laser diodes selected were good options. The low cost and easy integration to the ESP32 microcontroller were key features, along with tuneability of the laser dot. The laser diode module came with the driver circuit built in, which saves time for our electrical engineers and allows for plug and play usage within the 5V rails of the microcontroller. The 5mW output is considered class I, which is safe for the eye. The 650nm wavelength is compatible with the DOE, which were all recommendations given by the LLM and it is said that should be visible indoors and outdoors in short ranges.

ChatGPT was helpful in the evaluation of the light stripes generated by the DOE on selection. The structured light system that will be implemented for this project will be a series of horizontal stripes. For a mechanical system, one stripe could be scanned up and down and side to side. For our project the DOE will create a series of lines that can be scanned with one frame and eliminate the need for a mechanically active scanner. Going back to the basis for the idea of our project, object detection and avoidance is key. Therefore, the structured light system used needs to be able to pick up details in the frame for ditches, curbs, and any drop offs or obstacles. The choice for the DOE directly affects what can be mapped by the distortion in the stripes caught by the camera. For example, one option was a 7-stripe option, and if this DOE were to be chose, there is a good chance, that one of the obstacles that needs to be detected falls through the lines. With 25-line DOE's there could be overlap in the lines that can be hard to register on the camera, but there was a 15-line option, that according to ChatGPT would be a good option for our structured light sensing system. ChatGPT also gave a recommendation for sellers to be able to source the DOE, but ultimately the DOE was ordered from a website found by word of mouth from another group doing a similar project.

Many other options for sourcing were done for the DOE. It is always helpful to have more options in case the first component ordered was not functioning correctly or optimally. The main benefit is to have a multitude of options that one can research on a deeper level to be a able to come to a selection. It is the hope of the user that after research is done and if there are options to choose from, these options for components can be ranked from good to best. This is the idea for using an LLM for a project like this. You would want a prompt where you ask for a specific task or need, and with the generated response, the user can further research these options and make a decision on the best component.

In terms of prototyping ChatGPT and other language models are beneficial with CAD designs needed for 3D printing. One of the challenges of this project is going to be mounting the structured light system on the front of the shin guard. On top of that, the PCB board needs to be onboard and attached to the microcontroller. A battery needs to be attached as well. For this having at least a starting off point available from an LLM is going to save a significant amount of time on the design process.

When initially prototyping the design for the shin guard, we came up with multiple hand drawn ideas that were adequate for our early ideas. However, using ChatGPT sped up the process exponentially. We were able to get a clear image and actually be able to picture what this product could be like in real life. This also helped clear up any confusion group members had when trying to describe where components needed to be placed on the shin guards. For example, Camera and laser need to be placed at the shin of the shin guard to see the farthest forward and a rechargeable battery would need to be mounted somewhere on the shin guard as well. However, this did not mean that ChatGPT was able to apply all aspects of our design. After many tests ChatGPT could not understand where the ultrasonic sensors should be placed or adding an LCD screen. Ultimately, we settled on a mixed combination of the ChatGPT design and hand-drawing our components onto the shin guard.

Overall ChatGPT can be said to have a positive experience on learning for senior design by streamlining the design and sourcing timeline for components for our project. With the many time and size constraints for the summer semester, having a tool that can help save any time on the more tedious and administrative parts of the project, this allows more time for prototyping and more research and development.

### 5.1.4 Limitations and Risks

As much as ChatGPT and other LLM's have helped and enhanced the learning experience in this senior design class, there are also examples of them hurting the learning experience during this senior design process. Of the specific experiences these include, directly giving an answer that one might be better served looking oneself, oversimplification of engineering concepts and decisions, the encouragement of over-reliance on tools instead of thinking about design, and not challenging unjustified choices.

The most negative way that ChatGPT has affected the learning process in senior design is the direct answering of questions that may have been better for the team to think critically for a solution or component. For example, there may be a time when a calculation will be more appropriate to find a lens where ChatGPT could recommend something without the user doing any work. This is a problem because the key idea for senior design is to get something out of the class that we don't get in other classes. If ChatGPT can just give you answers instead of working through a problem and finding the best solution, this leaves something to be desired in the learning process.

A second way in which the learning process suffered under the use of ChatGPT during senior design is the oversimplification of complex engineering decisions. There were times when the LLM presented the use of a lens or DOE with limited comments on nuance or constraints that can only be considered through testing and prototyping. There are times that tradeoffs in components need to be considered. It would be better not to rely on ChatGPT and consider the opinion of a faculty member on the committee. A specific example of this can be that the LLM gives a recommendation on a laser diode module, but it could be that the LLM does not have a full grasp of lab availability and components, the testing environment, or safety concerns. Doing this research will increase the scope of the analysis and feasibility of the project.

A third example of the use of ChatGPT hurting the learning experience during senior design is the encouragement of use of tools over design thinking. Many times, an LLM can provide flowcharts, Gantt charts, and other diagrams. Thinking about these processes as an engineer is crucial in the design process and can hurt the student learning experience. Flowcharts and diagrams should be original, and tools should be used, but not overly relied upon.

The final way in which the use of ChatGPT has hurt the learning experience in senior design is not pushing back on unjustified choices. For example, for our project, we are using a structured light sensing system. Even though heavy research was done on many different ranging systems, such as time of flight, machine learning, stereo vision, and triangulation, when the idea was presented to ChatGPT, the LLM did not ask if we had considered other options. Perhaps if we had not done the research and other options were better suited for our project, this would not have been recommended by ChatGPT. Even though ChatGPT can be a powerful tool in the modern world, the overreliance on this LLM can be harmful in the learning experience needed for ChatGPT.

The use of ChatGPT has had both positive and negative effects on the learning process for senior design. There are many benefits to the learning process by using the LLM, such as a streamline design process, easy to access component sourcing and background information, and help in the decision-making process for the design. There are also negative effects of ChatGPT on the learning experience during senior design. These include oversimplifications of complex design concepts. A component can be recommended that also is not in stock or could take a significant amount of time to arrive. An overreliance on ChatGPT instead of doing proper research is a danger of using the LLM.

## 5.2 Other AI Platforms

### 5.2.1 Claude AI

#### 5.2.1.1 Overview

Claude is an AI assistant developed by Anthropic. Founded in 2021 by former OpenAI executives and researchers, they're known for focusing on building controllable and reliable AI systems. It belongs to the family of Claude 4 models, which is made to be intelligent and effective for daily use. It is powered by large language models (LLMs) that are trained on large datasets. The way these LLMs work is by using deep learning techniques based on systems that can learn from data and make decisions. Other examples of LLMs are ChatGPT, Google Gemini, and Microsoft Copilot. Claude (much like its other AI counterparts) is trained with data provided by users, the internet, and even licensed content from third parties. Claude can assist with research, coding, and other features. Its main difference from the other AI chatbots is that Claude can produce writing that is human-like compared to other platforms. Claude is especially useful when it comes to finding educational sources, engaging in human-like conversations, coding, and uploading files. Claude is constantly learning from the conversations it engages in due to its model style.

This is why Anthropic has made safety one of its top priorities. With the rise of AI, many people have questioned its ethical use and the possible dangers that it can create. Anthropic has taken it upon itself to be positioned as the “golden standard” of today’s AI companies and models. Harmful prompts and responses are trained to be avoided in order to prevent the misuse of AI. Constitutional AI was created for the sole purpose of setting the example of AI ethics and safety created by Anthropic itself. Users are presented with options of Claude’s responses that closely align with being reliable, clear intention, and least dangerous. Based on users' responses and guidelines, the model is able to train itself to meet safety standards. These are especially useful when it comes to providing information to the user that is as accurate as possible.

We used Claude as an alternative tool for tasks such as component research assistance, comparing power options, sensor modules, and more. It also served a vital purpose of explaining and reviewing technical concepts as a reference for other sources during our time developing the A Smart Haptic Alert Obstacle Detection System for the Visually Impaired (SightSense) wearable shin guard for the visually impaired. This reference/guidance is complementary to instructor feedback, team collaboration, and course materials provided. Claude was primarily used as an unofficial advisor who helped support decision-making for components and strategy, such as the tradeoffs and technical justifications. It streamlined and improved the understanding of identifying and comparing compatible electrical components like battery packs and power regulators.

### 5.2.2 Pros and Cons in Our Project

As we started this project, we knew that AI was going to be a major learning tool to assist us in the early planning and research phase. For the SightSense system, we used Claude as a support and reference tool to help guide decisions related to multiple areas of engineering for development. This includes but is not limited to electrical components, power systems, research sources, optical design, and more. One of the biggest pros of using Claude was its ability to explain technical concepts in a simple, easy-to-understand way. This is due to Claude’s AI being known as being able to have human-like conversations compared to other AI tools. When we were deciding between certain components, such as power sources, Claude excelled in showing the differences between each component and even provided additional feedback on items we may be missing or have to do more research on. This allowed us to work efficiently and manage our time effectively when narrowing down which parts to use for our wearable shin guard system. Another strength of Claude was its usefulness for additional brainstorming as an advisory role once we had a human brainstorming session. These ideas ranged from communication methods, how to structure our development timeline, items to research on our own, and organizing our own thoughts, such as logical steps on how to begin and approach the design of the model. The main selling point of Claude is its security/privacy priorities, which means it doesn’t store or use data without permission, which gave us more comfort when working on the project.

However, this doesn’t mean that Claude is perfect and was the only tool we used. Several limitations and drawbacks, such as analyzing images or diagrams, were something we wouldn't be able to use Claude for. As with any AI tool, there are massive cons when it comes to real world design and testing. The main con is the inability of AI to provide feedback on simulations, testing in real time, which is something we will begin once we move onto the next phase of the project. Physical design, like board spacing or wiring, is up to us as engineers, and we cannot rely on AI for everything. Claude won't be able to catch future problems, such as malfunctioning circuits or sensors. Claude also tends to give more cautious or general responses, which can lead to slow decision-making and cause us to do more follow-up research on our own, since we cannot rely on the information it provides, since AI tends to be inaccurate. Prompts must be specific and include important information, as it might recommend parts or sources that won't work in our planned setup. Claude (and any AI) is best used as a support tool during the research and planning stages, but not as a replacement for hands-on work, engineering experience, first-hand decision making, and real testing. Claude helps guide and educate, but the most important skill we can develop will come from our own experiences with building, testing, and problem-solving using everything we've learned in our previous and current classes.

### 5.2.3 Differences between Claude and ChatGPT

This section outlines the key differences between Claude and ChatGPT, both AI language models developed by Anthropic and OpenAI. The basic design ideas, training methods, capabilities, and interference styles of the two systems vary, despite the fact that both are made to produce text that is human like and help with a variety of activities. Knowing these distinctions helps one better understand how each model meets the demands of users in different applications.

Table 31: Differences between Claude and Chat GPT

| | Claude | ChatGPT |
|---|---|---|
| **Company** | Anthropic | OpenAI |
| **AI Models** | • Claude Sonnet 4<br>• Claude 3.5 Haiku<br>• Claude Opus 4 | • GPT-4o<br>• GPT-4o mini<br>• o1<br>• o1-mini |
| **Web Search** | Yes (available in some versions) | Yes (available in Plus/Pro plans and some free versions) |
| **User Interaction Style** | More cautious, reflective, asks questions, good for brainstorming | More direct, decisive, and often faster to provide solutions |
| **Image Generation** | Not Supported | Supported (via Dall-E in GPT-4o) |
| **Performance/Capabilities** | File uploading (useful for analyzing datasheets or technical docs), lacks image creation, | Image creation, internet search are available in some versions |
| **Data usage and storage** | Doesn't use prompts or responses for training without permission, retains data for 90 days | May use conversations for training unless you opt-out |

| | | |
|---|---|---|
| **Ethical and safety focus** | Uses constitutional AI principles for self-learning | Uses reinforcement learning from human feedback |
| **Context Window** | 200,000 - 500,000 tokens | Typically 32,768 tokens - 128,000 tokens |

### 5.2.4 Learning Impact with Examples

Utilizing Claude during the development of the SightSense shin guard, it offered significant learning opportunities, particularly when addressing hardware design and component integration.

The first example, where we used Claude was to learn about how to figure what power to use to connect to several parts using a single battery, which included the ESP32-CAM, vibrational motor, LCD screen, audio speakers, and two ultrasonic sensors. We used Claude about safe and effective ways to handle various voltage requirements. We then were able to figure out what power distribution for our shin guard design needed so it didn't cause any damage to components or the users that will be using our product. Overall, Claude gave us multiple resources to standards to research about and this helped a lot for Chapter 4 when writing about standards.

Another example where the team used Claude was for assisting with components specifications and how to read their respective datasheets. Things like the LCD screen display and the ultrasonic sensors. Rather than providing brief responses, it clarified the why we would need a certain wire or component.

All things considered, Claude was a helpful resource that helped with improving our understanding of the backgrounds of some of our components.

### 5.2.5 Limitations and Risks

Claude is able to play a key role in assisting in research, advising, learning, and even design exploration. However, since it is only an AI model, it's unable to be used as a tool that interacts with the physical hardware itself or provide real-time analysis of SightSense being built. It is massively unsuitable for tasks such as custom PCB configuration, physical fit, and real-world integration. Recommendations are able to be made as a reference point for the project. However, Claude isn't able to verify specific components' compatibility, performance, or reliability. Identifying these tasks is up to us by using our best judgment and experience. Physical integration, choosing the correct parts, and design are something AI cannot replace just yet. Claude is effective for clarifying technical ideas/strategies, offering initial component comparisons, or serving as a starting point for code and documentation. A major risk is using Claude without verifying safety guidelines or other information provided, as with any other AI model. This can lead to making wrong decisions, a waste of resources, or even incompatible and unsafe configurations. Component recommendations provided by Claude could pose a risk in wearable electronics. Another risk is the possibility of generic/incomplete answers based on the prompt given. It is our job to verify and validate the information AI gives us.

All in all, Claude was used for some parts of the SightSense shin guard process for research and planning purposes. From helping the team break down complex engineering topics to helping us find datasheets for some components that we needed to use. Having Claude be able to do human like communication made it easier to use as well and easier for us to understand.

## 5.3 Copilot by Microsoft

GitHub Copilot is an AI-powered coding assistant developed by Microsoft and OpenAI. It integrates directly into code editors like Visual Studio Code and provides real-time code suggestions, autocompletions, and context-aware snippets. For engineering students, Copilot serves as a powerful tool for accelerating development, especially in low-level or syntax-heavy environments like C/C++ used in embedded systems.

### 5.3.1 Pros and Cons of Our GitHub

The following table presents a comparison of GitHub Copilot and ChatGPT, two popular AI tools that are both helpful in their own ways. Although they both use sophisticated language models to increase productivity, their ideal use cases, design, and interface style are different. The tables below outline key pros and cons of each tool to help users determine the best option.

Table 32: Benefits of Using GitHub Copilot in Our Project

| **Rapid Code Generation** | **Copilot helped scaffold initial functions for sensor reading (e.g., ultrasonic distance), timer setup, and interrupt-based button handling.** |
|---|---|
| **Syntax Assistance** | Reduced time spent looking up obscure C syntax for ESP32 libraries. |
| **Comment-to-Code Conversion** | Enabled us to write natural-language comments like “read ultrasonic sensor and return distance in cm,” and receive full function definitions. |
| **Helps Avoid Common Errors** | Suggested proper pin Mode and analogRead/digitalRead sequences compatible with ESP32. |
| **Code Style Consistency** | Copilot maintained consistent indentation and variable naming, reducing stylistic mismatches when multiple team members worked on the same files. |
| **Learning Accelerator** | By watching Copilot’s suggestions, we learned new C++ idioms, array handling, and efficient loop control mechanisms. |
| **Library Integration** | It recognized libraries like Adafruit_NeoPixel or ESP32Servo and |

| | |
|---|---|
| | scaffolded setup code that saved hours of manual trial-and-error. |

Table 33: Limitations of Using GitHub Copilot in Our Project

| **Context Limitations** | **Sometimes misunderstood the project's real-world application (e.g., it would generate LCD display code when our system uses haptics).** |
|---|---|
| **Over-Suggesting** | At times, Copilot generated redundant or insufficient code requiring manual cleanup. |
| **Debugging Dependence** | Risk of treating Copilot as a crutch, delaying deeper understanding of microcontroller architecture or communication protocols. |
| **Lack of Project Memory** | It didn't remember context across multiple files, which led to inconsistent suggestions unless comments were added repeatedly. |
| **Security Oversights** | Occasionally, it suggested code with potential vulnerabilities, like reading uninitialized memory or skipping null checks in Bluetooth setup. |
| **No Context of Sensor Hardware** | For example, Copilot sometimes treated our ultrasonic sensor as an analog device, suggesting analogRead() instead of using pulseIn() or digitalWrite(). |

### 5.3.2 Differences between Copilot and ChatGPT

In our senior design project, we extensively used both GitHub Copilot and ChatGPT to accelerate development, debug code, and gain a deeper understanding of embedded system design. While both tools use AI to assist developers, they serve different purposes and complement each other in functionally different ways.

**Copilot** GitHub Copilot is integrated directly into the code editor (Visual Studio Code). This will provide inline suggestions as developers type. It is particularly useful for syntax-heavy or repetitive tasks. It learns from context within the file and auto-completes functions or logic blocks. This would be helpful in writing C++ code for the ESP32.

**Use Case in Our Project:** While working on sensor interfacing, Copilot was useful in writing initialization logic for the ultrasonic module. For example, typing a comment like "// measure distance using HC-SR04" would result in Copilot generating a fully functional function with “pulseIn()” and “digital pin control”. Copilot also helped us avoid small but critical errors like mismatched brackets, incorrect syntax, or uninitialized variables.

**ChatGPT**
On the other hand, ChatGPT serves as a technical consultant throughout the design process. Unlike Copilot, which operates line-by-line, ChatGPT allowed us to explore high-level system design, generate diagrams, and troubleshoot issues that could span across various files. It provides code explanations, helps with writing state machines, and generates initial pseudocode from logic descriptions.

In Our Use Case:
When designing the overall software state machine, ChatGPT could be used to effectively convert written state descriptions into functional state diagrams and supporting code. ChatGPT could also help understand how interrupts, delays, and memory could affect real-time responsiveness on the ESP32.

Table 34: Comparison for Copilot vs ChatGPT

| Feature | Copilot | ChatGPT |
|---|---|---|
| **Integration** | Inside VS Code/IDE | Web-based or plugin via browser/API |
| **Best For** | Code completion and boilerplate generation | Explaining logic, system architecture, debugging |
| **Speed** | Real-time suggestions while coding | Slower, but more in-depth answers |
| **Code Explanation** | Minimal | Extensive and detailed |
| **System Design Support** | Limited to file context | Great for flowcharts, architecture, and logic development |

### 5.3.3 Learning Impact with Examples
AI tools had a strong positive impact on our learning process. They were used to:

- Explain unfamiliar C++ constructs in the Arduino environment.
- Generate pseudocode and convert it to working code.
- Create system diagrams (flowcharts, state machines) using prompts like “generate a state diagram with idle, detecting, alert, and SOS states.”
- Accelerate troubleshooting such as resolving ESP pin conflicts or misconfigured PWM outputs.

### 5.3.4 Limitations and Risks

- **False Confidence:** AI can sometimes give incorrect answers which could cause issues throughout the project. This required us to manually validate results, especially for sensor interfacing or pin configurations.
- **Outdated Context:** Copilot and ChatGPT can occasionally suggest libraries or APIs that are outdated or lack compatibility with the ESP32.
- **Plagiarism Risk:** Over-reliance on generated content without understanding it could violate academic integrity or result in undebuggable code.
- **Lack of Physical Awareness:** AI does not account for electrical limitations (e.g., current draw, real-world timing issues), which must be tested manually.

The integration of AI tools such as GitHub Copilot, ChatGPT, and Claude significantly enhanced our development workflow and technical learning. These tools acted as accelerators and were not replacements for real understanding. When used responsibly, they enabled rapid prototyping, deeper comprehension of embedded systems, and clear documentation. However, we remained aware of their limitations and exercised judgement in applying their suggestions. Overall, AI is a valuable tool throughout our Senior Design journey. However, there are some strong limitations within using AI that are strongly observed.

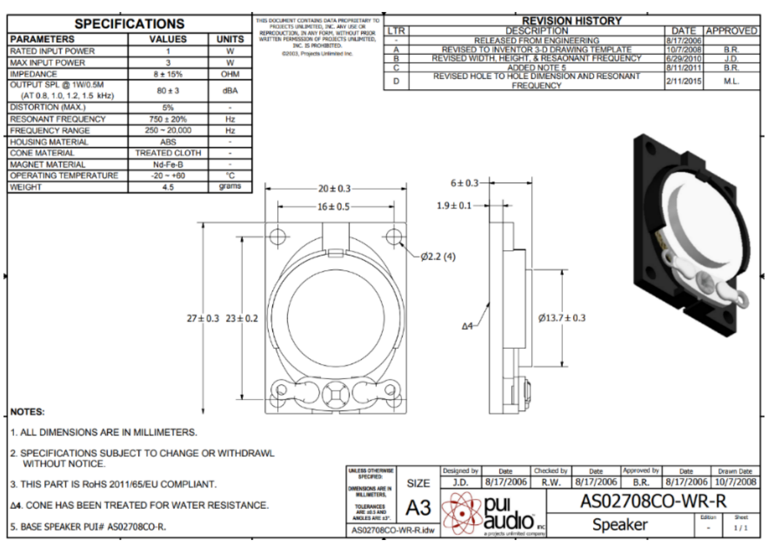
# Chapter 6 Hardware Design

This chapter outlines the hardware design of the SightSense shin guard system which is developed to enhance the navigation for the visually impaired through tactile and auditory alerts. The system is embedded into the shin guard and integrates many hardware subsystems. By combining distance measurement, real-time processing, and a multimodal alert system, the SightSense shin guard system provides the user with appropriately timed obstacle warnings through vibration and audio feedback. The major components included in the product are a microcontroller (ESP32-S3-Wroom), two ultrasonic distance sensors (HC-SR04), a vibration motor, a speaker, a rechargeable lithium-ion battery, a camera (ESP32-CAM), and a laser module. The hardware was selected with an emphasis on durability, long-lasting power supply, and seamless integration within the shin guard environment. The following sections detail the architecture, subsystems, schematic overview, and physical layout of the device.

## 6.1 System Architecture

We will begin this section by giving a brief introduction to each component we will be using in our product. The core of the system is built around the ESP32-CAM, which is a low-power microcontroller equipped with Wi-Fi and a camera interface. It will be responsible for processing sensor inputs and controlling output devices. The ultrasonic sensor, HC-SR04 will measure the distances of nearby obstacles while the LCD Display will print these values to show the product is working. The Vybronics VG0840001D vibration motor and PUI AS02708CO-WR-R waterproof speaker will provide haptic and audio feedback, respectively. And lastly the Meshnology 3.7V 3000mAh Li-ion battery supplies power to the entire system. The architecture following the modular design will allow for easy future upgrades or replacements and power regulation will be managed through a compact onboard voltage regulation system. Below are photos of the components listed above for easier visualization.

Speaker: PUI Audio AS02708CO-WR-R:



| SPECIFICATIONS | | |
|---|---|---|
| PARAMETERS | VALUES | UNITS |
| RATED INPUT POWER | 1 | W |
| MAX INPUT POWER | 3 | W |
| IMPEDANCE | 8 ± 15% | OHM |
| OUTPUT SPL @ 1W/0.5M (AT 0.8, 1.0, 1.2, 1.5 kHz) | 80 ± 3 | dBA |
| DISTORTION (MAX.) | 5% | - |
| RESONANT FREQUENCY | 750 ± 20% | Hz |
| FREQUENCY RANGE | 250 ~ 20,000 | Hz |
| HOUSING MATERIAL | ABS | - |
| CONE MATERIAL | TREATED CLOTH | - |
| MAGNET MATERIAL | Nd-Fe-B | - |
| OPERATING TEMPERATURE | -20 ~ +60 | °C |
| WEIGHT | 4.5 | grams |

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| REVISION HISTORY | | | |
|---|---|---|---|
| LTR | DESCRIPTION | DATE | APPROVED |
| - | RELEASED FROM ENGINEERING | 8/17/2006 | |
| A | REVISED TO INVENTOR 3-D DRAWING TEMPLATE | 10/7/2008 | B.R. |
| B | REVISED WIDTH, HEIGHT, & RESAONANT FREQUENCY | 6/29/2010 | J.D. |
| C | ADDED NOTE 5 | 8/11/2011 | B.R. |
| D | REVISED HOLE TO HOLE DIMENSION AND RESONANT FREQUENCY | 2/11/2015 | M.L. |



NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETERS.
2. SPECIFICATIONS SUBJECT TO CHANGE OR WITHDRAWL WITHOUT NOTICE.
3. THIS PART IS RoHS 2011/65/EU COMPLIANT.
Δ4. CONE HAS BEEN TREATED FOR WATER RESISTANCE.
5. BASE SPEAKER PUI# AS02708CO-R.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS, TOLERANCES ARE ±0.5 AND ANGLES ARE ±3°.

| SIZE | Designed by | Date | Checked by | Date | Approved by | Date | Drawn Date |
|---|---|---|---|---|---|---|---|
| A3 | J.D. | 8/17/2006 | R.W. | 8/17/2006 | B.R. | 8/17/2006 | 10/7/2008 |

AS02708CO-WR-R.idw
pui audio inc — a projects unlimited company
AS02708CO-WR-R
Speaker
Edition: -
Sheet: 1 / 1

Figure 13: Speaker Illustration

This speaker is compact and waterproof. It can deliver sound output between the ranges of 800Hz-20kHz and has an impedance of 8 ohms. It is small and portable and due to its weather resistance, it is ideal for outdoor use. However, due to its small size we needed to upgrade this to a much larger speaker to increase the volume and therefore safety of the user.

Audio Amplifier:

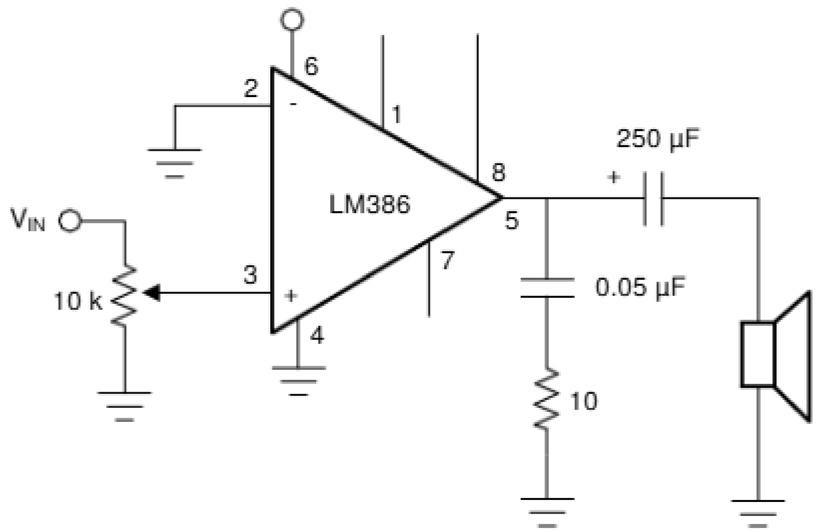





Figure 14: LM386 Low Voltage Audio Power Amplifier

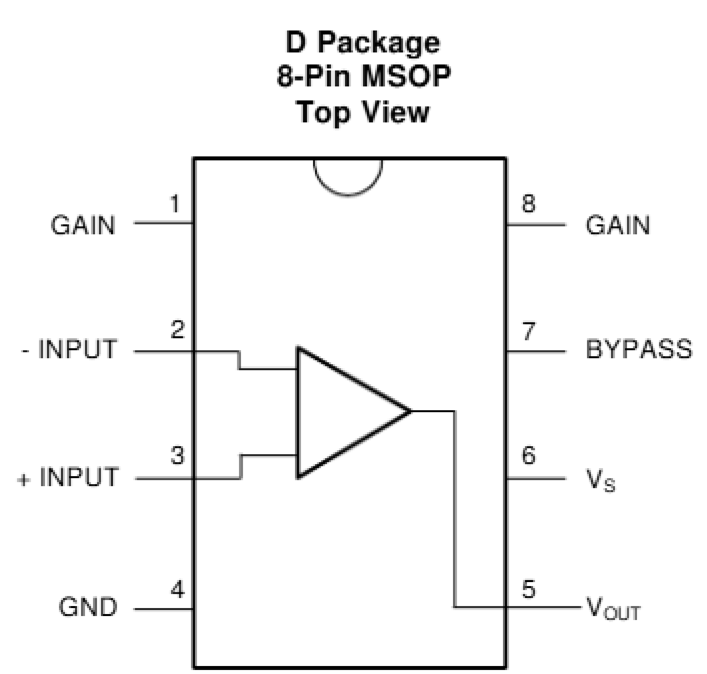



Figure 15: LM386 Low Voltage Audio Power Amplifier

The LM386 is a low-voltage audio power amplifier designed to drive small speakers directly from simple power supplies. It typically operates from about 4V to 12V, so it can run off a single 5V battery or a low-voltage DC rail. Internally, the LM386 is configured for a default voltage gain of 20, but its gain can be increased up to 200 by adding a simple RC network between the gain pins. Because it’s optimized for low power and small signals, it doesn’t require a large heat sink in most applications and only needs a handful of external components to function. Its simplicity, low part count, and ability to run from low supply voltages make the LM386 a great choice for small audio projects such as this one that need basic audible feedback without a complex audio chain.

Vibration Motor: Vybronics VG0840001D:

Figure 16: Vibration Motor Illustration

This vibration motor is a coin-shaped linear resonant actuator. It operates at a frequency of 170-175Hz and provides a strong clear haptic response. It has a low operating voltage and fast rise time. These reasons make it ideal for applications which require localized tactile feedback specifically in wearable haptic interfaces.

Haptic Driver:

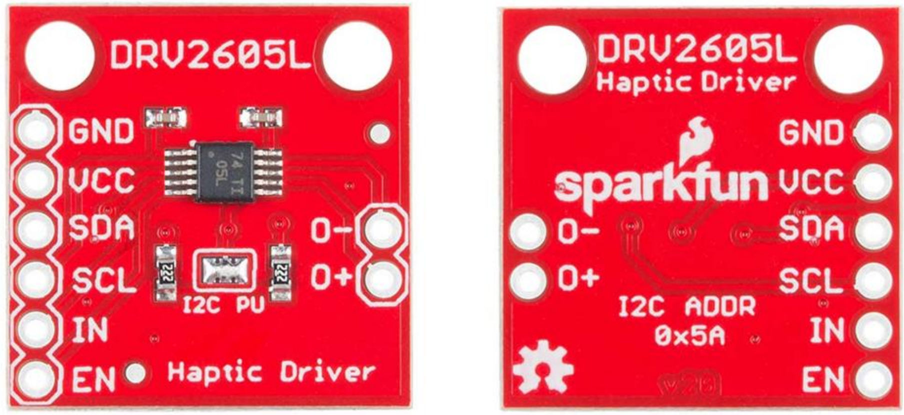



Figure 17: SparkFun Haptic Motor Driver - DRV2605L

The haptic driver enables precise control of the linear resonant actuator. It includes a waveform library (click, buzz, ramp effects) and has an automatic resonance tracking to optimize motor performance. Due to its size (compact) it is easy to integrate onto PCBs and allows for seamless haptic feedback implementation.

Ultrasonic Sensor: HC-SR04:

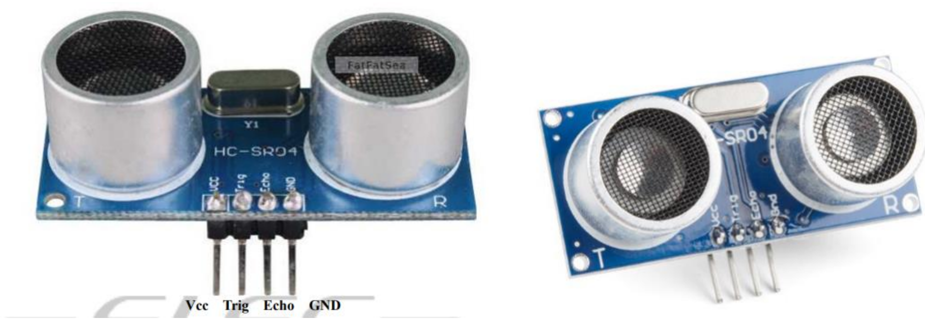



Figure 18: Ultrasonic Sensors

The ultrasonic sensor will be used for precise, no-contact distant measuring. It operates by emitting high frequency pulses which calculates the time delay of the reflected echo to determine the distance of objects. We use this to get an accurate measure of obstacles in front of our product. This ultrasonic sensor allows flexible integration, supporting both serial and pulse-width interfaces and will allow the MCU to have smooth integration.

Battery: Meshnology 3.7V 3000 mAh:


Figure 19: Battery

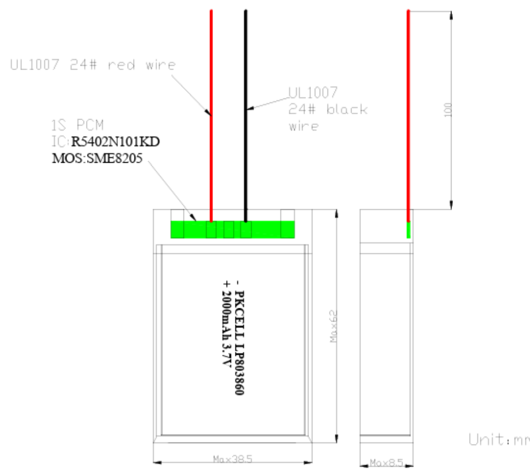



Figure 20: Battery Schematic

This rechargeable lithium-ion battery is ideal for our product. It delivers a nominal voltage of 3.7V and has a capacity of 3000mAh. This means it is ideal for providing power for low-medium current devices. It has a standard connector and includes built-in protection circuitry to prevent overcharging, over-discharging and short circuiting.

Battery Charger:

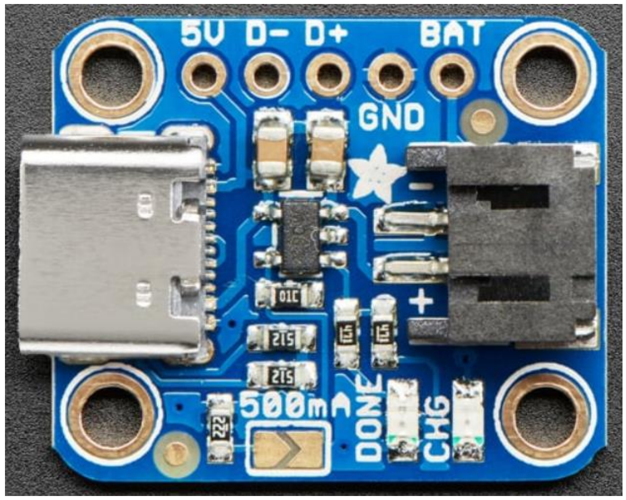


Figure 21: Adafruit Industries LLC 4410

MCU: ESP32-CAM:

Figure 22: ESP32-CAM MCU

The ESP32-CAM is the second MCU for our product and provides the camera we will be using to track obstacles. This ESP-CAM is highly performing and with the additional laser and camera lens we are able to implement a highly efficient obstacle tracking system.

LCD Screen:

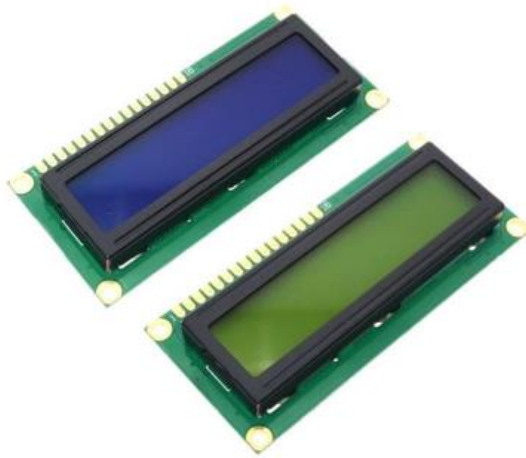


Figure 23: LCD 1602 Screen

The LCD display board is a 16-character 2-line alphanumeric screen. It runs on a 5-volt power supply and has an adjustable contrast potentiometer and backlight. This is the ideal display screen for real time data for our product. This LCD display will demonstrate to others that the ultrasonic sensor is working efficiently. This display is typically used with I2C interface since it reduces GPIO usage.

## 6.2 Subsystem Block Diagram

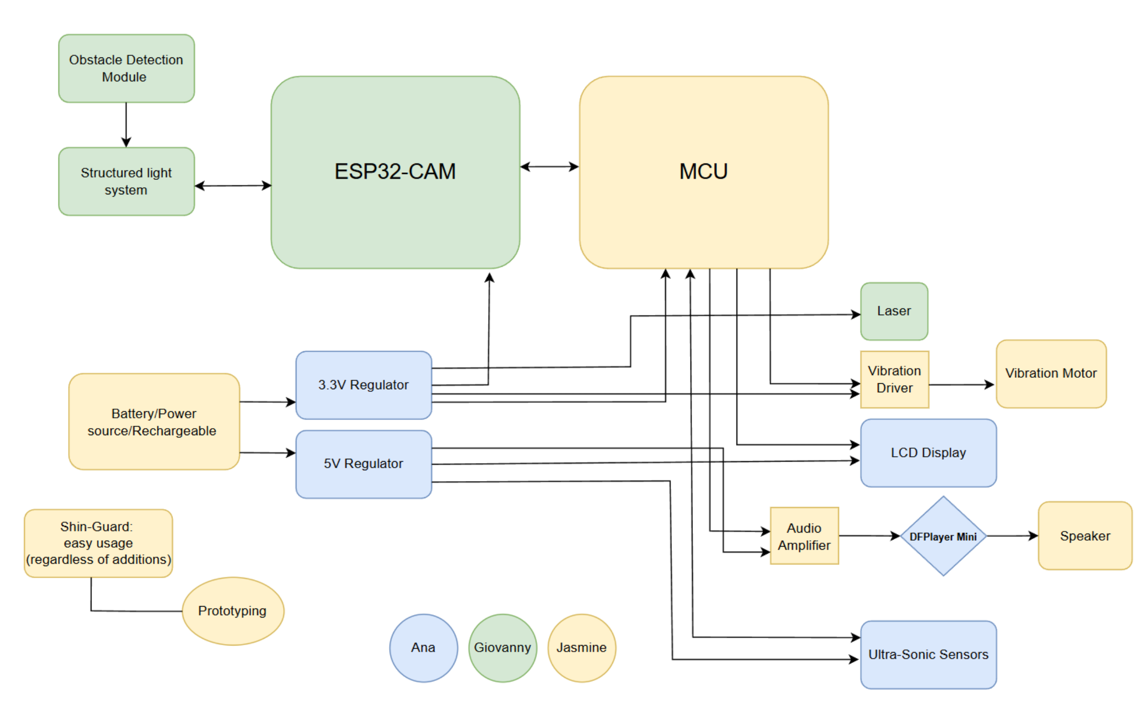



Figure 24: Block Diagram

This block diagram shows the overall architecture of our shin-mounted obstacle detection system. A rechargeable battery feeds both a 3.3 V and 5 V regulator, which provides stable power rails for all the electronics. The ESP32-CAM handles the structured-light obstacle detection module, capturing images and communicating processed information with the main microcontroller (MCU). The MCU acts as the central hub, exchanging data with the ESP32-CAM while driving the system's feedback and sensing peripherals. From the MCU, control lines show the power flow and connections out to the dual ultrasonic sensors, vibration driver and motor, LCD display, and the audio path. Audio cues are generated using a DFPlayer Mini and are amplified by the audio amplifier before being sent to the speaker, while haptic feedback is created by the vibration motor. The LCD provides visual status information to the creators and reviews for real-time system updates. All these elements are integrated into a shin-guard platform designed for easy usage during prototyping and future iterations.

Camera:

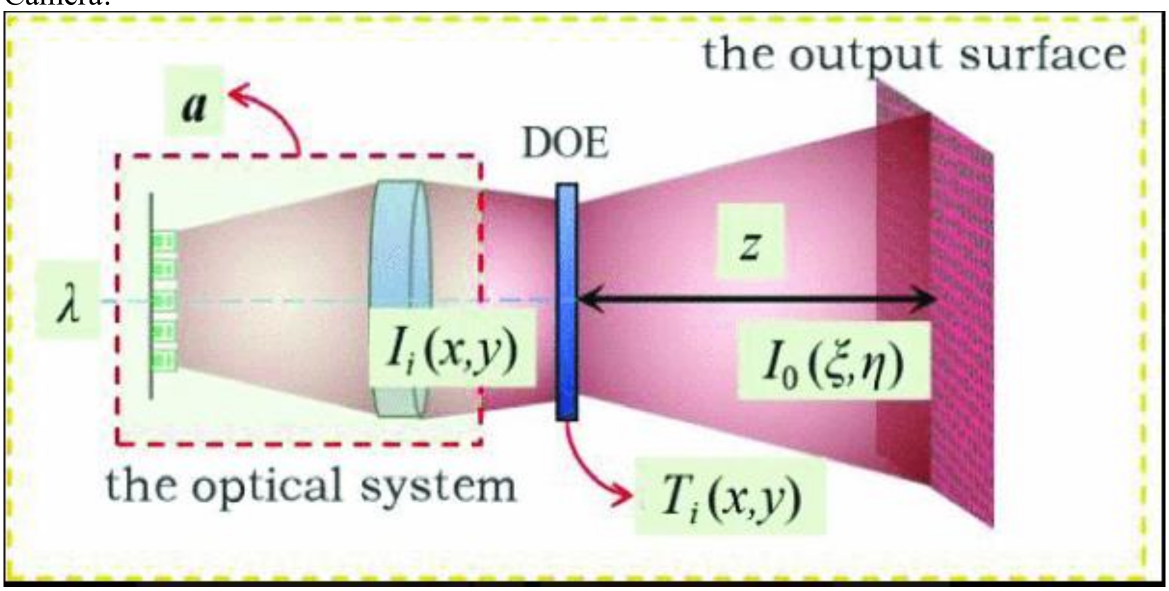



Figure 25: Optical System Diagram

The figure above is a typical diffraction optical element (DOE) based optical system which is used for beam shaping or wavefront transformation. In the figure above the wavelength enters the optical system, the system contains an input plane with an input field, the beam is manipulated using lenses and a DOE. After passing through the DOE, the beam propagates a distance, z, to reach the output intensity distribution is $I_0$. The system is designed to shape light from a known input intensity profile $I_i$ into a desired output distribution $I_0$ at a distance z, using the DOE to modulate the phase and/or amplitude of the light.

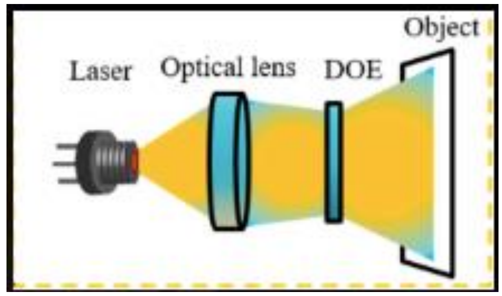


Figure 26: Laser with Optical Lens Diagram

The figure above illustrates a basic laser illumination and beam shaping system using a DOE. The laser, a coherent light source, emits a collimated beam which is usually monochromatic and narrow-divergent, which is ideal for precise optical control. The optical lens focuses or collimates the laser beam and shapes the beam into an intermediate profile which prepares it for modulation. The DOE alters the phase (sometimes amplitude) of the beam, transforms the beam shape or directs the light into a desires intensity pattern and often is used to generate structured light. And finally, the object is the target plane where the beam hits, for this project this is an image plane for analysis or processing to determine if it is an obstacle. This configuration is typical in systems where someone would want to generate a specific light pattern on an object using a DOE.

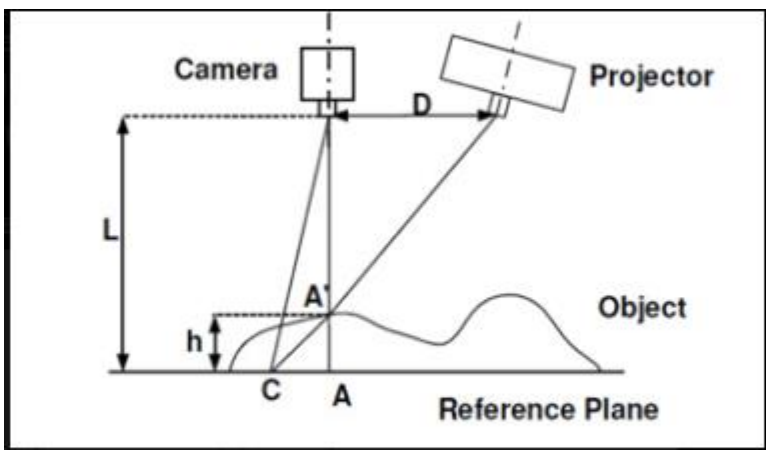


Figure 27: Camera Diagram

The figure above represents a structured light scanning system using triangulation. We are using a typical setup in machine vision, optical metrology, and 3D reconstruction. The projector will project a known light pattern onto an object and is positioned at a certain distance from the camera. The camera captures the deformation of the projected pattern caused by the shape of the object and is located directly above the reference plane. The reference plane is a flat baseline surface used for calibration, point A lies on the plane directly below the cameras line of sight and point C is the corresponding projection from the projector onto the reference plane. The object is the 3D surface being scanned and at point A the object deviates upward from the reference plane at a particular height. This diagram is known as a triangulation principle, in which the projector and camera form a triangle with a point on the surface of an object. By knowing the geometry (distance, height, and angles) the system can calculate the depth information using triangulation.

Laser:

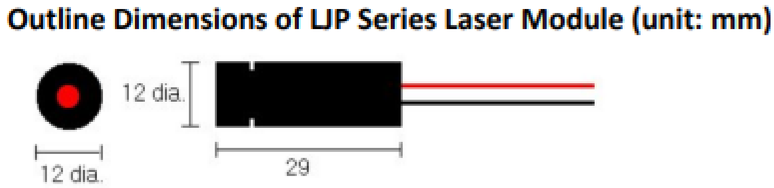



Figure 28: Laser Diagram

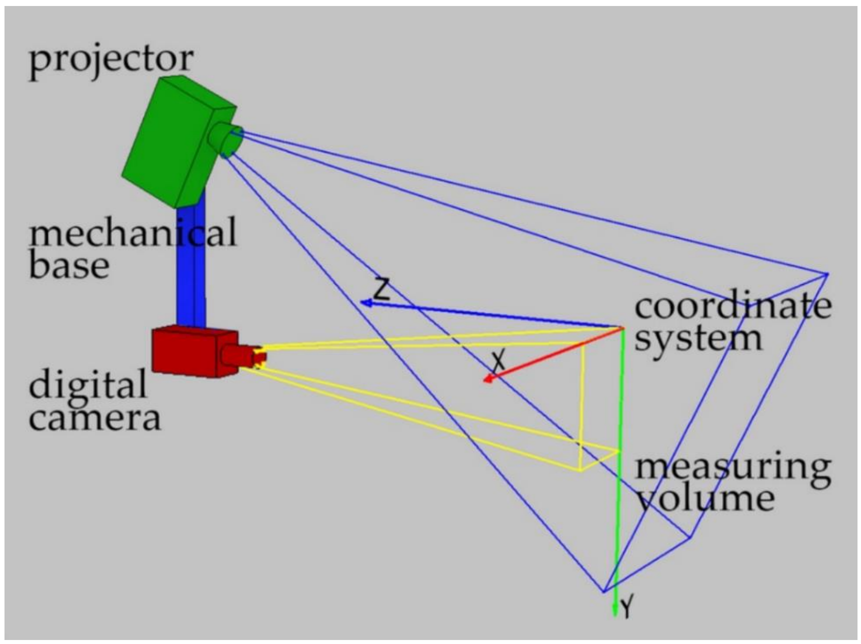



Figure 29: Camera and Laser Diagram

## 6.3 Schematics

Schematics are important tools for electrical components and systems. They provide a clear standardized visual representation of how the components are connected and how the system should function. Schematics let everyone interpret the layout regardless of who builds or troubleshoots the circuit. They show the logical flow of electricity (which makes it easier to understand how the system works). They are an important form of documentation, especially if the product requires safety standards. And lastly, if something should go wrong, schematics can help trace back the connections and components to find the issue.

Listed below are just some of the component's schematics we were able to find. This includes the ESP32-CAM, speaker, vibration motor, and ultrasonic sensor. The HC-SR04 sensor is connected to two GPIO pins, the vibration motor is driven by a transistor controller, and the battery connects through a power management IC regulator.

MCU: ESP32-CAM

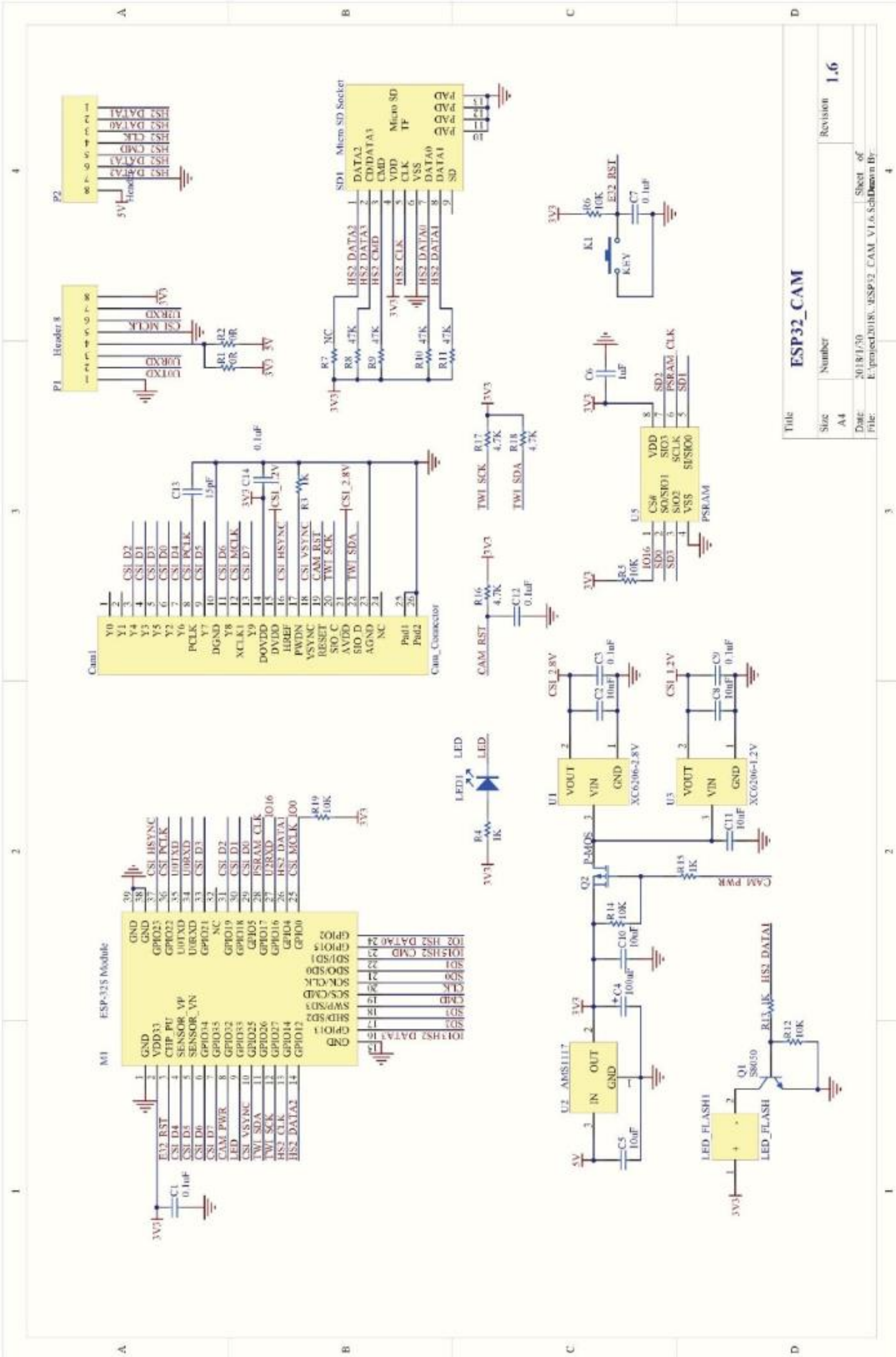



Figure 30: ESP32CAM Schematic

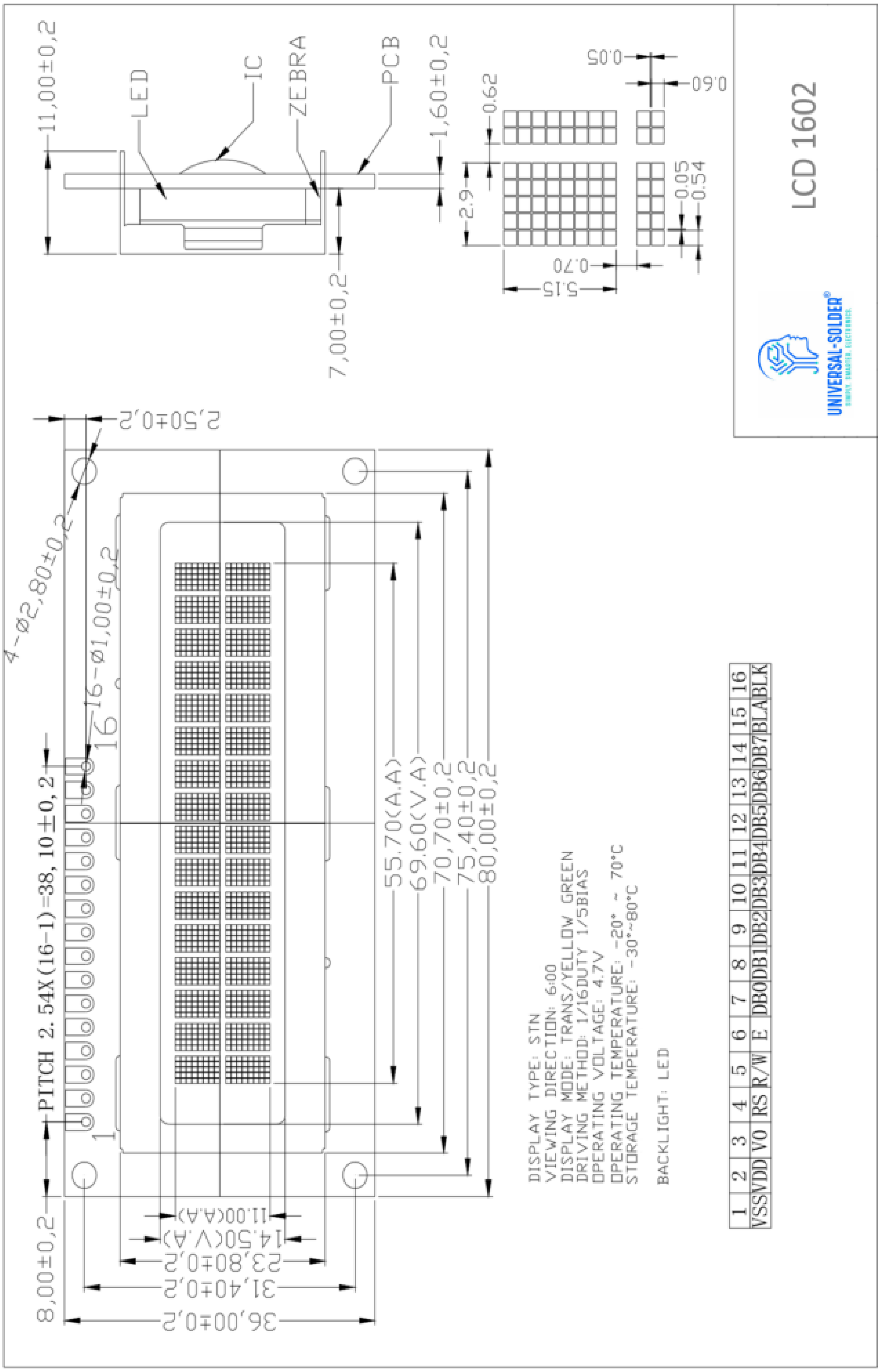



Figure 31: 5V standard LCD with HD44780 compatible controller and backlight

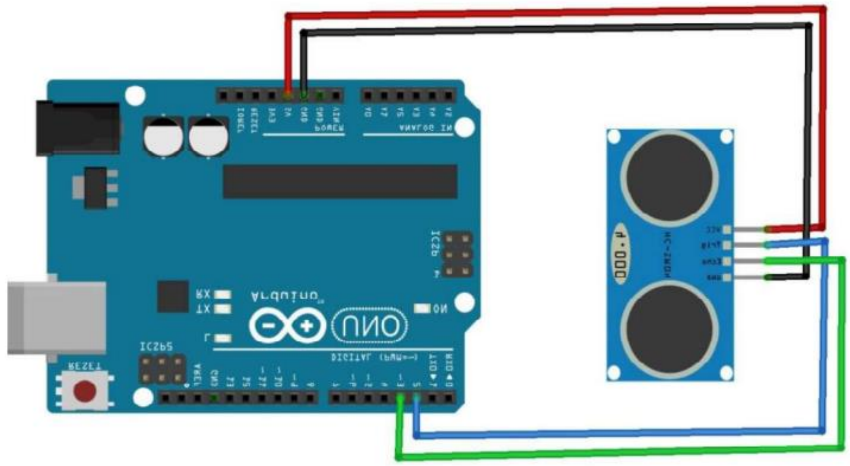
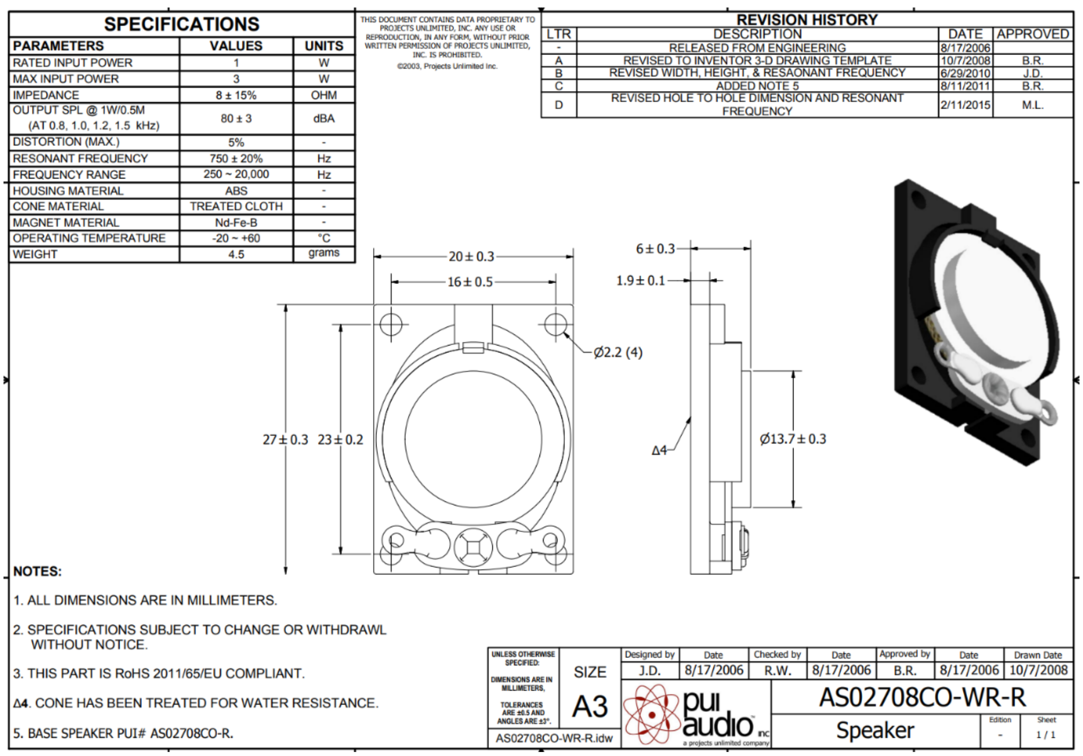


Figure 32:Ultrasonic sensor



| SPECIFICATIONS | | |
|---|---|---|
| PARAMETERS | VALUES | UNITS |
| RATED INPUT POWER | 1 | W |
| MAX INPUT POWER | 3 | W |
| IMPEDANCE | 8 ± 15% | OHM |
| OUTPUT SPL @ 1W/0.5M (AT 0.8, 1.0, 1.2, 1.5 kHz) | 80 ± 3 | dBA |
| DISTORTION (MAX.) | 5% | - |
| RESONANT FREQUENCY | 750 ± 20% | Hz |
| FREQUENCY RANGE | 250 ~ 20,000 | Hz |
| HOUSING MATERIAL | ABS | - |
| CONE MATERIAL | TREATED CLOTH | - |
| MAGNET MATERIAL | Nd-Fe-B | - |
| OPERATING TEMPERATURE | -20 ~ +60 | °C |
| WEIGHT | 4.5 | grams |

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| REVISION HISTORY | | | |
|---|---|---|---|
| LTR | DESCRIPTION | DATE | APPROVED |
| - | RELEASED FROM ENGINEERING | 8/17/2006 | |
| A | REVISED TO INVENTOR 3-D DRAWING TEMPLATE | 10/7/2008 | B.R. |
| B | REVISED WIDTH, HEIGHT, & RESAONANT FREQUENCY | 6/29/2010 | J.D. |
| C | ADDED NOTE 5 | 8/11/2011 | B.R. |
| D | REVISED HOLE TO HOLE DIMENSION AND RESONANT FREQUENCY | 2/11/2015 | M.L. |



NOTES:

1. ALL DIMENSIONS ARE IN MILLIMETERS.
2. SPECIFICATIONS SUBJECT TO CHANGE OR WITHDRAWL WITHOUT NOTICE.
3. THIS PART IS RoHS 2011/65/EU COMPLIANT.
Δ4. CONE HAS BEEN TREATED FOR WATER RESISTANCE.
5. BASE SPEAKER PUI# AS02708CO-R.

| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS, TOLERANCES ARE ±0.5 AND ANGLES ARE ±3°. | SIZE A3 | Designed by J.D. | Date 8/17/2006 | Checked by R.W. | Date 8/17/2006 | Approved by B.R. | Date 8/17/2006 | Drawn Date 10/7/2008 |
|---|---|---|---|---|---|---|---|---|
| AS02708CO-WR-R.idw | pui audio inc a projects unlimited company | AS02708CO-WR-R | Speaker | Edition - | Sheet 1 / 1 | | | |

Figure 33: Speaker

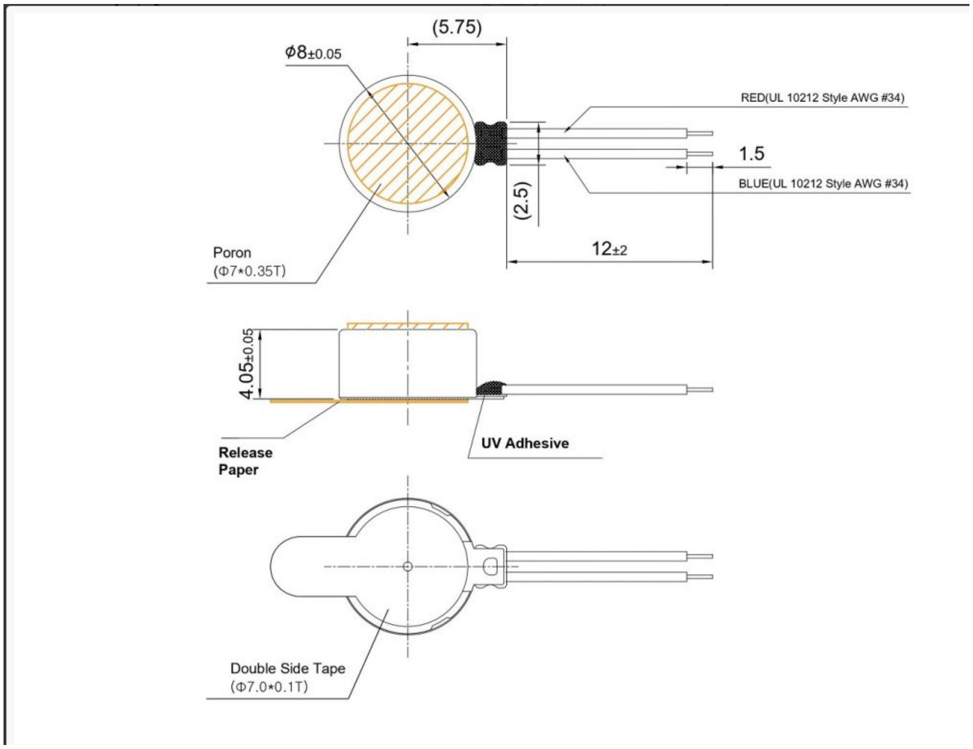


Figure 34:Vibration Motor

## 6.4 Structural Design

For the last section of this chapter, we will go over a rough structural design of our product. Throughout the designing process we have changed this concept many times, however, the components have never changed. The shin guard itself will be a rain shin guard to have stability, durability, and safety. An added bonus when selecting rainshin guards is the weather resistant material. Starting with the ultrasonic sensor, it will be placed at the bottom front sides of the shin guard in order for it to give an accurate reading of distance from an obstacle. The ESP32-CAM are enclosed on the inside of the shin guard away from significant damage. The battery is also placed on the inside of the shin guard. An LCD display will be placed in a cutout hole (only allowing for the screen to show) and project the distance the ultrasonic sensor is reading. The speakers will be placed as close to the top of the shin guard as possible, to bridge the gap even slightly between the user's ear and speaker. The vibration motor will be placed on the back inside lining of the shin guard. The benefit to this vibration motor is that it is weather resistant, which means we can place the motor near the top and should run fine. The Camera and laser will be mounted in front of the shin guard and will be aimed down at the ground to help detect obstacles.

The hardware platform serves as the foundation of the SightSense shin guard system, enabling real-time perception and feedback for visually impaired users. Each component, from the ESP32-CAM microcontroller to the vibration motor and speaker—was chosen to balance functionality, compactness, and efficiency. Together, these elements form a cohesive system that supports the core objective of improving user “visibility” and autonomy through technology.

# Chapter 7 Software Design

This chapter presents the software design of the SightSense system shin guard, detailing the logic and flow that enables the smart shin guard to interpret environmental data and provide real-time feedback to the user. Building on the hardware framework described in the previous chapter, this section outlines how software modules interact with sensors, control haptic and audio outputs, and manage system states for obstacle detection and guidance. We included a high-level overview of the program structure, followed by diagrams and explanations of the key operational states, logic sequences, use cases, and class/module architecture. Additionally, this chapter highlights the data transfer mechanisms, user interface logic, and memory-efficient data structures used to ensure the system is responsive enough for embedded implementation on the ESP32 microcontrollers.

## 7.1 Overview

The software design for SightSense: A Smart Haptic Alert Obstacle Detection System for the Visually Impaired is designed to provide real-time sensing, decision-making, and feedback across two microcontrollers, an ESP32-CAM and an ESP32-S3-WROOM-1. The software is developed using Arduino (C/C++ style) using Arduino IDE, with the ESP32-S3 acting as the primary control system and the ESP32-CAM acting as the distortion detection system.

At a high level, the software for SightSense does the following:

- Continuously measure the distance of nearby obstacles using the ultrasonic sensors.
- Captures images of a laser grid with the ESP32-CAM and classifies them as distorted, undistorted, or unknown using a machine learning model from Edge Impulse.
- Combines the ultrasonic distance readings and the camera results to decide how close an obstacle is.
- Send feedback to the user in several ways:
    - Strong vibration patterns which happen when less than 0.50m
    - Audio prompts directing the user around obstacles
    - LEDs to send a bit over from the CAM to the S3
    - LCD text that displays the distance and undistorted/distorted messages

The rest of this chapter explains how the software is organized. From the software architecture to main models and their respective flow charts, state diagrams, data structures, and how data is passed between the ESP32-CAM and ESP32-S3 to make SightSense work.

## 7.2 Software Architecture

The SightSense software architecture is split into separate parts that each have a clear job. When both codes are combined together, we get a final system working. The following figure below shows our software architecture flowchart.

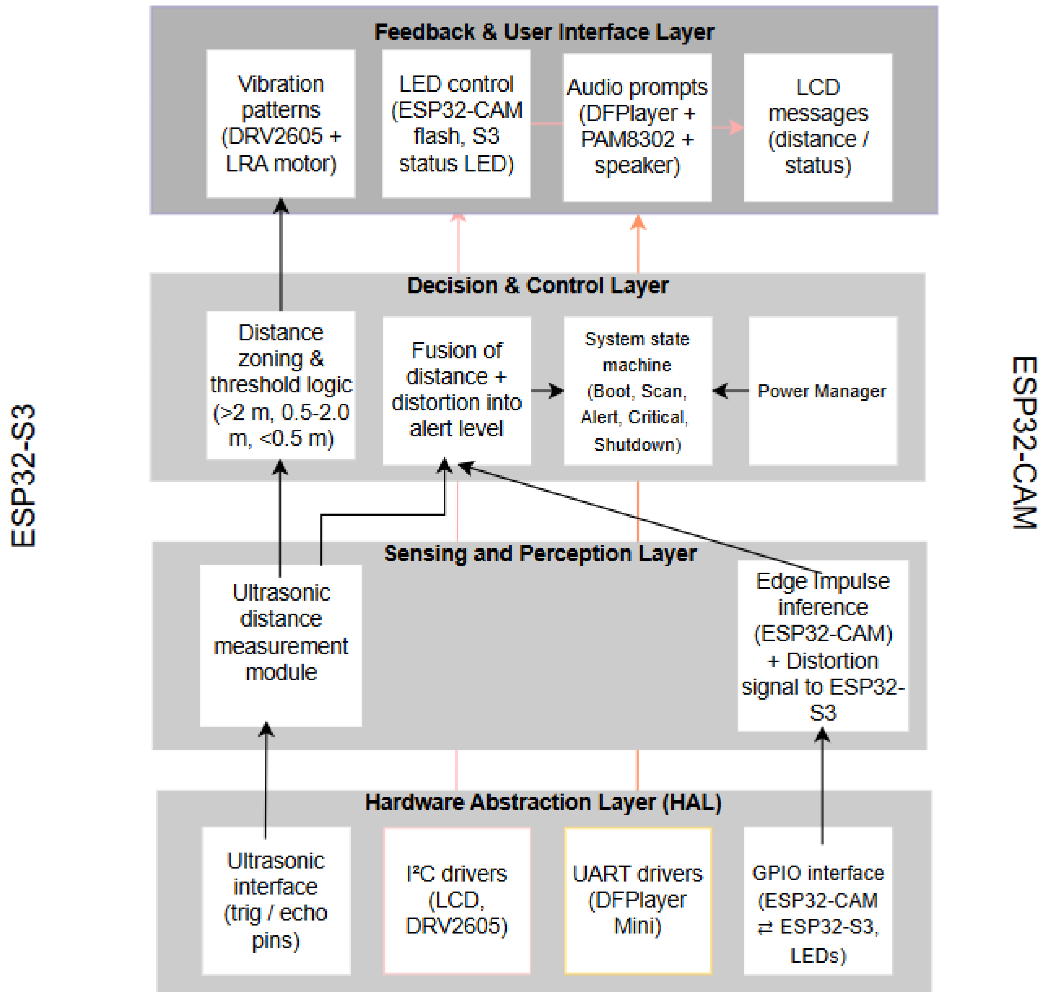


Figure 35: SightSense Software Architecture

The ESP32-CAM runs its own firmware. It handles camera setup, image capture, Edge Impulse, and simple GPIO/LED signaling. The ESP32-S3 runs the main code that controls the system, combines sensor inputs, and drives all feedback to the user.

## 7.3 Module Decomposition

The table below summarizes the main firmware modules and their responsibilities.

Table 35:Major Software Modules

| Module Name | Microcontroller | Responsibility |
|---|---|---|
| CamInit | ESP32-CAM | Set up camera pins, frame size, pixel format, and start the camera sensor. |
| EIInterface | ESP32-CAM | Run the Edge Impulse model and decide if the image is distorted, undistorted, or unknown. |
| CamSignal | ESP32-CAM | Control the flash LED and send a digital output signal to the ESP32-S3 based on the prediction. |
| UltrasonicSensor (L and R) | ESP32-S3 | Trigger the ultrasonic sensors, measure echo time, and calculate distance in meters. |
| DistanceReader | ESP32-S3 | Apply averaging/basic filtering to distance readings to reduce jitter (noise). |
| FeedbackManager | ESP32-S3 | Decide what vibration pattern, audio track, and LED state to use based on alerts. |
| VibrationDriver | ESP32-S3 | Talk to the DRV2605 to pick pattern and start/stop the vibration motor. |
| Audio | ESP32-S3 | Talk to the DFPlayer Mini to pay, stop, set volume, and choose audio track. |
| LED and LCD Manager | ESP32-S3 | Update the S3 status LED and show distance/status text on the LCD. |
| PowerManager | ESP32-S3 | Monitor battery/power signals. |

Each module is made up of functions and in some cases, small C++ classes or structs. Modules are separated into different header and source files to keep the code organized and easier to maintain.

## 7.4 Main Flowcharts

In this section we will go over the main flowcharts that are needed to produce the firmware for each of our microcontrollers so that SightSense can work reliably.

### 7.4.1 Overall System Flow (ESP32-S3 and ESP32-CAM)

The figure down below outlines the top-level software flow for the full SightSense system, combining the ESP32-S3 and ESP32-CAM. This flowchart summarizes how the device starts up, initializes, the microcontrollers and peripherals, then enters a continuous loop. In the loop, the ESP32-CAM captures the images and checks for distortion, while the ESP32-S3 reads the distortion bit, measures distance, decides the current state of the system, and triggers the correct feedback. The loop repeats as long as the device has power, and obstacles are detected.

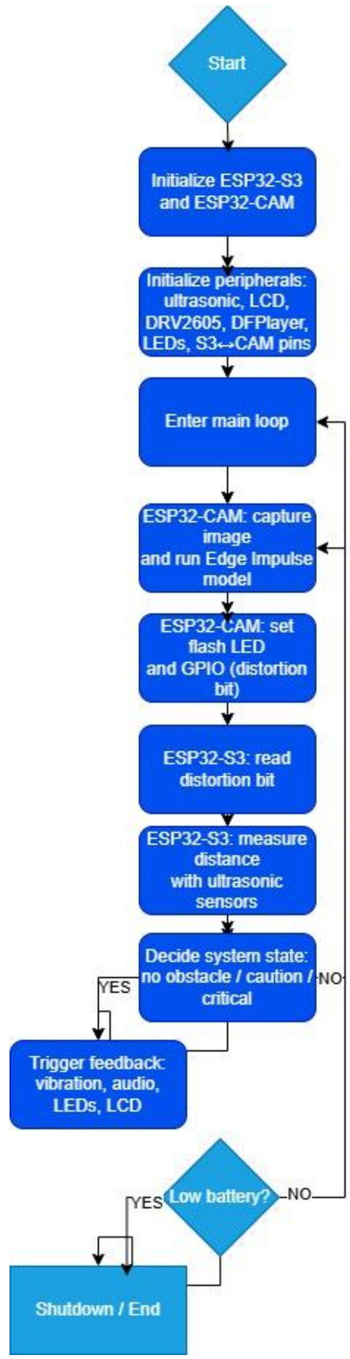


Figure 36: Overall System

## 7.4.2 Camera Inference and Signaling (ESP32-CAM)

The figure below focuses on the firmware running on the ESP32-CAM. This flowchart shows how the camera board initializes its hardware, loads the Edge Impulse model, and then repeatedly captures laser grid images, classifies them, and sets both the onboard flash

LED and the distortion signal sent to the ESP32-S3. The ESP32-CAM stays in this loop until the system is powered off.

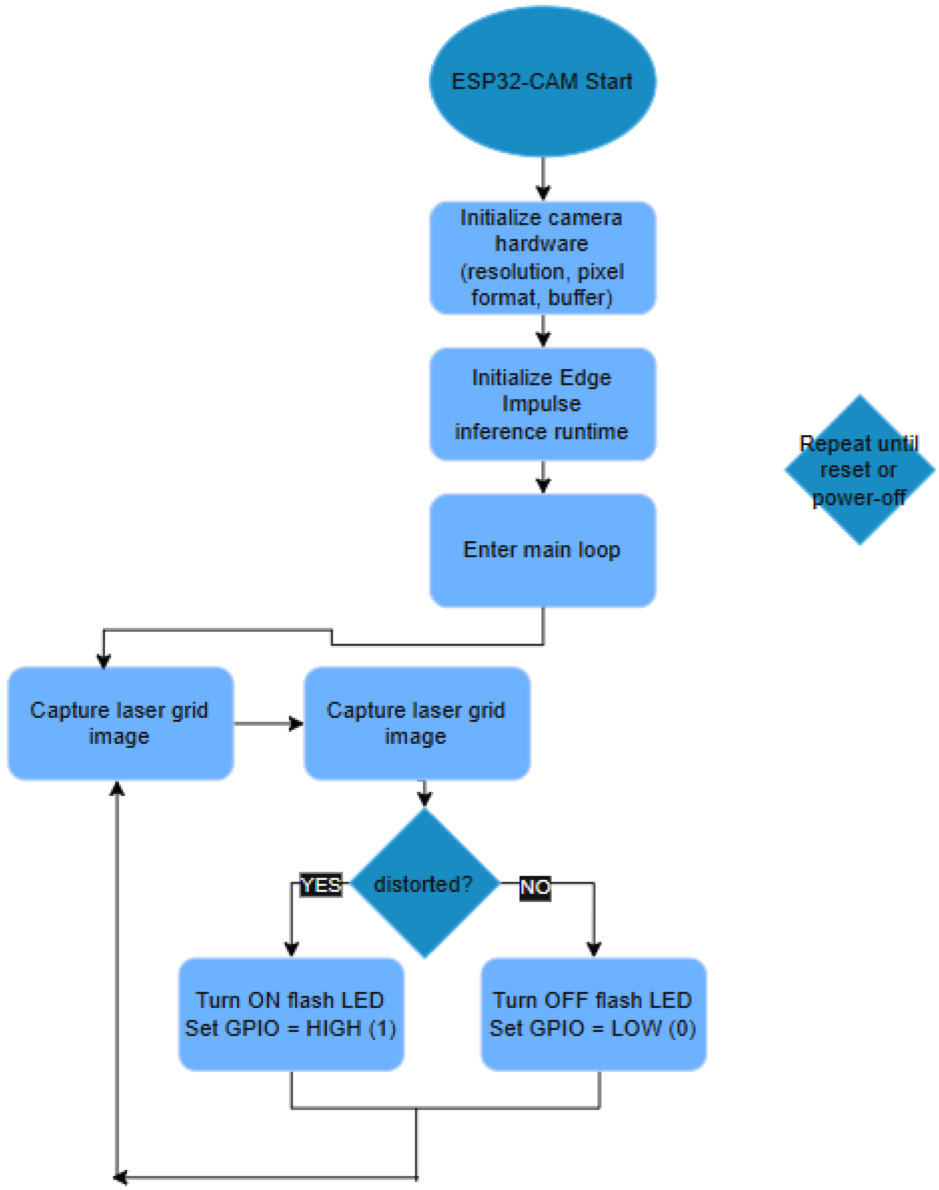


Figure 37: Camera Inference and Signaling (ESP32-CAM)

### 7.4.3 Distance-Based Feedback Flow (ESP32-S3)

The last figure below details how the ESP32-S3 processes distance readings and triggers feedback. The flowchart shows how the S3 triggers the ultrasonic sensors, converts echo time to distance, and classifies the distance into clear, caution, or  critical zones. Then it combines this information with the distortion bit from the ESP32-CAM to choose the strength of the vibration and audio alerts, updates the LEDs and LCD, and repeats the process while the device is powered on.

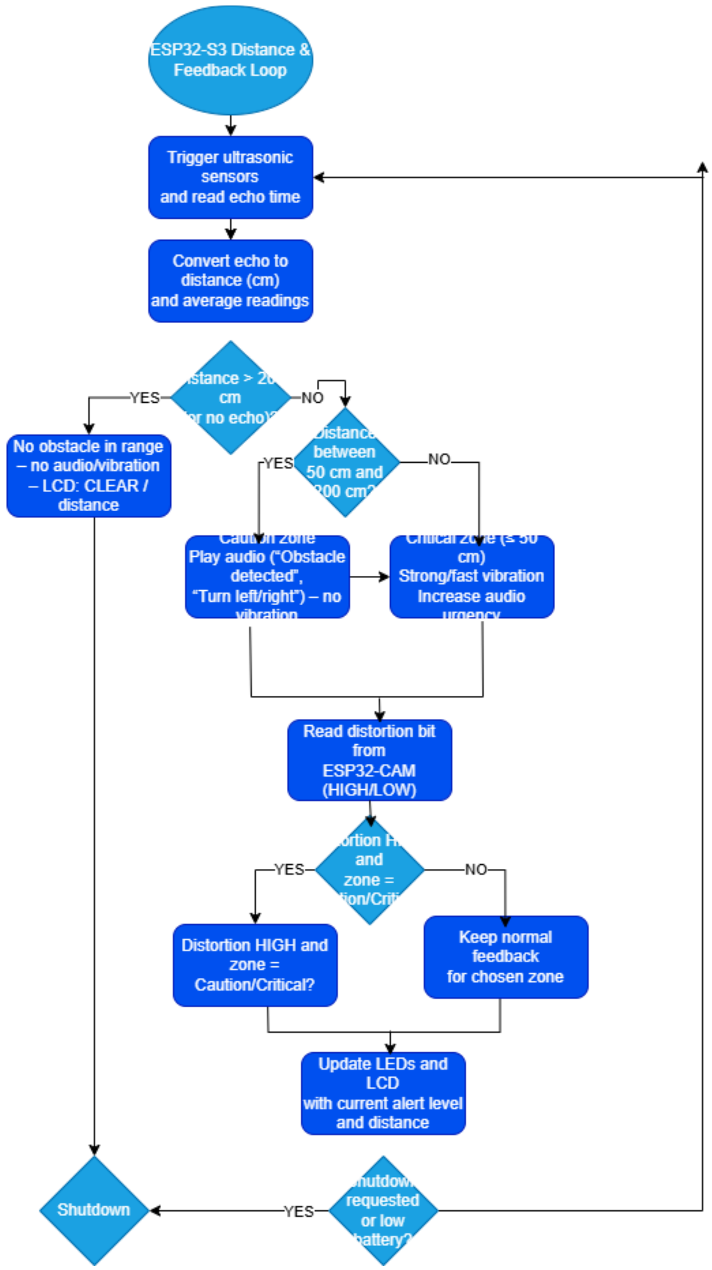


Figure 38: Distance-Based Feedback Flow (ESP32-S3)

## 7.5 State Diagram

The figure below illustrates the finite state machine governing the behavior of the SightSense system. The transitions ensure that the device reacts appropriately to both normal navigation and emergency events, enabling adaptive user assistance.

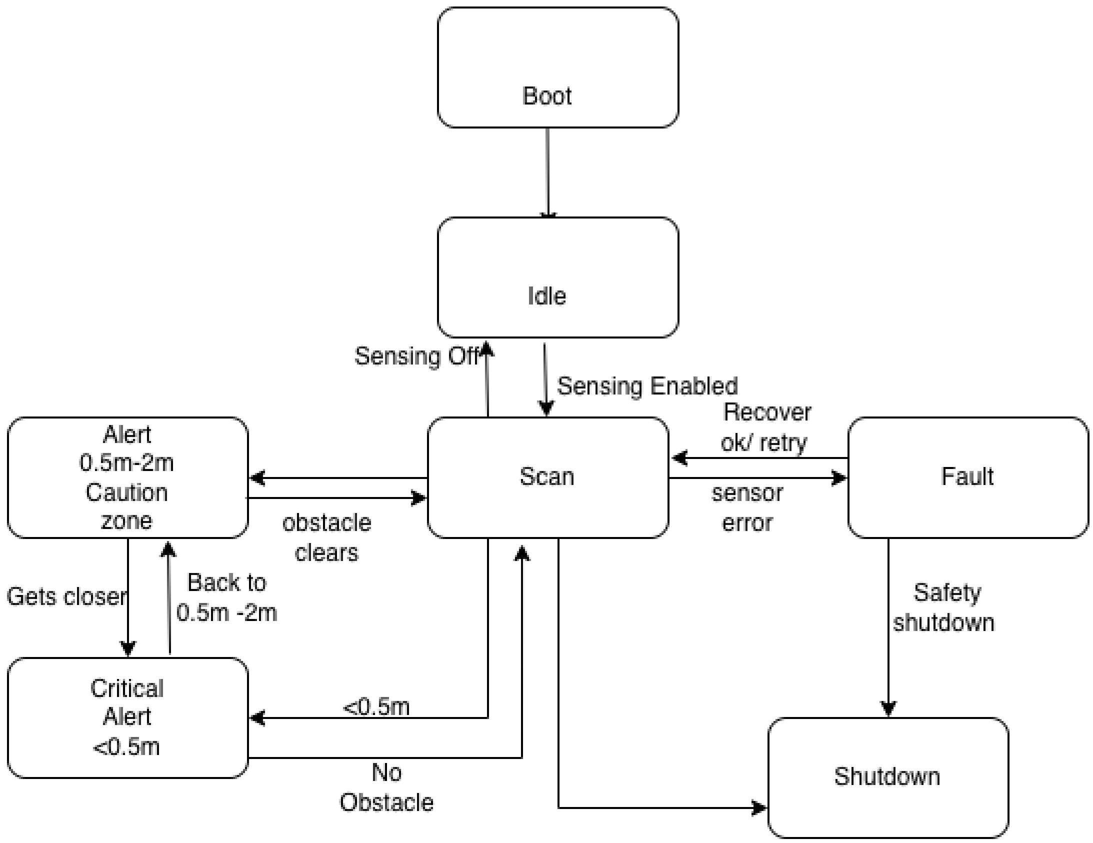


Figure 39: System State Machine Diagram

## 7.6 Use Case Diagram

The SightSense software uses a case diagram as shown in the figure below. This design separates the functions of the code into separate classes that work independently to handle user interaction, sensing, feedback, communication, and logic to accomplish the tasks intended.
Main use cases:

**Power On / Off Device**

- The user connects the battery to turn the system on or off.

**Walk and Receive Alerts**

- The user walks and the system provides distance-based audio and vibration feedback about nearby obstacles.

**Interpret Alerts**

- The user listens to audio cues (“Obstacle detected,” “Turn left,” “Turn right”) and feels vibration strength to decide how to move.

**Adjust Volume / Feedback**

- The user or a caregiver adjusts volume or vibration intensity based on personal needs or environment.

**Charge Device**

- Not purely a software action, but the firmware may show charging or battery status on the LCD.

## 7.7 Class/Module Diagram

The software architecture for SightSense can be described in terms of logical modules or classes, even though the actual implementation used Arduino framework and mostly function based code. The table below shows this modular structure. These key modules work in coordination to ensure seamless performance, responsiveness, and adaptability in real-world environments.

Table 36: Class/Module Diagram

| Logical Module | Code Functions | Description/ Responsibility |
|---|---|---|
| I²C & LCD Display | Wire.begin(SDA_PIN, SCL_PIN), LiquidCrystal_I2C lcd(0x27, 16, 2), lcd.init(), lcd.print(), lcd.setCursor() | Initializes the I²C bus on SDA_PIN / SCL_PIN and controls the 16×2 LCD to show distances and status/messages. |
| Ultrasonic Sensing | Pins: trigLeft, echoLeft, trigRight, echoRight; function: measureDistance(int trig, int echo) | Generates trigger pulses, measures echo time, converts to distance in cm, and clamps values to MAX_DIST. |
| Distance Zoning | Constants: DIST_1, DIST_2, DIST_3, DIST_4, MAX_DIST; variables: lastZone; logic in loop() | Computes left, right, nearest, assigns a zone (0–4), and tracks when the zone changes |
| Audio Feedback | DFRobotDFPlayerMini dfplayer, HardwareSerial dfSerial(2), pins DF_TX, DF_RX, function playSafe(int track) | Initializes DFPlayer over UART2, sets volume, and safely plays numbered audio tracks with rate limiting. |
| Vibration Feedback | Adafruit_DRV2605 drv, drv.begin(), drv.selectLibrary(1), drv.setMode(), drv.setWaveform(), drv.go(), drv.stop() | Configures the DRV2605 haptic driver and generates strong buzz patterns continuously when the user is too close. |
| Timing and State | Variables: lastLCD, lastSpeak, | Ensures LCD updates happen every 500 ms and |

| | | |
|---|---|---|
| | SPEAK_INTERVAL; use of millis() in loop() | spoken alerts are spaced out by SPEAK_INTERVAL to avoid overlap. |
| Serial Message Display | Serial.begin(115200), Serial.available(), Serial.readStringUntil('\n') with lcd.print() on line 2 | Reads text from the serial port and displays it on the second LCD line, overriding the status line when present. |
| System Controller | setup(), loop() | Performs all initialization (sensors, LCD, DFPlayer, DRV2605) and coordinates sensing, zoning, LCD, audio, and vibration behavior. |

## 7.8 Data Structure

The data structures in this code are simple variables and constants that keep track of distances, zones, and timing, rather than full C++ classes or structs. The code maintains separate values for the left and right ultrasonic sensors, computes the nearest distance and then maps that distance into its dedicated zone (0-4). State variables like lastZone, lastLCD, lastSpeak remember what the system did last time so the firmware can update the LCD at fixed intervals and avoid playing overlapping audio alerts.

Table 37: Data Structures for the SightSense

| Data Group Element | Variables / Constants | Type/Range | Description/Role |
|---|---|---|---|
| Distance Values | float left, float right, float nearest (computed in loop()); return of measureDistance() | float (cm, clamped to MAX_DIST) | Store the current measured distance for left and right sensors and the nearest of the two. |
| Distance Thresholds | #define DIST_1 150, #define DIST_2 100, #define DIST_3 75, #define DIST_4 50, #define MAX_DIST 200 | Integer constants (cm) | Define the distance bands for zoning: 1.5 m, 1.0 m, 0.75 m, 0.50 m, and the maximum valid distance. |
| Zone State | int zone, int lastZone | Int(0-4) | zone holds the current distance zone; lastZone remembers the previous zone to detect changes |

| | | | |
|---|---|---|---|
| Timing and debouncing | unsigned long lastLCD, unsigned long lastSpeak, const unsigned long SPEAK_INTERVAL, static lastPlay (in playSafe()), static lastVibe (in loop) | unsigned long (ms) | Control how often the LCD is refreshed, how frequently spoken alerts can occur, and how often vibration fires. |
| LCD display state | LiquidCrystal_I2C lcd(0x27, 16, 2) | Object (16×2 I²C LCD) | Holds the LCD instance used to print distance readings and messages (e.g., serial messages on line 2). |
| Audio | DFRobotDFPlayerMini dfplayer, HardwareSerial dfSerial(2), dfplayer.volume(25) | Objects + volume level (0–30) | Represents the DFPlayer Mini audio module and its UART connection; volume(25) sets the default loudness. |
| Vibration | Adafruit_DRV2605 drv, drv.setWaveform(0, 47) | Object + pattern ID | Represents the DRV2605 haptic driver; waveform 47 is used for a strong buzz when the user is very close (zone 4). |

## 7.9 Data Transfer Between ESP32-CAM and ESP32-S3

The data transfer between the ESP32-CAM and ESP32-S3 is designed to be simple and reliable:

- The ESP32-CAM runs an Edge Impulse model and decides if the laser grid pattern is distorted or not distorted.

**When the model predicts distorted, the ESP32-CAM:**

- Turns its onboard flash LED ON.
- Sets a dedicated GPIO pin to HIGH, which is wired to a digital input on the ESP32-S3.

**When the model predicts undistorted or unknown:**

- The flash LED is OFF.
- The GPIO pin is kept LOW.

On the ESP32-S3 side, a simple digitalRead() on this pin turns the signal into a binary distortion flag that the alert logic uses. This avoids complex communication protocols and keeps delays very low, which is important for real-time feedback.

## 7.10 Use Interface Design

In the current code, the user interface is built around audio prompts, vibration feedback and a simple LCD display that is mainly used for testing and demonstrations. The system continuously measures the left and right distances, picks the nearest one and assigns it to a distance zone based on the thresholds DIST_1 (150 cm), DIST_2 (100 cm), DIST_3 (75 cm), and DIST_4 (50 cm). For each zone, the DFPlayer Mini plays a specific combination of pre-recorded tracks, at around 1.5 m and 1.0 m the user hears an obstacle warning plus the distance, at about 0.75 m they receive a directional prompt ("Turn left" or "Turn right"), and at 0.5 m or closer they hear a strong stop warning followed by a turn direction. The DRV2605 haptic driver provides a strong, repeated vibration pattern only in the closest zone which is zone 4, buzzing every ~200ms until the obstacle is no longer close. Meanwhile, the I²C LCD shows the left and right distances on the first line in meters (L: and R:), and the second line is used to display any status text sent over the serial port, which is helpful during development and demonstrations. Audio volume is set programmatically (volume(25)) to a comfortable default level.

Table 38: User interface elements in the current firmware

| UI Element | Implementation | User Experience |
|---|---|---|
| Distance zones | DIST_1–DIST_4, zone computed from nearest in loop() | Obstacle distance grouped into four bands (1.5 m → 0.5 m). |
| Audio prompts | switch (zone) with playSafe(track) in cases 1–4 | Spoken warnings like "Obstacle ahead" and turn directions. |
| Vibration Feedback | if (zone == 4) uses drv.setWaveform(0, 47); drv.go(); else drv.stop() | Strong repeating buzz only when the obstacle is very close. |
| LCD Display | First line: L: and R: distances; second line from Serial | Live left/right distances plus status or debug messages. |
| Audio volume | dfplayer.volume(25); in setup() | Comfortable default volume, adjustable in future versions. |

## 7.11 Summary

This chapter describes the software design for the SightSense smart shin guard. It explained the overall architecture, how the Arduino C++ code is divided between the ESP32-S3 and ESP32-CAM, and the main control flow used to support real-time sensing and feedback.

The ESP32-S3 acts as the primary controller which continuously reads the ultrasonic sensor distance measurements, receives bits from the ESP32-CAM for classification, and runs the main decision logic. The ESP32-CAM captures all images from the projected laser grid pattern and uses Edge Impulse, a machine learning program, to classify each frame as it shows distorted, undistorted, and unknown before passing a result back to the ESP32-S3. Using these MCU’s together, these modules merge the camera and ultrasonic data to determine how close an obstacle is and what type of auditory and vibration response is needed.

# Chapter 8 System Fabrication/Prototype Construction

This section is about the printable circuit board (PCB) layout and how we were able to integrate all our components for our project on our PCB's. Printable Circuit Board (PCB) design is a fundamental aspect of modern electronics and serves as the physical foundation in which electronic systems are built. PCBs provide a compact, long-lasting, and electrically reliable way to interconnect components. Unlike with breadboards PCBs are permanent precise connections that ensure signals are carried smoothly across a device. They minimize interference especially in high-frequency or sensitive applications. By using specific elements in PCBs (like copper) and embedding traces of them into the boards, the PCBs allow for efficient flow of power and signal between components while maintaining structural integrity.

The layout of a PCB is incredibly important, since this can influence the performance, reliability, and manufacturability of the actual product. Good practices for PCB design layout are optimizing component placement, routing traces with appropriate width and spacing, implementing a ground plate, and managing heat. By following these tips we can prevent issues like noise, voltage drops, or thermal buildup. Another aspect to consider is the physical arrangement of the components and not just their functionality. Each product's size, weight, and cooling capabilities also have a major effect on how the PCB can carry each load. For our product we needed to focus on the size and weight of the board since we were looking for a compact system. We needed to reduce space while maintaining accessibility and repairability - which was crucial since our layout design was originally created for someone visually impaired.

In the PCB below we can see at its core is the ESP32-CAM and ESP32-S3-Wroom, which are our selected MCU's and the ESP32-CAM includes the camera for our optical design. The ESP32-S3-Wroom is the core of the system and coordinates communication with all connected components. The components surrounding the ESP32-S3 are the vibration motor - which will not be connected to the MCU but rather feed through the vibration driver which does connect to the main MCU, the speaker which does not connect but will use the audio amplifier and DFPlayer as a feed which then connects to the MCU, and lastly the LCD display and ultrasonic sensor that both connect directly to the board and MCU. All these components will be connected to the battery and the battery regulators depending on which item is needed. The 3.3V regulator will bring down the voltage from 3.7V to 3.3V while the 5.0V regulator will bring up the voltage from 3.7V to 5V.

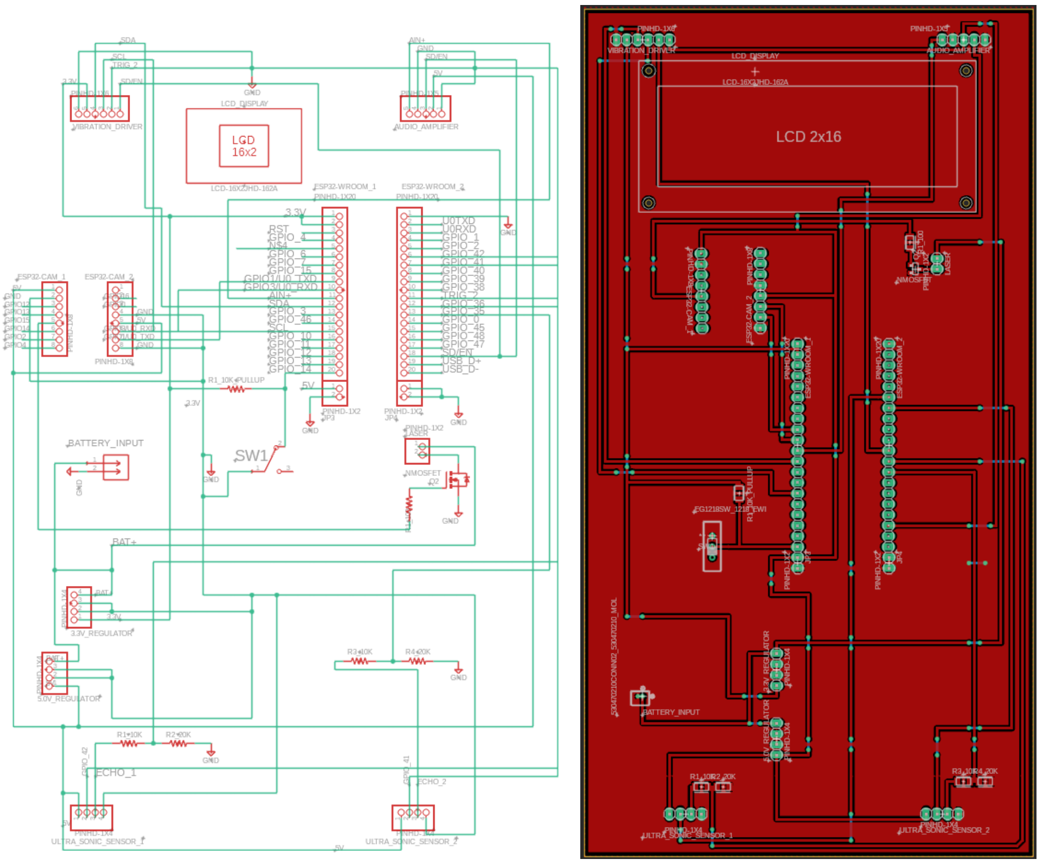


Figure 40: Schematic and PCB for Main Board

This schematic and PCB layout represent the “main board” that ties together all the subsystems in the wearable obstacle-detection device. At the top of the board is a 16x2 character LCD footprint, which serves as the primary user interface for status messages and distance readouts. Adjacent pin headers connect to the off-board vibration driver and audio amplifier modules, bringing there I²C and analog lines back to the central controller. In the middle of the design are two ESP32-S3-WROOM headers and two ESP32-CAM connectors, allowing the main microcontroller and vision module(s) to plug directly into this board without additional wiring. This backplane approach makes it easy to assemble and service the system while keeping all the high-pin-count connections well organized.

The schematic also shows how power and sensing are managed across the system. A dedicated battery input feeds both the 3.3V and 5V regulator boards through separate headers, with SW1 used as a master power switch so the entire device can be turned on or off from one location. The regulated rails are then distributed to the ESP32 modules, LCD, drivers, and sensors. At the bottom of the schematic, connectors for two ultrasonic sensors are included along with resistor dividers on the echo lines, ensuring that the 5V sensor outputs are safely shifted down to the ESP32’s 3.3V inputs. Additional MOSFET circuitry provides switched power to where the laser was, allowing high-current loads to be controlled from the microcontroller while protecting the logic pins.

On the PCB, these functions are laid out in a tall, narrow form factor that matches the shin-mounted enclosure. The LCD occupies the top of the board, so its screen is easy to read, while the headers for the ESP32 modules and smaller boards are clustered in the center to keep signal traces short and direct. The power-handling sections, regulators, battery input, and ultrasonic sensor connectors are grouped toward the bottom, away from the display and digital logic to reduce noise coupling. Wide traces and a solid ground pour carry battery, 3.3V, and 5V rails, down the length of the board and the through-hole headers along the edges add both electrical connectivity and mechanical strength. Together, this design turns the main PCB into a clean backplane that mechanically supports the device and electrically coordinates all its sensing, feedback, and control modules.

Keeping all these components in mind we also needed to make sure that components that although need to connect to the PCB can also connect to the user. For example, the vibration motor needs to be connected to the PCB but also attached to the user and needs to be kept away from the camera so that it did not cause disturbance to the machine. The speaker is another good example. The speaker needs to be high enough on the shin guard for the user to hear it and therefore can be positioned at a further distance on the board. The ultrasonic sensors need to be placed at the bottom side or in front of the shin guards to ensure optimum obstacle detection. This means that it will need to be spaced out as well from the board (although attached by wires). And finally, the ESP32-CAM is the most difficult component we needed to mount on our device. Since the MCU we have chosen has a camera accompanying it, and we are using it for obstacle detection, we needed the camera to be mounted in such a way that would not hinder any obstacle detection implementation. The camera and laser will need to be mounted standing up at a 40-degree angle to get a clear visual at the obstacles surrounding the user. The PCB had to stand with it. This means that all components attached need to fit on a board that could stand up with the camera and not be affected. For our design we decided on a vertical PCB board which would allow user friendly connectivity and easy to space and reduce the risk of interference from the haptic components to the more sensitive ones.

The components we provided above all support multimodal feedback to the user which ensures the obstacles detected will communicate through sounds, vibration and visualizations. However, to get all these components working correctly the battery had to be prioritized. The battery and regulators had to be mounted in such a way that they did not interfere with the other components. This means the PCB was safe and could easily be reached to recharge the battery and will not cause the user any harm on recharge. Since we used a rechargeable battery for the user's convenience, we had to design our PCB in a way that could comply with the functionality of having that capability. Thus, the battery gets placed at the bottom of the PCB for user-friendly access and the charger on top, the regulators above that but side-by-side. This completes our Main PCB design.

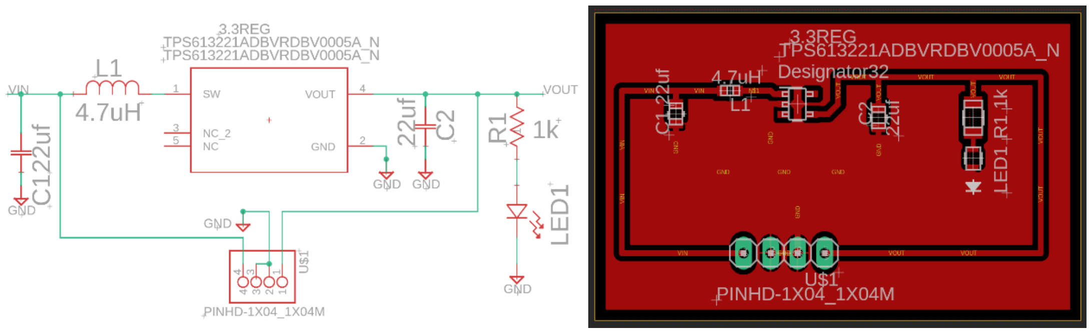


Figure 41: 3.3 Regulator

This circuit implements a dedicated 3.3V regulator stage for our system using the TPS613221A boost converter. The schematic shows a simple but robust topology: the input voltage is filtered by a 22µF capacitor and fed through a 4.7µH inductor into the pin of the TPS613221A. The converter steps the input up to a regulated 3.3V output, which is then smoothed by another 22 µF output capacitor to reduce ripple and provide stable power to downstream electronics. A 1kΩ resistor and indicator LED are tied to VOUT so we have a quick visual confirmation that the regulator is powered and operating correctly. A 4-pin header breaks out VIN, GND, and VOUT so this board can plug cleanly into the rest of the project.

The PCB layout translates this schematic into a compact, single-board power module optimized for current handling and noise performance. Wide copper traces run around the perimeter of the board to carry VIN and VOUT, minimizing voltage drop and heating under load. The inductor, input capacitor, and output capacitor are placed close to the regulator IC to keep the high-current switching loop tight and reduce EMI. A solid ground pour fills the interior of the board to provide a low impedance return path and improve overall stability. The LED and its series resistor are positioned near the VOUT trace for easy visibility, while the 4-pin header is mounted along the edge of the board to simplify wiring into the main system. Together, these design choices create a small, reliable 3.3V power module tailored to the needs of our project.

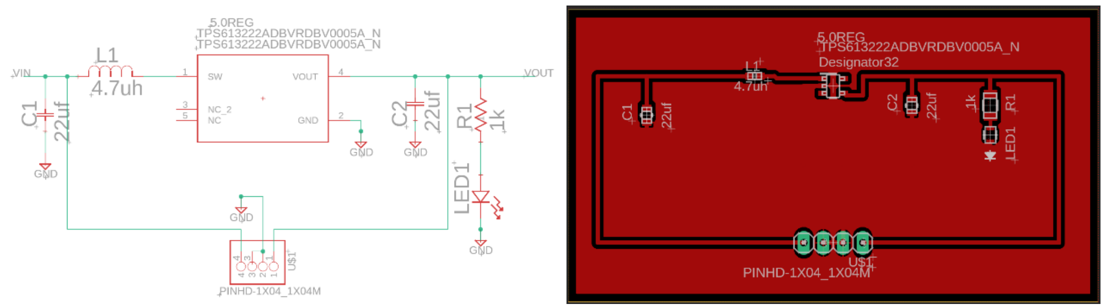


Figure 42: 5.0 Regulator

The images above show the dedicated 5.0V regulator board we designed around the TPS613222A boost converter. In the schematic, the input rail is first decoupled with a 22µF capacitor and then passed through a 4.7µH inductor into the pin of the IC, which boosts the lower battery voltage up to a stable 5V at VOUT. The output is smoothed with another 22µF capacitor, and a 1kΩ resistor with an indicator LED provides a simple visual check that the 5V rail is active. On the PCB layout, these components are arranged in a compact line with short, wide traces on the high-current paths and a thick outer loop carrying VIN and VOUT around the board, helping reduce voltage drop and improve thermal performance. A 4-pin header along the bottom edge breaks out VIN, GND, and 5V so this board can plug directly into the rest of the system as a self-contained 5V power module.

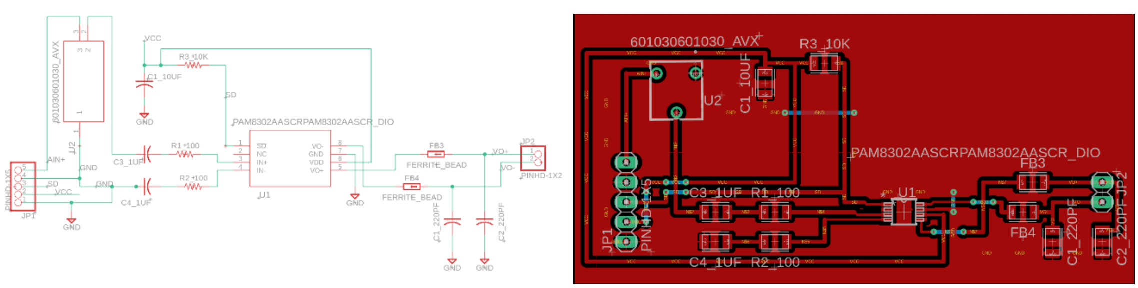


Figure 43: Audio Amplifier

These images show the custom audio amplifier module we designed around the PAM8302A class-D amplifier (which has now been adjusted to the LM386 to accommodate for our DFPlayer and larger speaker). The schematic takes an audio input from a 5-pin header and then AC-couples it into the PAM8302 using the 1µF capacitors and 100Ω series resistors. A 10µF bypass capacitor provides local decoupling on the VCC rail, while a 10kΩ resistor ties the shutdown pin high so the amplifier is enabled by default. On the output side, the differential VO signals pass through ferrite beads and small 220pF capacitors to ground, forming a simple output filter to reduce switching noise before the signal reaches the speaker connector. Together, these components create a compact, self-contained audio path that can take a low-level signal from the main controller and drive the project's speaker with clear, amplified sound.

The PCB layout translates this schematic into a noise-aware physical design. The high-current VCC and output paths are routed with wide traces around the perimeter of the board, while the low-level audio input traces are kept shorter and separated to minimize coupling from the switching outputs. The PAM8302 IC sits near the center of the board with its decoupling capacitor and shutdown pull-up placed close to the power pins to keep the supply stable. The ferrite beads and 220pF capacitors are located near the output header so that EMI filtering happens right before the signal leaves the board, helping to keep radiated noise away from the rest of the system. A solid ground pour fills the remaining area to provide a low impedance return path and additional shielding. This layout makes the amplifier module easy to integrate while maintaining signal integrity and reducing interference with nearby circuitry.

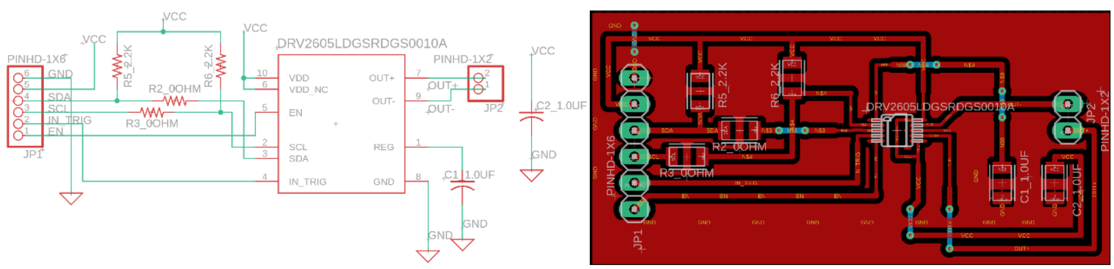


Figure 44: Vibration Driver

These images show the custom haptic driver board built around the DRV2605L. The schematic brings in power and control signals from a 6-pin header, which carries EN, trigger, I²C (SCL/SDA), VCC, and GND from the main controller. The DRV2605L handles all the waveform generation for the vibration motor, with the I²C pins pulled up to VCC through 2.2kΩ resistors so the microcontroller can configure vibration patterns digitally. 0Ω Resistors are used as jumpers in the Trig path, allowing the board to support either I²C-only control or an external trigger input if needed. 1µF Capacitors provide decoupling for the driver's supply and internal regulator, helping keep the I$^2$C stable when the motor current changes quickly.

On the PCB layout, the DRV2605L is placed near the center of the board with short, direct routes to its decoupling capacitors and to the motor output header. 20mil VCC and GND traces run around the perimeter to minimize voltage drop and provide a solid return path for the relatively high motor currents. The I²C and control traces are kept together and routed cleanly into the driver to reduce noise pickup. The OUT+ and OUT- lines are routed as a pair to, where the vibration motor connects, ensuring a clear, low-impedance drive path. Overall, this layout turns the DRV2605L into a compact, plug-in haptic module that can be dropped into the larger system to provide reliable, programmable vibration feedback.

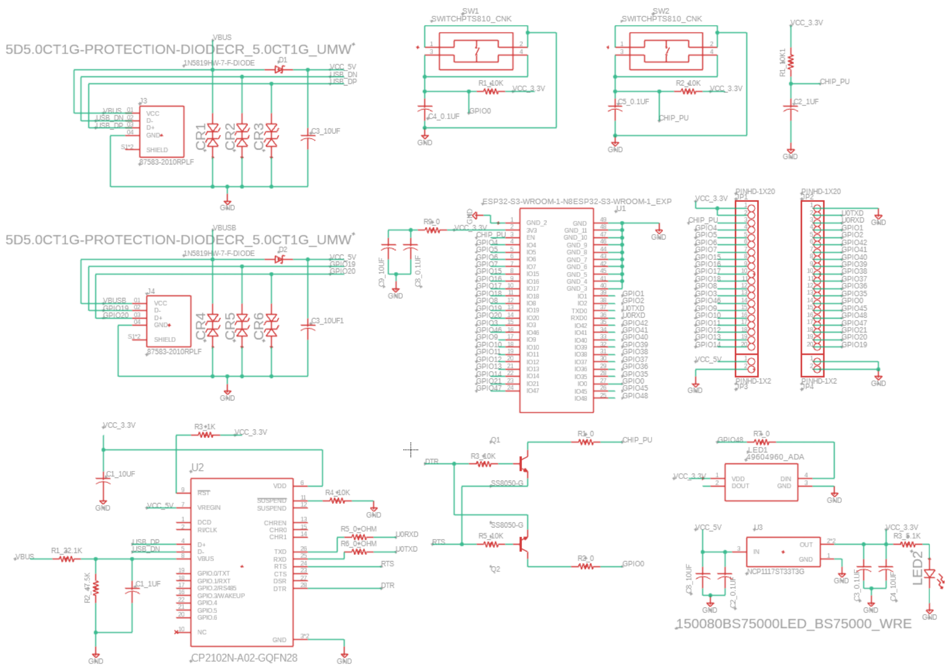


Figure 45: ESP32-S3-WROOM

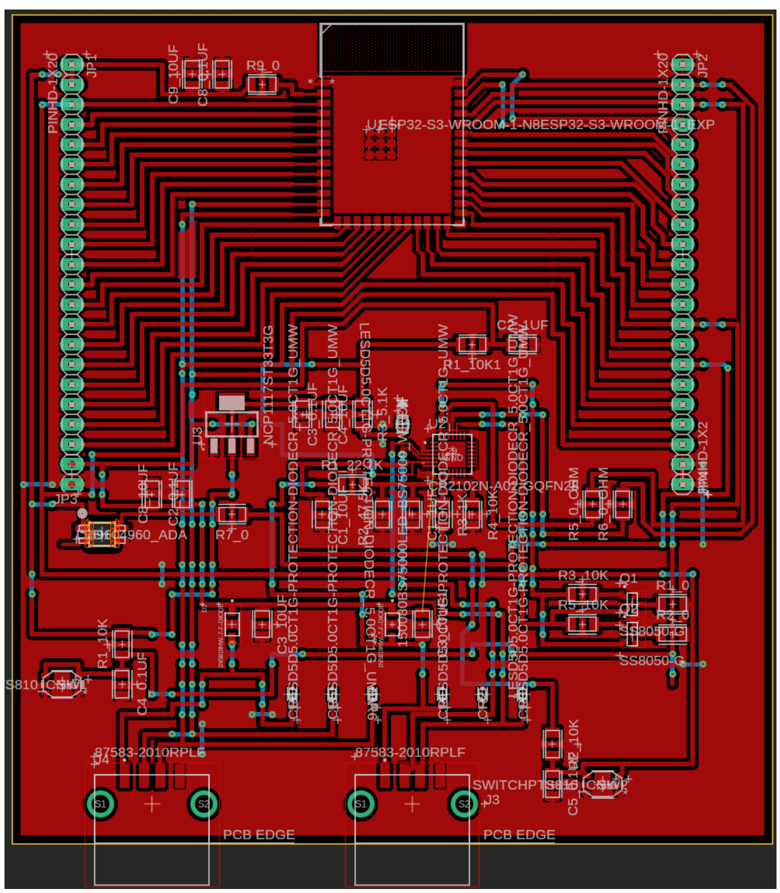


Figure 46: ESP32-S3 PCB

These images show the main controller board for the project, built around the ESP32-S3-WROOM-1 module. The schematic fans nearly all of the ESP32's GPIO out to two 20-pin headers along the left and right edges, giving plenty of flexibility for connecting sensors, regulators, and daughter boards. A dedicated reset/boot circuit with push-buttons and pull-up resistors makes it easy to enter programming mode without extra hardware, while an on-board status LED provides a simple visual check that the microcontroller is powered and running. Overall, this board acts as the central "brain" that ties together the audio, haptic, sensor, and power subsystems used elsewhere in the project.

The lower portion of the schematic focuses on USB connectivity and power management. A CP2102 USB-to-UART bridge handles programming and serial monitoring, with its USB D+ and D– lines protected by LESD5D5 ESD diode arrays and a series Schottky diode on VBUS for reverse-polarity protection. The 5 V coming from USB is regulated down to 3.3 V by an on-board LDO, with multiple decoupling capacitors placed close to the ICs to keep the supply rails clean during Wi-Fi and I/O transients. This arrangement allows the board to be powered and programmed over a single USB connection while still protecting the microcontroller and interface chip from electrostatic events and cable faults.

On the PCB layout, the ESP32-S3 module is centered near the top with a clear keep-out region around its antenna to preserve wireless performance, while the dense support circuitry is clustered near the bottom for short, direct routing. The USB and CP2102N section is placed close to the board edge so the connector can line up with an enclosure, and the high-speed D+ / D– traces are routed as a tight pair with a solid ground pour underneath to control impedance and reduce noise. Wide power traces distribute 3.3 V and ground across the board, and the long pin headers on each side create a convenient interface for ribbon cables or daughter boards. Together, the schematic and layout turn the ESP32-S3 into a robust, easy-to-use controller module tailored specifically for this wearable obstacle-detection system.

Throughout the development of our shin-mounted obstacle detection system, we encountered several hardware challenges that forced us to rethink major parts of the design. One of the first issues we ran into was not having enough current available for key components, which caused unreliable behavior from devices such as the speaker and ultrasonic sensors. As we debugged the power path, we realized that both of our original regulators were buck regulators rather than boost regulators, so they could only step our battery voltage down and could not maintain the required voltage level as the battery discharged. This mismatch between our power architecture and the system requirements meant we needed to redesign portions of the power stage to ensure stable operation.

These power-related challenges also led us to reevaluate several component choices. We upgraded to a larger speaker so that our audio alerts would be louder and clearer for the user, and we added a DFPlayer module specifically to handle stored audio cues more reliably. In addition, we changed our audio amplifier to a design that provided better sound quality and more consistent performance with our new speaker. While these changes required extra prototyping, testing, and troubleshooting, they significantly improved the overall usability and robustness of the final system.

# Chapter 9 System Testing and Evaluation

As the SightSense shin guard progresses from initial prototyping toward full implementation, we will need to ensure reliability, safety, and efficiency of our final product by having an evaluation plan. This chapter will define the procedures for testing and evaluating each subsystem from hardware to software components. Our ultimate objective is to ensure that the SightSense shin guard functions reliably in a range of settings so that users can move more confidently and independently. As we move to the next stage of the design and as we prepare to finish Senior Design II, the outcomes of these testing procedures will directly influence enhancements in functionality, comfort, and usability as well as ensuring a smooth transition into the next phase.

## 9.1 Hardware and Software Testing

During the hardware and software testing phase of the project, most of the experimentation will take place under regular and low light ambient settings in the CREOL optics laboratory. As the project progresses and we enter Senior Design II, testing will be conducted outside, in ambient light conditions. The outdoor testing is crucial, because the final design for the SightSense shin guard will need to be reliable and accurate in an outdoor setting. To verify calibration of the projected visual stripe pattern by the laser, a gridded pattern with known distances can be used. For a more basic goal of stripe distortion, this is not needed.

Component level hardware testing will take place as well, for the laser diode module, diffractive optical element, and camera module. For the laser diode module, stable output needs to be verified, and how long the laser diode module can continuously operate. The diffractive optical element needs to operate at the same wavelength as the laser diode module. The camera needs to be tested for image quality, field of view, and proper alignment with the laser projection.

For the structured light system to work effectively, the laser diode module needs to be properly collimated before passing through the diffractive optical element. This can be done with the aspheric plano convex lens mentioned earlier in the chapter. Through proper collimation, the diffractive optical element will be filled fully, and the full projected stripe pattern will be visible.

Functional system integration tests will be conducted to test the power supply under continuous use. Microcontroller testing will be done to determine connectivity between the subsystems. Obstacle detection tests will be conducted to determine the various distance and angles for which objects will be detected, and latency time will be measured as well.

## 9.2 Performance Evaluation

The main goal of the performance evaluation is to determine how effectively the SightSense shin guard achieves its design goals. More importantly, make sure that the requirements for the final product are met. Which includes 90% obstacle detection accuracy, response time, and power efficiency. For our requirements specifications table please go to chapter 2 section 2.5 table 2. All these metrics need to be thoroughly validated as this product is intended for individuals with visual impairments. This section describes how we measure and evaluate system performance. During Senior Design II, the main setting for performance evaluation will be for both outdoor and indoor testing. The table below summarizes a key performance plan that we will need to make sure that the final product meets.

Table 39: Performance Testing Plan for the SightSense shin guard

| Metric | Test Method | Tool/Equipment | Pass Criteria |
|---|---|---|---|
| Obstacle Detection Range | Place object at increasing distances and record detection distance | Laser rangefinder, ruler, ultrasonic sensor distance | Must detect obstacles at 2.0+0.2 meters |
| Accuracy | When testing outdoor/indoors place multiple objects at random distances/angles | Multiple object types (tree, door, person, wall, pothole, curves/step) | 90% detection of objects within range |
| Battery Life | Fully charge system and run in idle/active conditions for extended duration | Stopwatch | Last at least 6 hours under active usage |
| Response Time | Measure time from obstacle appearance to actuator output | ESP32-CAM | Signal sent to actuator ≤250ms after detection |
| Light Compatibility | Test detection in full daylight and dim room conditions | Outdoor test during the day, and indoor settings. | Detection is consistent in both lighting cases. |

This performance evaluation plan guided us through the critical metrics to verify safety, responsiveness, and usability of the SightSense shin guard.

## 9.3 Optoelectronics Feasibility Study and Testing (for all CREOL projects)

The purpose of a feasibility study and testing for the optoelectronics subsystem is to verify that the performance and functionality of the system meets the required specifications and intended use of the product. For our SightSense project, structured light will be used for obstacle detection. Testing will be crucial to check for the reliability and performance of the structured light system for obstacle detection in real time. This includes evaluating metrics for optical output and wavelength to confirm that they meet standards. We will also check the subsystem for failures and points where the design might be able to be improved. Individual components will be tested and verified, such as the laser diode and camera system. Through this testing, the quality of the final product will be verified as throughout the study improvements will be made to the system to ensure functionality. For object detection to be viable, and for other obstacles and drop-offs, such as ditches and curbs, to be detected, these obstacles need to be visible to the camera module. The structured light system needs to be able to capture a field of view directly in front and under the foot and needs to be able to project fully through the DOE to project full stripes. The camera module will be taking measurements of distortion in the stripes. For the stripes to be fully visible to the camera, the optoelectronics system needs to be optimized through this feasibility study and testing.

The components used in the optoelectronics subsystem that will be evaluated include the laser diode module, diffractive optical element (DOE), ESP-32-CAM, and collimating lens. For the laser diode, the optical power of the emitted light will be measured using a power meter. The wavelength of the laser diode will be measured using a spectrometer. There are electrical components to consider for laser diodes, for example threshold current, slope efficiency, and optical degradation. Finally, the beam profile of the laser will be evaluated as well, by looking at the shape, size, and beam divergence. The DOE will be evaluated for its diffraction efficiency, which shows how well light is redirected into the correct diffraction order. Since our structured light system needs a pattern striped light design, this testing is crucial. The wavefront quality of the DOE will also be tested as well to get the best striped light projection. The overall beam shape will attempt to have uniformity in its diffraction pattern and that it operates at the same wavelength as the laser diode. Control of feature size is crucial to create the desired output diffraction pattern. Defects in the DOE are inspected to avoid any issues with performance. The ESP-32-CAM will also be tested at various image resolutions to check for image quality and for the detection of distortion in the stripes produced by the projector. The RAW image capture data will be evaluated to verify the integrity of the image data. The testing of the frame rate of the camera will be helpful in verifying real-time object detection. A collimating lens will be used in the laser module projection subsystem. Focal length testing will be done to verify that the light is focused on the intended distance. Choosing a quality collimating lens can ensure that light that is exiting the plane is parallel. Aberration and distortion need to be as minimal as possible to get clean straight stripes. The alignment of the lens system will be tested to ensure the highest quality beam output and ensure overall alignment of the system.

There are certain constraints to be considered for our overall project, which are time, power consumption, and environmental factors. The time constraints, including Senior Design I, taking place in the summer, which compared to a regular semester, will be missing 4 weeks. There are also power limits on the design because of the size and space on the shin guard. Also, the imaging system cannot draw too much power or current. The battery cannot be too big as the space is limited.

## Description of Optoelectronics System

The laser diode that will be used for SightSense is at 650nm wavelength, has an optical output power of 200-250mw, and has a dot or circular beam shape. The reason for the 650nm wavelength is that the DOE is 650nm. In our case it is easier to source a laser diode module than the DOE, therefore if the available DOE is for 650nm, then we will use a 650nm laser module. This is considered a safe rating, but the eye could still be potentially harmed. It will be important to see what angle the laser can be positioned to avoid potentially harming a fellow pedestrian. This power output rating will also be tested to see if there is a correlation with ambient light visibility. The Diffractive Optical Element (DOE) is transmissive where the stripe fans out to create a pattern. This stripe pattern is key in structured light because the base line can be measured between stripes. If there is any distortion in these stripes, the depth can be obtained for the measured area. This DOE creates the stripes that enable the structured light patterns to be measured. The camera system used is an ESP-32-CAM which is a small low power OV2640 camera built on an ESP-32 microcontroller. The camera uses a 2-megapixel sensor to record images and videos. The microcontroller used includes an onboard SD card slot, as well as Bluetooth and Wi-Fi capabilities. The system uses low power consumption as well, and this should improve the battery life of the project. The last component to be tested for in the optoelectronic subsystem is the collimating lens. Focal length will be calculated for the lens to achieve the correct distance in object detection. The effects of the collimating lens on beam shape and projection of the stripes need to be updated.

## Testing Methodology

To validate the performance and reliability of the laser diode, diffractive optical element, collimating lens, and camera module, a controlled test bench environment will be set up in our optics lab. The purpose of the test bench experiments will be to simulate the real-world environment a user will encounter to allow fine tuning of the optical components to enable obstacle detection in real time. The laser diode module is aligned with the collimating lens and DOE on an optical breadboard with metric holes to verify stable placement and alignment. The laser diode module is attached to an optical post, which should be connected to a translation stage that can be finely tuned in the x, y, and z direction for alignment. The DOE will be fixed to a separate mounting post directly in front of the laser diode module using either an adjustable cage plate or lens holder. Proper spacing is to be found between the laser diode module and DOE to find the optimal 15 stripe fan out, where all the stripes are visible, and the projection is clear. The next steps include testing the target projection surface, where a flat checkerboard with even distribution between the squares can be used to calibrate the structured light system. The stripe design is then projected onto the checkboard with a starting distance of approximately 1 meter. The surface is then held vertically and perpendicular to the laser axis to evaluate uniform stripe distribution and calculate the distortion of the stripes. To validate the best placement for the camera sensor, the camera is mounted on an optical post, with a baseline that can be measured to the laser projector and can be tilted in a downward position. This simulates different viewing angles and fields of view can be captured and assessed. Ambient conditions also need to be tested to observe system reliability in low light, normal light, and ambient light conditions. A multimeter will be used to measure the laser diode voltage draw, and operating current. A ruler and calipers can be used to measure beam divergence and spot size for the laser diode module. The safety considerations needed in the lab during testbench experiments include the use of beam stops and warning signs when a laser is in use, as well as proper eye protection when necessary.

## Feasibility Considerations

Optical alignment will be tested to ensure that the diffractive optical element (DOE) is positioned correctly with respect to the laser diode module to produce clear and distinct light stripes. The baseline to the camera module needs to be calibrated to measure the distortion in the light stripes to give proper depth reading in real time. Beam visibility needs to be clear to be captured by the camera sensor. Field of view testing will be done to confirm that the projected grid will cover the most important area in front of the user to be able to detect ditches/potholes, steps, and curbs. Compatibility between the ESP-32-CAM, laser diode module will be tested as well to be able to ensure real time object detection without lagging in signal to make sure the SightSense hits its specification detection zone regarding object detection out to 2 feet. The laser diode module and camera will be tested for operating current and voltage drawing to calculate the operating time for the SightSense and make sure that components fall within the constraints of the battery powering the system. Overheating issues and thermal behavior will be tested as well to test the SightSense under continuous use. Laser safety will be accounted for during lab testing and the laser module itself for its safety in public.

<u>Preliminary Results and Observations</u>

The laser diode module that will be used during the prototyping process was able to get baseline tested for optical output power and its wavelength using a spectrometer. The calculated optical output power measured was 4MW and measured wavelength was 655 nm. The image below represents the wavelength.

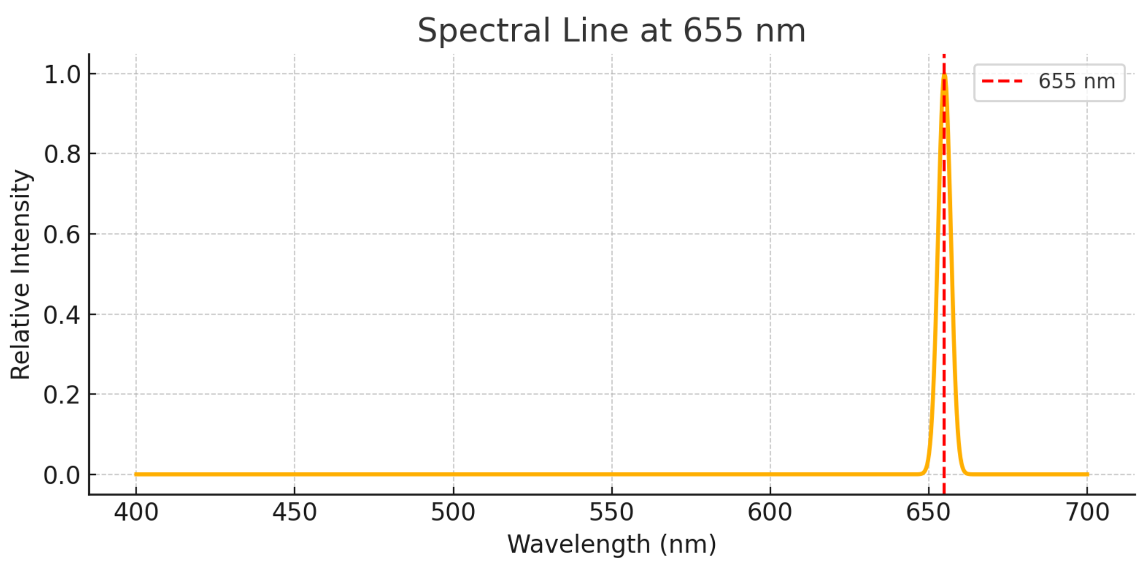


Figure 47: above shows measured wavelength of laser diode module

Potentially down the road for final demonstrations, there could be issues with the DOE wavelength being set at 650nm and this laser diode module at 655nm being slightly off. At this point for prototyping, these will be due, but down the line a more precise laser diode module may be needed. Through the first demonstration it seems as if a camera module will be able to capture the image of the laser projection of the 15-line fan out. Using the baseline between the camera sensor and laser diode module, the distortion in the light pattern will be able to give a depth mapping. Through a matrix-based algorithm, any object distorting the stripe pattern will be observed, and the user will be alerted.

### Analysis and Discussion

The proposed setup for the design should meet and exceed project goals. The components needed to make the structured light system viable are available. Correct alignment and housing for the optical setup are crucial and will be worked on through the prototyping process. The key ideas on the sensing technology are able to be achieved by the ESP-32-CAM microcontroller and laser diode module with 15-line fan out DOE. This technology, which is used in 3D scanning, can be easily used as an application for object detection of ditches, curbs, and steps. Some early issues that may need to be addressed in the design will be housing that most likely will need to be 3D printed to align the laser diode module with DOE. Because of the relatively small size of the shin guard, placing and spacing will need to be optimized. A field of view will be very important to be able to detect the area needed to be able to walk safely and assist the visually impaired user. Sensitivity to different light situations, most importantly ambient, will need to be tested and ensure that the projected stripes will be visible by the camera sensor. Lens tuning for the camera sensor might be necessary to get the clearest image, but this can be simulated in the optics lab and can be calibrated to the 2-meter distance needed specifications set for the project. Through testing for SightSense housing to hold the optoelectronic system will need to be built. This housing will need to account for any extra filters that may need to be added, either to better capture the light stripes in ambient light, or perhaps a 650nm filter may be used to correct the output of the prototyping laser diode module. Depending on the performance of the DOE with the laser diode module, a more powerful laser might need to be tested, or a beam expander might be to uniformly fit the DOE to project evenly space lines.

### Future Testing and Improvements

The group anticipates having to create mechanical housing higher up the shin guard design to get the best field of view to be able to detect ditches, curbs, and steps. Depending on if the housing can be attached to the front of the top of the shin guard can hold the optoelectronic subsystem, this might need to be built separately and then be attached to the shin guard in another way. A narrow bandpass filter of 650nm was added to the optical system for better pattern distortion detection. Increasing the number of classified images and augmenting the data set with more time will improve the performance of the algorithm.

## 9.4 Overall Integration

All of SightSense shin guard’s hardware and software components will be combined into a single cohesive platform.

Table 40: Overall Integration

| Subsystem | Description | Purpose in System |
|---|---|---|
| Obstacle detection and feedback module | This system will include ultrasonic sensors, a microcontroller with camera, vibration and speaker. | This will help detect obstacles in real-time and alerts the user through haptic and audio feedback. |

| | | |
|---|---|---|
| Power supply and battery management | Provides regulated voltage and power to all system components for extended periods. | Ensures consistent and reliable operation of the system over 6-10 hours of usage. |
| User interface and display | LCD and LED indicators used for real time debugging and feedback during testing phases. | Assists in development and debugging during SD2. |
| Housing and enclosure | Encloses and mounts all hardware components on and around the shin guard without messing with user movement. | Protects the hardware, ensures safety, and maintains comfort for visually impaired users. |

The Sightsense project has fully integrated both sensor systems. The ultrasonic sensors measure objects up to 2 meters away from the user, while the camera and laser system have successfully detected distortion from objects such as chairs, steps, and potholes. When the system detects these obstacles the LCD screen reads “distorted” or “undistorted”. With further improvements, this audio alert will be sent to the user.

# Chapter 10: Administrative Content

## 10.1 Budget and Financing

An itemized list of materials needed for this project, their costs, and their quantity, are shown on the table below. These costs will be covered by the group and split into equal amounts. Our goal for this project is to not exceed more than $500 dollars but just in case we have allocated $200 each.

Table *41*: Bill of Materials Needed for the SightSense Shin Guard

| Item # | Component Name | Qty | Unit Cost ($) | Total Cost ($) plus taxes | Supplier | Description |
|---|---|---|---|---|---|---|
| **1** | ESP32-CAM | 1 | $ 7.54 | $ 15.08 | Amazon | Bundle of 2; only 1 used; Main MCU with camera and Wi-Fi/Bluetooth |
| **2** | Ultrasonic Sensor | 2 | $ 3.84 | $ 7.68 | Amazon | For obstacle detection via distance sensing on the sides |
| **3** | 1602 LCD Display | 1 | $ - | $ - | Previously owned | Displays distance readings |
| **4** | Vibrational Motor | 1 | $ 5.39 | $ 6.68 | Digi-Key | Provides haptic feedback to user |
| **5** | Haptic Driver for Vibrational motor | 1 | $ 11.95 | $ 13.24 | Digi-Key | Controls vibration patterns to user |
| **6** | Speaker | 1 | $ 3.34 | $ 4.63 | Digi-Key | Audio output for alerts |
| **7** | Audio Amplifier Evaluation Board | 1 | $ 3.95 | $ 5.24 | Digi-Key | Amplifies signal to drive the speaker |
| **8** | Battery | 1 | $ 12.50 | $ 13.79 | Digi-Key | BATTERY LITH-ION 3.7V 2AH - power supply |
| **9** | Charging Module | 1 | $ 5.95 | $ 7.24 | Digi-Key | LIPOLY BATTERY CHARGER W/USB C |
| **10** | USB 2.0 Cable A Male to C Male | 1 | $ 1.76 | $ 3.05 | Digi-Key | Cable used for charging |
| **11** | Voltage Regulator | 1 | $ 7.95 | $ 8.57 | Amazon | Regulates input voltage to a stable output level (e.g., 5V or 3.3V) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **12** | Laser Module | 2 | $ 11.89 | $ 23.78 | Amazon | 650nm red laser module that projects a visible dot for alignment |
| **13** | Lens | 1 | $ - | $ - | Amazon | Used to focus camera and laser module |
| **14** | Diffractive Optical Elements | 2 | $ 32.00 | $ 64.00 | From the lab | Optical component used to shape laser beams into a specific grid pattern |
| **15** | FTDI Board | 1 | $ 6.49 | $ 6.91 | Amazon | USB-to-Serial interface for programming ESP32-CAM |
| **16** | Shoes (Boots) | 1 | $ - | $ - | Already own | Physical platform for mounting all wearable hardware |
| **17** | Shin guard | 1 | $ 9.74 | $ 10.36 | Amazon | Protective attachment to mount components on the leg and hold wiring securely |
| **18** | Sock | 1 | $ 10.79 | $ 11.41 | Amazon | Soft base layer worn under the device to improve comfort and prevent skin irritation from the electronics |
| **19** | PCB | - | $ - | - | JLCPCB | Custom printed circuit board for integrating and routing all components |
| **20** | Jumper Wires | - | $ - | - | Previously owned | Wiring connections between components on breadboard or PCB |
| **21** | 3D Filament | - | $ - | - | Previously owned | Used for printing custom enclosure or mounts for hardware |
| **Total** | | | **$ 135.08** | **$ 201.65** | | |

The table shown below provides a comparison between the estimated and actual cost for our components used for the SightSense shin guard project. This breakdown highlights how well the project stayed within its original spending plan. While there are some components in the table that are slightly over budget, most of our other parts are within reasonable bounds. In order to evaluate overall cost efficiency and guide future purchase decisions, the table additionally features a computed difference column that indicates where savings or surpluses occurred.

Table 42: Budget vs. Actual Cost Comparison

| Component Name | Estimated Total ($) | Actual Total ($) | Difference ($) | Status |
|---|---|---|---|---|
| **ESP32-CAM (1 of 2 used)** | $ 10.00 | $ 15.08 | -5.08 | Over Budget |

| | | | | |
|---|---|---|---|---|
| **MB boards for the ESP32** | $ 20.00 | $ 17.49 | 2.51 | Under Budget |
| **1602 LCD Display** | $ 5.00 | $ - | 5.00 | Under Budget |
| **Vibrational Motor (3x)** | $ 6.00 | | 6.00 | Under Budget |
| **Speaker** | $ 10.00 | $ 4.63 | 5.37 | Under Budget |
| **Battery** | $ 30.00 | $ 20.52 | 9.48 | Under Budget |
| **USB 2.0 Cable A Male to C Male** | $ 8.00 | $ 3.05 | 4.95 | Under Budget |
| **Laser Module (2x)** | $ 16.00 | $ 23.78 | -7.78 | Over Budget |
| **Lens** | $ - | $ - | 0.00 | Under Budget |
| **Diffractive Optical Elements (2x)** | $ - | $ - | 0.00 | Under Budget |
| **Shin guard** | $ 10.00 | $ 10.36 | -0.36 | Over Budget |
| **Sock** | $ 15.00 | $ 11.41 | 3.59 | Under Budget |
| **PCB** | $ 200.00 | $ 180.00 | 20.00 | Under Budget |
| **DigiKey Parts (2 orders total)** | $ 100.00 | $ 90.10 | 9.90 | Under Budget |
| **3D Filament** | $ 40.00 | $ 25.00 | 15.00 | Under Budget |
| **SD cards** | $ 10.00 | $ 9.56 | 0.44 | Under Budget |
| **cones** | $ 5.00 | $ 3.00 | 2.00 | Under Budget |
| **bolts** | $ 10.00 | $ 9.05 | 0.95 | Under Budget |
| **Female to male A cable** | $ 12.00 | $ 10.64 | 1.36 | Under Budget |
| **50MW Laser** | $ 20.00 | $ 18.88 | 1.12 | Under Budget |
| **250MW Laser** | $ 30.00 | $ 30.00 | 0.00 | Under Budget |
| **DF Mini Player** | $ 10.00 | $ 10.54 | -0.54 | Over Budget |
| **total** | $ 567.00 | $ 493.09 | | |

## 10.2 Project Milestones and Timeline

To ensure steady progress, the group has made a thorough project milestone table that lists important tasks, their respective time periods, due dates, and assigned responsibilities in order to guarantee consistent progress and efficient time management. Over the course of the two-semester project, this schedule helps track the timely completion of goals while minimizing the risk of delays. The table below shows the complete list of project milestones we have met.

Table 43: Project Milestones

| **Senior Design I – Summer 2025** | | | | |
|---|---|---|---|---|
| **Task** | **Time Period** | **Dates** | **Responsibility** | **Status** |
| Project Selection | 1 Week | 5/13 - 5/17 | All | Complete |
| D&C Documentation | 1 Week | 5/23 – 5/30 | All | Complete |
| D&C Meeting with Advisors | 30 Minutes | 6/2 | All | Complete |
| Update and Upload D&C report onto website | 1 Week | 6/6 | Ana | Complete |
| Research Obstacle Sensor | 1 Week | 6/6 | Giovanny | Complete |
| Research Laser Types | 1 Week | 6/6 | Giovanny | Complete |
| Research Battery | 1Week | 6/6 | Jasmine | Complete |
| Research Vibration & Audio Haptic Feedback | 1 Week | 6/6 | Ana | Complete |
| Research Water-Resistant Material | 1 Week | 6/6 | Jasmine | Complete |
| Start Coding | 3 Weeks | 6/30 – 7/20 | Ana | Complete |
| Start PCB Design | 3 Weeks | 7/1 – 7/21 | All | Complete |
| Final Decision on PCB Design | 1 Week | 7/21-7/27 | All | Complete |
| Order PCB and Other Materials | 1 Week | 7/28-7/30 | All | Complete |
| Midterm Report | 2 Weeks | 6/23 -7/7 | All | Complete |
| Midterm Report Meeting | 1 Week | 7/9 – 7/11 | All | Complete |
| Update and Upload Midterm onto Website | 1 Week | 7/18 | Ana | Complete |
| 120 Page Draft | 2 Weeks | 7/14 – 7/23 | All | Complete |
| Final Documentation & Mini Demo Video | 2 Weeks | 7/14 -7/23 | All | Complete |

| Senior Design II – Fall 2025 | | | | |
|---|---|---|---|---|
| **Task** | **Time Period** | **Dates** | **Responsibility** | **Status** |
| Start Project Prototype | 4 Weeks | ~8/11 – 9/1 | All | Complete |
| Start Model Building | 4 Weeks | ~8/11 – 9/1 | All | Complete |
| Connect the Obstacle Sensor to ESP32-S3 | 4 Weeks | ~8/11 – 9/1 | Ana | Complete |
| Connect the Laser to Microcontroller | 4 Weeks | ~8/11 – 9/1 | Giovanny | Complete |
| Connect Battery to charging module and then to Microcontroller | 4 Weeks | ~8/11 – 9/1 | Ana and Jasmine | Complete |
| Use both Serial/I2C to Connect to Microcontroller's UART/I2C Port | 2 Weeks | ~9/1 – 9/15 | Ana | Complete |
| Implement all code and make sure it is fully working | 4 Weeks | ~9/15 – 10/8 | All | Complete |
| Final Testing and Adjustments | 4 Weeks | ~10/8 – 11/5 | All | Complete |
| Final Testing | 2 Weeks | 11/10 - 11/24 | All | Complete |
| Final Presentation | 30 min | ~11/25 | All | Complete |

The table below outlines our current plan for the distribution of work. The project has been divided into multiple tasks, and each task is assigned to a primary team member for its completion along with a secondary member who will assist and help ensure accountability throughout the development process.

Table 44: Work Distribution

| Task | Primary | Secondary |
|---|---|---|
| Obstacle Sensor | Giovanny | Ana |
| Laser | Giovanny | Ana |
| Rechargeable battery | Jasmine | Ana |
| Ultrasonic sensor | Ana | Jasmine |
| Camera Module | Giovanny | Ana |

| | | |
|---|---|---|
| Vibrational Motor System | Ana | Jasmine |
| Coding | Ana | Ana |
| PCB Design | Jasmine | Ana |
| Durable Enclosure Design | Jasmine | Jasmine |
| Speaker System | Ana | Jasmine |

The table shown below outlines the chapter distributions among the team members for the SightSense shin guard final report. Each member was assigned specific chapters based on their contribution to the project while certain sections were completed collaboratively to ensure accuracy and completeness.

Table 45: Chapter distribution of final report responsibilities

| Team Member | Assigned Chapters | Group Chapters |
|---|---|---|
| **Ana** | Ch 1,7, 10,11 | Ch 2, 3, 4, 5, |
| **Jasmine** | Ch 6, 8 | Ch 2, 3, 4, 5, |
| **Giovanny** | Ch 5, 9 | Ch 2, 3, 4, 5, |

# Chapter 11 Conclusion

Over the course of Senior Design I and II, SightSense: A Smart Haptic Alert Obstacle Detection System for the Visually Impaired evolved from an initial concept into a fully integrated, working smart shin guard prototype. What began as a general initial idea for a wearable assistive device became a modular system that can reliably detect nearby obstacles and give the user feedback through vibration, audio prompts, and visual indicators. Throughout both semesters, our team designed the embedded system, selected and tested the hardware, wrote the firmware, and refined on the physical enclosure until we reached a functional, user centered solution that met our main engineering specifications.

Our focus during Senior Design I was to establish a proof of concept that prioritized the core functionalities of obstacle detection, haptic and audio feedback, battery operation, and strong protective enclosure. These were chosen based on direct input from visually impaired users and gaps identified in prior smart footwear solutions. We also began by thoroughly researching past projects and commercially available products to understand both the potential and the limitations of current technologies. This led to a well-defined set of engineering requirements that balanced cost, performance, modularity, and user comfort.

One of the primary subsystems we tested was the ultrasonic-based obstacle detection. Using the HC-SR04 sensor, we were able to consistently detect objects in our target range of about 0.50m to 2.00m. The sensor is mounted on the shin area of our prototype and calibrated using a basic averaging algorithm to minimize erratic readings caused by sensor jitter or awkward reflection angles. On top of this, we implemented a structured light camera-based subsystem using an ESP32-CAM and Edge Impulse. This module captures laser grid images, classifies them as distorted or undistorted, and signals the ESP32-S3 when a potential obstacle disrupts the pattern. Together, these subsystems give the user both range-based awareness and an additional layer of confirmation using sensing. Our firmware was structured to support fast sensor reading with minimal latency, which is essential for real-time navigation.

The feedback system proves equally critical to our design and receives a lot of attention. We implemented a vibration motor (Vybronics VG0840001D) and speaker (PUI Audio AS02708CO-WR-R) to create two separate channels of feedback. This ensures that the user can receive alerts even if one modality is momentarily ineffective due to environmental conditions or personal sensory limitations. The DRV2605L motor driver allows us to vary vibration patterns based on obstacle distance, which adds intuitive feedback cues. Similarly, the speaker system, initially limited by PWM distortion, is refined through signal filtering and physical mounting improvements, leading to clear tones in testing environments. Overall, these outputs are key to building a system that users can both hear and feel, depending on their needs and preference.

Power management was another major priority. After evaluating multiple battery options, we selected a 3.7V 3000mAh lithium-ion battery with built-in protection circuitry to provide safe and reliable energy for the system.

Housing and structural durability were evaluated through the use of our model which was printed out of PLA filament with a 15% grid infill and was designed in SOLIDWORKS. The large internal volume and rugged exterior provided a stable platform for securely mounting the electronic components, including the battery, sensors, speaker, and motor.
Despite these successes, some parts of the system are still limited and could be improved in future work. Our structured light module, which uses a laser projection and camera system for advanced obstacle detection, encountered some issues with bright lighting. Early experiments revealed challenges with pattern distortion analysis under variable lighting and uneven surfaces, suggesting the need for more advanced image processing algorithms, potentially powered by machine learning and better environmental calibration.

Another challenge involves refining tactile and audio feedback for different users. In testing with team members and preliminary users, we note differences in sensitivity to vibration and sound cues. Some users prefer more intense and longer vibration pulses, while others require greater audio volume or more distinct pitch differentiation. These observations highlight the importance of configurable settings in the final design, such as adjustable vibration strength or multiple audio feedback.

Software reliability was another big focus. We encountered a few issues with UART buffer overflows and interrupt conflicts, which sometimes caused the system to behave incorrectly or freeze. We fixed these problems by restructuring our code, so it handled sensor reading and feedback triggering more safely and efficiently. This experience highlighted the importance of writing robust firmware, especially in wearable devices where real-time response and system stability are essential for user safety.

In summary, the work completed in this phase of the SightSense smart shin guard project met its main goals. We built a modular, wearable prototype that can detect short-range obstacles and respond with haptic and audio feedback. We selected and validated the key hardware components, wrote and debugged the firmware in the Arduino IDE that also works with Edge Impulse, and adjusted the mechanical design to meet real-world usability needs. These efforts led to a successful early demonstration of our system in realistic indoor and outdoor settings. The lessons we learned in this process create a strong foundation for any future improvements to SightSense. Most importantly, this work supports our larger goal: to offer a reliable, affordable, and user-friendly assistive device that can help improve mobility and confidence for people with visual impairments.

Looking ahead, one of the most significant outcomes is that our team agreed on a clear design philosophy: modularity, accessibility, and adaptability. We designed every subsystem to be as modular as possible, so that future versions can be upgraded without rebuilding everything from scratch. For example, we can swap sensors, upgrade the processor, or add new types of feedback while keeping the same basic structure. This approach will make it easier to add features like automatic sensor calibration and more advanced object classification in future work.

We also made a deliberate effort to follow human-centered design principles. As engineering students, it's easy to become absorbed by hardware specs and algorithm performance, but we tried to keep our focus on how real users will actually experience the device. Our target users, individuals with limited or no vision, need more than just functionality. They need tools they can trust, that feel comfortable, and that behave in a consistent way. We've learned that clear feedback, reliable performance, and ease of use are essential criteria. Features like adjustable vibration intensity and multilingual audio alerts are more than stretch milestones, they represent our growing commitment to making the system more inclusive.

Our progress has also led us to think more about ethical and social issues. As assistive technology designers, we have a responsibility not only to meet functional requirements but to ensure independence and safety for our users. For example, we deliberately avoided camera-based facial detection and location tracking features unless absolutely necessary, to protect user privacy. We will remain careful about data handling, user control, and basic cybersecurity, especially since our target demographic may include individuals unfamiliar with advanced digital interfaces.

On a larger scale, the SightSense project has shown us how accessible technology can help lower income individuals. We imagine that a more refined version of this system could eventually be shared through nonprofits, rehabilitation centers, or low-cost programs to ensure affordability. Even within our university, the interest in SightSense has shown that there's a real need for practical, student-developed solutions that address day-to-day challenges.

In short, Senior Design I and II have been far more than technical experience. It's been an opportunity to practice engineering with empathy, purpose, and real-world impact. The skills, knowledge, and momentum we gained will support any future iterations of SightSense and will remind us of the kind of innovation that is possible when technology is designed with people in mind.

# Appendices

Appendix A – reference


[1] W. H. Organization, "Blindness and visual impairment," WHO, 10 August 2023. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment. [Accessed 28 May 2025].

[2] A. Sharma and K. Lawrence, "Lechal Smart Shoes Guide Wearers With Haptic Feedback," 13 Augut 2014. [Online]. Available: https://design-milk.com/lechal-smart-shin guards/. [Accessed 17 July 2025].

[3] N. Vignesh, M. S. Reddy and N. e. Raja, "Smart Shoe for Visually Impaired Person," *International Journal of Engineering & Technology,* vol. 7, no. 3.12, p. 116–119, 2018.

[4] R. Hegde, G. Pradyumna and Kabbala B. B. et al., "Recent Innovations in Footwear and the Role of Smart Footwear in Healthcare—A Survey," *Sensors,* vol. 24, no. 4301, 2024.

[5] Vilros, " Raspberry Pi 4 Model B – Product Page," 2025. [Online]. Available: https://vilros.com/products/raspberry-pi-4-model-b-1. [Accessed 29 June 2025].

[6] Texas Instruments, "MSP430FR6989 – Ultra-low-power MCU with 128KB FRAM, LCD, 12-bit ADC, and comparators," [Online]. Available: https://www.ti.com/product/MSP430FR6989. [Accessed 29 June 2025].

[7] AI-Thinker Co., Ltd., "ESP32-CAM Development Board Documentation," 2020. [Online]. Available: https://docs.ai-thinker.com/en/esp32-cam. [Accessed 7 July 2025].

[8] DFRobot, "DFR0602 – Gravity: Analog Sound Level Meter Sensor (Arduino Compatible)," 2018. [Online]. Available: https://media.digikey.com/pdf/Data%20Sheets/DFRobot%20PDFs/DFR0602_Web.pdf. [Accessed 29 June 2025].

[9] Amazon.com, Inc., "650nm 5mW Red Laser Diode Module with Wires," Amazon, 2024. [Online]. Available: https://www.amazon.com/dp/B01M7VET3M. [Accessed 24 July 2025].

[10] Lasermate Group, Inc, "LDM-655-04 650nm 4mW Laser Diode Module," Lasermate Group, Inc., 2024. [Online]. Available: https://lasermate.com/products/lasers/laser-modules/low-cost/ldm-655-04/. [Accessed 24 July 2025].

[11] Thorlabs, Inc., "CPS635R – Red Laser Diode Module," Thorlabs, 2025. [Online]. Available: https://www.thorlabs.com/thorproduct.cfm?partnumber=CPS635R. [Accessed 24 July 2025].

[1 Amazon, "2.1mm 160 Degree Wide Angle M12 Lens," Amazon, 2024. [Online]. Available: https://www.amazon.com/dp/B07VGR3G9Y. [Accessed 24 July 2025].

2]

[13] e-con Systems, "6mm M12 Standard Lens – Multi-Element Glass," e-con systems, 2025. [Online]. Available: https://www.aliexpress.com/item/1005003924017641.html. [Accessed 24 July 2025].

[14] Thorlabs, Inc., "LA1401 – Plano-Convex Lens, Ø1”, f = 80.0 mm, ARC: 350–700 nm," Thorlabs, 2025. [Online]. Available: https://www.thorlabs.com/thorproduct.cfm?partnumber=LA1401. [Accessed 24 July 2025].

[15] AI-Thinker, "ESP32-CAM (ESP32-S with OV2640 camera module) details," AI-Thinker, 2025. [Online]. Available: https://www.espressif.com/en/products/modules/esp32-cam. [Accessed 24 July 2025].

[16] ArduCAM, "ArduCAM Mini 2MP Plus – OV2640 SPI Camera Module," ArduCAM, 2025. [Online]. Available: https://www.arducam.com/arducam-2mp-spi-camera-b0067-arduino.html. [Accessed 24 July 2025].

[17] Raspberry Pi Ltd., "Camera Module 3 – Product Brief," Raspberry Pi Ltd., 2023. [Online]. Available: https://datasheets.raspberrypi.com/camera/camera-module-3-product-brief.pdf. [Accessed 24 July 2025].

[18] Manorshi, "JSN-SR04T-3.0 Ultrasonic Sensor Datasheet," [Online]. Available: https://rjrorwxhjiilll5q.ldycdn.com/JSN-SR04T-3.0-aidnqBpoKliRljSlqnqkilqj.pdf. [Accessed 30 June 2025].

[19] Elecfreaks, " HC-SR04 Ultrasonic Distance Sensor Datasheet," [Online]. Available: HC-SR04 Ultrasonic Distance Sensor Datasheet. [Accessed 30 June 2025].

[20] Adafruit, "Ultrasonic Distance Sensor - 3V or 5V - HC-SR04 compatible - RCWL-1601," [Online]. Available: https://media.digikey.com/pdf/Data%20Sheets/Adafruit%20PDFs/4007_Web.pdf. [Accessed 30 June 2025].

[21] Soldered, " DISPLAY OLED I2C 0.96" SSD1306," [Online]. Available: https://www.mouser.com/datasheet/2/1398/Soldered_333099-3395096.pdf?srsltid=AfmBOop6N29N6bxoap79TyX3YZVrFdovNVIYsnKgA8TTyUhLRUuOubin. [Accessed 22 July 2025].

[22] ProtoSupplies, "LCD1602 16×2 Blue LCD Display," [Online]. Available: https://protosupplies.com/product/lcd1602-16x2-blue-lcd-display/. [Accessed 22 July 2025].

[2 EastRising Technology Co., Ltd., "TFT LCD Display Module Datasheet ER-TFTM1.44-3," 9 March 2024. [Online]. Available:

https://www.buydisplay.com/download/manual/ER-TFTM1.44-3_Datasheet.pdf. [Accessed 22 July 2025].

[24] Texas Instruments, "DRV2605L 2- to 5.2-V Haptic Driver for LRA and ERM with Effect Library and Smart-Loop Architecture," March 2018. [Online]. Available: https://www.ti.com/lit/ds/symlink/drv2605l.pdf?ts=1753120753038&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FDRV2605L. [Accessed 21 July 2025].

[25] S. Electronics, "SparkFun ROB-14538," [Online]. Available: https://www.mouser.com/ProductDetail/SparkFun/ROB-14538?qs=r5DSvlrkXmI1RMfOGdAcVg%3D%3D&srsltid=AfmBOoptHKwADb7ZcBJJ5EDo97AmcnxduzXjy_ybsW5gJw4qFO4rjYbz. [Accessed 21 July 2025].

[26] SparkFun Electronics, "SparkFun Haptic Motor Driver - DRV2605L ROB-14538," 5 May 2018. [Online]. Available: https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/778/ROB-14538_Web.pdf. [Accessed 21 July 2025].

[27] Texas Instruments , " DRV8833 Dual H-Bridge Motor Driver," July 2015. [Online]. Available: https://www.ti.com/lit/ds/symlink/drv8833.pdf?ts=1753142237533&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FDRV8833%253Futm_source%253Dgoogle%2526utm_medium%253Dcpc%2526utm_campaign%253Dasc-null-null-GPN_EN-cpc-pf-google-ww_en_cons%2526utm_conte. [Accessed 21 July 2025].

[28] Microchip, "MCP73831/2 Miniature Single-Cell, Fully Integrated Li-Ion, Li-Polymer Charge Management Controllers," 2013. [Online]. Available: https://cdn.sparkfun.com/datasheets/Components/General%20IC/33244_SPCN.pdf. [Accessed 22 July 2025].

[29] NanJing Top Power ASIC Corp., "TP4056 1A Standalone Linear Li-lon Battery Charger with Thermal Regulation in SOP-8," [Online]. Available: https://dlnmh9ip6v2uc.cloudfront.net/datasheets/Prototyping/TP4056.pdf. [Accessed 22 Juy 2025].

[30] Adafruit Industries, "Adafruit Mono 2.5W Class D Audio Amplifier - PAM8302," [Online]. Available: https://www.adafruit.com/product/2130?srsltid=AfmBOoqYt5UAgXcCx6e4EEPJ4UvMxGHoGvRF6ZxLwTuE8i4GLbppkPxW. [Accessed 22 July 2025].

[31] Diodes Incorporated, " PAM8403 FILTERLESS 3W CLASS-D STEREO AUDIO AMPLIFIER," November 2012. [Online]. Available: https://www.mouser.com/datasheet/2/115/PAM8403-247318.pdf?srsltid=AfmBOorJGewVnbHlkPfFKOY6DdysQ52RjNxJ0VwRof0hcVWQjVLN5XgG. [Accessed 22 July 2025].

[32] Texas Instruments , "LM386 Low Voltage Audio Power Amplifier," August 2023. [Online]. Available: https://www.ti.com/lit/ds/symlink/lm386.pdf. [Accessed 22 July 2025].

[3 INTERNATIONAL ELECTROTECHNICAL COMMISSION, "IEC 62133-2:2017 — Secondary cells and batteries containing alkaline or other non-acid," 2017. [Online]. Available:

https://cdn.standards.iteh.ai/samples/21479/fc1425401c494ac88927998737150b9b/IEC-62133-2-2017.pdf. [Accessed 03 July 2025].

[34] [Online].

[35] International Organization for Standardization, "ISO 9241-210:2019 — Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems," 2019. [Online]. Available: https://www.iso.org/standard/77520.html. [Accessed 3 July 2025].

[36] International Organization for Standardization, "ISO-9241-210-2019 – Ergonomics of human-system interaction – Human-centred design for interactive systems," 2019. [Online]. Available: https://cdn.standards.iteh.ai/samples/77520/8cac787a9e1549e1a7ffa0171dfa33e0/ISO-9241-210-2019.pdf. [Accessed 3 July 2025].

[37] American National Standards Institute, "ANSI Z136.1-2022 – Safe Use of Lasers," Laser Institute of America, orlando, fl, 2022.

[38] [Online].

[39] [Online].

[40] Amazon.com, "DUNLOP Protective Footwear, Chesapeake plain toe Black Amazon, 100% Waterproof PVC, Lightweight and Durable, 8677577.09, Size 9 US," [Online]. [Accessed 1 July 2025].

**Appendix C – data sheet (if necessary)**

STlife.augmented. "VL53L0X Datasheet Time-of-Flight ranging sensor." https://www.st.com/resource/en/datasheet/vl53l0x.pdf (accessed May 28, 2005)

Coherent Inc., LDM-0655-C-0004-04-99-000-A: Laser Diode Module Datasheet, Coherent, 2022. [Online]. Available: https://www.coherent.com/resources/datasheet/components-and-accessories/ldm-0655-c-0004-04-99-000-a.pdf Accessed: Jul. 7, 2025.

Thorlabs Inc., CPS635R Collimated Laser Diode Module – Product Specifications, Thorlabs, 2023. [Online]. Available: https://www.thorlabs.com/thorproduct.cfm?partnumber=CPS635R Accessed: Jul. 7, 2025.

**Appendix D – software code (if necessary)**

The following code represents the core object-oriented structure used in the SightSense firmware. It defines the major software modules: SensorManager, FeedbackManager, CommunicationModule, and MainController.

```
// SensorManager handles obstacle detection logic
class SensorManager {
 public:
  float getUltrasonicDistance();     // Returns distance in centimeters
  bool isObstacleNear();             // Returns true if obstacle within threshold
};

// FeedbackManager handles haptic and audio feedback
class FeedbackManager {
 public:
  void vibrateShort();               // Vibrates once briefly
  void vibrateWarning();             // Vibrates rapidly to indicate danger
  void playAudioFeedback(String type);  // Plays audio cue based on type
};

// CommunicationModule manages BLE or Wi-Fi messaging
class CommunicationModule {
 public:
  void sendSOSMessage();             // Sends an SOS message (future feature)
};

// MainController orchestrates system operation
class MainController {
 SensorManager sensor;
 FeedbackManager feedback;
 CommunicationModule comm;

 public:
  void run();                        // Main loop controlling system states
};
```

The following MATLAB script demonstrates a basic image comparison method used in the SightSense system to identify object-induced distortions in a projected grid pattern. By converting both undistorted and distorted images to grayscale and applying Canny edge detection, the code highlights structural differences between the two. It then compares edge patterns to detect anomalies that may indicate the presence of nearby obstacles:

```
% full path of images
imageNormal = imread('C:\\Users\\johan\\OneDrive\\Desktop\\SD1 video demo\\undistorted_image.jpg');  % Full path to undistorted image
imageDistorted = imread('C:\\Users\\johan\\OneDrive\\Desktop\\SD1 video demo\\distorted_image.jpg');  % Full path to distorted image

% both images to gray scale
grayImageNormal = rgb2gray(imageNormal);
grayImageDistorted = rgb2gray(imageDistorted);

% apply canny edge detection
edgesNormal = edge(grayImageNormal, 'Canny');
edgesDistorted = edge(grayImageDistorted, 'Canny');

% compare two images by subtracting edges
diffImageNormal = abs(edgesNormal - edgesNormal);  % Compare normal with itself
diffImageDistorted = abs(edgesNormal - edgesDistorted);  % Compare normal with distorted

% threshold for detecting changes
threshold = 100000;

% dif greater/less than threshold of normal image
if sum(diffImageNormal(:)) > threshold
   disp('Object detected');
else
   disp('Detecting');
end

% dif greater/less than threshold of distorted image
if sum(diffImageDistorted(:)) > threshold
   disp('Object detected');
else
   disp('Detecting');
end
```

**Appendix E – ChatGPT prompts and outcomes (if necessary)**

**Appendix F – Links to Items**

Amazon.com, "DUNLOP Protective Footwear, Chesapeake plain toe Black Amazon, 100% Waterproof PVC, Lightweight and Durable, 8677577.09, Size 9 US," https://www.amazon.com/dp/B00H9KKIG8 (accessed July 1, 2025).

Target.com, "Women's Chelsea Rain Boots - A New Day™ Black 9: Waterproof Ankle Block Heel, Pull-On Style," https://www.target.com/p/-/A-82359134 (accessed July 1, 2025).

PUI Audio Inc., "AS02708CO-WR-R – Audio Indicators & Alerts," Digi-Key Electronics. [Online]. Available: https://www.digikey.com/en/products/detail/pui-audio-inc/AS02708CO-WR-R/1464851

Dantona Industries, "L37A26-1-0-2W – Battery Pack," Digi-Key Electronics. [Online]. Available: https://www.digikey.com/en/products/detail/dantona-industries/L37A26-1-0-2W/16539002

Vybronics Inc., "VG0840001D – Vibration Motor," Digi-Key Electronics. [Online]. Available: https://www.digikey.com/en/products/detail/vybronics-inc/VG0840001D/15220809

Accessed: Jul. 7, 2025.[13] Amazon.com, 6mm M12 Lens – Low Distortion for ESP32-CAM/OpenCV Projects, Amazon, 2024. [Online]. Available: https://www.amazon.com/dp/B07JQ1QFGK Accessed: Jul. 7, 2025

LaserMate Group Inc., DL655 Series: 655nm 100–1000mW Diode Laser Systems, LaserMate Group, 2023. [Online]. Available: https://www.lasermategroup.com/dl655-series-655nm-100-1000mw-diode-laser.pdf

Thorlabs, Inc., LA1131-A: Ø1/2in, f = 8.0 mm, N-BK7 Plano-Convex Lens, ARC: 350-700 nm, Thorlabs, 2023. [Online]. Available: https://www.thorlabs.com/thorproduct.cfm?partnumber=LA1131-A
Accessed: Jul. 7, 2025.