

Senior Design 2

SAFEPADS: Smart Animal Fencing and Emergency Predator Alert and Detection System



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1: Executive Summary

Our project is the Smart Pet Collar. This project entails multiple electrical, optical, and computer science components to create the following systems: temperature and moisture sensor, sensor to track activity, sensor to detect a moving body that employs a defense mechanism, IOT system that sends sensor data to a cell phone, indoor geofencing capabilities, and the use of a phone to activate a defense mechanism and vibrational training corrections. The pet collar also has a GPS-based locating device.

The temperature and moisture sensor were implemented into the smart pet collar. This feature is common to many other smart pet collars and proves as an important feature to implement for pet safety. This system is able to determine the temperature and moisture of the outside environment. This information is transmitted to the app so a pet owner can make an informed decision about the pet's safety in the environment the pet is in. This system implements a combined sensor that records temperature and humidity of the outside environment.

The pet collar has a defense mechanism used to protect the pet from predators. This is something not typical in multifaceted collars. Many pet collars offer this feature as the main and only feature in the collar. This system has two parts: identification and deployment. The identification part utilizes two cameras built into the collar. These cameras have a very wide field of view, with a combined field of view around 300 degrees. The camera sends notifications to the owner if a predator is detected and automatically triggers the defense mechanism which can also be manually operated from within the app. The defense mechanism is an LED strobe light. This strobe light consists of a collimating lens, LEDs, and a reflector to maximize brightness.

The IOT system serves to send the data collected from the sensor to the owner's cellphone. This system connects to the internet to send the sensor information, and it is embedded into a microprocessor chip.

The indoor geofencing system also consists of an indoor location and fencing system. This system is beneficial when users wish to designate a pet to certain places within a home. Information from this system can be viewed from within the app. This system consists of a transmitter and a receiver. The transmitter utilizes a pulsed light source that propagates to a receiver. The receiver uses a lens to direct light to a photodetector that sends a signal to the microcontroller. This data can then be used to locate the pet and be transmitted to the app with the pet's location.

The pet collar has a vibration mechanism for training purposes. This mechanism can be operated within the app, and it has multiple different intensity settings for the vibration. This system utilizes a vibration motor that is implemented into the collar.

The collar also has a GPS location system. This system is able to determine the pet's location, but is not as precise as the indoor location system. This system consists of a GPS module that is implemented into the collar which serves to transmit the location of

the pet. This system acts as a supplementary activity tracker because a pet's movement can be tracked with this system.

Our group number is Group 9. The team members and their majors are Nadia Khan majoring in Optics and Photonics, Rana Scherer majoring in Optics and Photonics, Austin Fugate majoring in Electrical Engineering, Sara Wijas majoring in Electrical Engineering, and Jesus Pagan Vela majoring in Computer Engineering. Our sponsor is Ramon Jimenez who is employed by Renesas Electronics. Through this sponsorship we were given \$1000 to work on this project.

2: Project Description

2.1: Project Motivation and Competitive Products

Many individuals are pet owners who deeply care about the safety and happiness of their beloved animals. However, due to their often busy schedules and other responsibilities, there are occasions when pet owners cannot provide continuous supervision or be physically present for their pets. When separated from their pets, pet owners may experience anxiety regarding their pets' safety, and the absence of owners heightens potential risks to pets' well-being.

While some opt to entrust their pets to friends or boarding services as needed, a more cost-effective and practical technological solution has emerged to address these concerns: the use of smart collars for pets. Smart collars offer a range of features that monitor environmental conditions crucial to pets' well-being and provide valuable insights into their overall health and happiness. Many competitive products exist in this sphere with different combinations of features desired by pet owners. Some of the more robust competitive products in this sphere are made by Halo, SpotOn, Fitbark, and RAWR [1].

Halo, Fi and SpotOn's collar features are primarily focused on GPS location tracking and geofencing capabilities. The geofencing systems in these products allow users to define a virtual fence around the area where their pet may explore, either by drawing it on a map within the product's companion app, or by walking around the desired perimeter with the collar in hand. Once the geofence is defined, if the pet attempts to leave the geofence boundary, the collar will give feedback to the pet. Types of feedback that have been used include haptic feedback, electric shocks, or tones [2], [3], [4].

Fitbark's products take a different approach, since, while one of its products does have GPS capabilities, all of their products' other features focus on health and fitness tracking. Specifically, it measures activity and sleep quality, allowing pet owners to get an overall picture of their pet's well-being [5].

RAWR, which has not been released to the market yet, is similar in that it has a GPS locator, activity tracker, and health monitoring, but it differs in that it has a flashlight and a personal assistance feature accessed through a phone. RAWR offers multiple features that cover all essential things for a pet. The GPS tracker shows the real-time GPS location, can track walk history, identifies multiple safe zones for the pet, and has live

S.O.S tracking. The collar's activity tracker offers a calorie expenditure, allows the user to set activity goals, and monitors the pet's activity and rest levels. If a pet is not as active or is resting more than normal, the collar can relay this information to the owner. The health monitoring of the collar is very extensive as it measures the resting heart rate, resting respiration rate, sleep patterns, and saves the pet's medical records. The smart assistance feature on the collar will allow the pet owner to schedule appointments, notify them of training opportunities, set reminders, and use a vibration used for training purposes. The pet collar also tracks temperature and has a water sensor which can notify an owner if a pet is drowning. There is also a customizable light-emitting diode (LED) flashlight which is useful for making the pet more visible to vehicles and people at night. The light is visible for up to 500 meters which would be essential in case the pet is in danger of being hit by a car. RAWR is very extensive and seems to cover a wide variety of features, however they lack a defense system that relies upon real-time environmental monitoring. These are both features that our collar has [6].

It is evident from our preliminary research that beyond those collars listed above, the market lacks many options for smart collars that include geofencing, training assistance, and environmental monitoring capabilities that are compatible with all species of pets – in a single, cost-effective product. Thus, to satisfy this gap in the established market, our collar includes some features that have appeared in competitor products. Furthermore, our sponsor, Ramon Jimenez, has seen the need for the inclusion of a feature that does not yet exist in competitive products – a system that accurately recognizes and defends the pet against predators.

Our preliminary research indicates that current collars and harnesses intended to defend pets from predators are primarily mechanical devices that rely on spiked protrusions which inflict pain upon predators to deter them. These devices include products by the companies CoyoteVest and PredatorBWear [7], [8]. While these products may successfully deter predators in some cases, the effect may be delayed until after the predator has attacked the pet and felt pain from the spikes. Thus, if the spikes do not initially scare away the predator, a pet may still sustain injury from attempting to fight or flee from an attacker, even while wearing these products. Another solution that has been devised by Defenders of Wildlife in partnership with the Animal Welfare Institute, but is not yet commonly implemented in the commercial sphere, is a harness with integrated LED lights that activates when pets bark. However, much of the additional efficacy from this product when compared to the spiked collars and harnesses on the market is only attained provided that its wearer barks in the presence of predators (thus, it is an ineffective solution for cats and other pet species). Furthermore, these products do not alert the owner when they are used to defend the pet, leaving owners unaware of what has happened to their pet and ignorant of whether they must take further action to ensure their pet's safety.

Another feature missing in the current smart collar market is the capacity to track the locations of pets indoors and establish geofence boundaries to restrict their access to certain areas. Many pets, like cats and smaller dogs, hide in tight spaces and can even get stuck, leaving them lost to their owners and potentially in harm's way. This issue is

compounded when pet owners have large houses or share indoor space (such as a townhouse or multistory apartment) with adjoining residents that may not be mindful of the pet's whereabouts or allow owners to search for pets in their space. Furthermore, some owners may wish to confirm the specific room that their pet is in while away from home to ensure their safety.

A solution that pet owners have devised for finding pets indoors is attaching key finder devices like the Tile Tracker or Apple AirTags to their pets. However, these solutions have some shortcomings. Bluetooth key finders are limited by their range, which can be less practical for pet owners with larger homes and entirely ineffective when owners are away from home. Furthermore, indoor obstacles like walls and personal belongings can further attenuate the signal when pets wearing them hide in cramped areas, making this solution ineffective in the very circumstances where it would be necessary [9].

Meanwhile, the Apple Airtag, while it overcomes the shortcomings of Bluetooth key finders by including GPS capabilities for longer-range tracking, is not capable of providing sufficient information about the altitude of the tracker, per third-party reviewers. This shortcoming makes the Airtag a less viable solution for those who live in multi-story buildings [10], [11].

Other pet owners may attempt to track their pets indoors using security cameras. One shortcoming of security cameras is that they have limited functionality in tight or dark spaces, like closets, where pet owners may wish to know if their pet is entering. Furthermore, it is not feasible or ethical to keep a stationary security camera in some areas in the home, like the bathroom, where privacy is a concern, but pet owners may still want to monitor their pets' activity in these areas. Furthermore, some pet owners may have general concerns about recording and storing historical data of their activities at home, and would prefer to track their pet specifically rather than capturing activities within their entire homes. While specialized pet cameras exist that recognize animal activity and provide alerts or summaries of pet activity to owners, more cost-effective security cameras require owners to sort through historical footage in order to know their pets' whereabouts [12].

Another concern pet owners may harbor is their pets gaining access to rooms the owner considers unsafe for the pet or rooms where the presence of a pet would cause issues related to hygiene, privacy, damage to home decor, or disruptions in spaces where uninterrupted quiet is essential. While the training capabilities of the aforementioned smart collars on the market could be used to help pet owners disincentivize pets from entering these spaces, using these would require the owner's supervision to provide correction, which makes this solution less viable for owners who are not willing or able to constantly monitor their pets at home (the target market for smart pet collars). Another solution to this issue is quite simple – using physical barriers like baby gates, boxes, or closed doors in front of rooms that the pet is not to access. However, this solution is inconvenient for the pet owner, who would have to move these physical barriers and replace them every time they enter and exit the room. Additionally, this solution may

diminish the aesthetic appeal of the homeowner's residence and could also be overcome by pets that are capable of leaping over or knocking down these barriers.

Indoor invisible fences for pets, such as PetSafe, are also commercially available [13]. These products utilize a ground-placed transmitter beacon that emits a radio signal. This signal is then received by a collar worn by the pet, which can emit a warning tone or deliver an electric shock as a response. However, these solutions utilize transmitter collars that lack other smart collar capabilities a pet owner may desire, as they are adapted from conventional outdoor invisible fence collars. Furthermore, these systems do not alert the owner that their pet has tried to access a forbidden area, so owners would be unable to determine if there is a significant issue that is causing the pet to try to access forbidden areas excessively.

Considering the above, implementing a supplementary indoor location system into our product would give pet owners an alternative, simpler solution to quickly obtain peace of mind that their pets are safe at home and track their activity as they move between rooms. Furthermore, this solution could be more robust than all of the above by working synergistically with our collar's training mechanism as a fencing system that can deter pets from entering a specific room.

Table 1: Comparison of Features in Existing Products vs. Our Planned Features

Product Name	Indoor Boundaries	Defense Against Predators	LED	Owner S.O.S Notification	Training Assistance	Outdoor Geofence	GPS
CoyoteVest		X					
PredatorB Wear		X					
PetSafe	X						
Fi			X			X	X
Fitbark				X		X	X
Halo					X	X	X
SpotOn					X	X	X
RAWR			X	X	X	X	X
Our Collar	X	X	X	X	X	X	X

The table above summarizes the comparison of the aforementioned products and some of the main features that our collar includes. It does not include peripheral features, such as

the temperature and humidity sensor and activity monitoring, due to formatting constraints.

2.2: Project Goals

The following are the goals initially outlined for this project.

2.2.1: Basic Goals

We strive for our collar to have many features included within competitor products. Accurate environmental temperature and humidity sensing, though seemingly simple to implement, is an invaluable feature that we plan to include in our smart collar. In our preliminary research, only one smart collar, RAWR, covered this feature, though a standalone temperature and humidity monitoring system, Waggle, is also coming out soon, however it isn't intended as an attachment on a pet collar [14]. However, given that heat-related illnesses are potentially fatal for pets, with one study claiming a mortality rate of 50% for canines [15], our decision to include temperature and humidity monitoring in our prototype will greatly improve the functionality of our collar as a device that promotes the overall wellbeing of pets. This data will be transmitted to the owner within a few minutes wirelessly..

Our collar would also have a geofencing feature. As is the case with competitor products, this feature would create a designated area established by the owner. Our goal is to have the collar send a response to the pet when they exit the designated region. The collar will notify the owner when the animal is outside the designated region, and the owner can then use the vibration feature on the app to encourage the dog to stay within the designated area by vibrating the collar. Our goal is to have the geofencing work within a 5 meter accuracy. The geofencing feature is included with multiple other smart pet collars so having our collar include this will make it competitive.

The collar will feature a vibration mechanism for training purposes, as previously mentioned. The owner will be able to use the app to trigger vibrations within the collar. The vibrations will be of varying intensities, decided by the owner. This feature would be useful when trying to train the dog; the vibration would help train the pet by getting the pet's attention during the training, and for some pets it would serve as negative feedback in response to an undesired behavior. This feature is used in other pet collars and is safe to use without hurting the pet.

Like other smart collars, our collar will be capable of sending and receiving data wirelessly. This capability will allow the owner to interact with the collar through an easy-to-use app. Specifically, the app will allow owners to enable or disable collar features as desired, see information gathered by the collar, and receive alerts about the status of their pet. The app would also allow the user to activate its in-built defense system, consisting of a strobe light designed to ward off any potential threats.

The defense system on our collar will also make use of image processing to activate itself even without the user's input. Using the on-board cameras, our collar would work to recognize a potential predator within a reasonable distance of the pet and activate the

deterrent system automatically. As a basic goal, the collar will be able to detect anomalies in the pet's environment, activate the defense system, and inform the user of potentially dangerous situations. The collar will also provide the user with an image of the entity that the pet interacted with, which would allow the user to make a more informed judgment about the level of danger their pet is in and act accordingly. Once a threat has been identified, the collar will notify the owner and automatically activate a deterrent system to attempt to disorient and frighten possible predators.

Our collar will also include a supplementary beacon system for locating the pet indoors. This Indoor Location and Fencing System will incorporate a freestanding receiver beacon that works concurrently with the collar to alert the owner of pet activity in the location where it is installed. A basic goal of this system is to determine whether a pet wearing the smart collar has passed the point-of-installation at walking-speed once (which could be assumed to indicate entrance into a room) or twice (which would then indicate exiting the room). The system would detect pets at a reasonable distance away from the beacon with a sufficient field-of-view to work in a doorway or hallway.

2.2.2: Advanced Goals

Our advanced goals for this project represent ideas that would make our product feel complete in a market sense. Though we will be focusing on our basic goals for the prototype, depending on development, we might be able to include some of these features to round out the product and make it commercially viable.

For the deterrent system, our advanced goals include further training of our image processing model to reduce the amount of false positives we receive. When it comes to a pet's safety, our team will always choose to err on the side of safety. Due to this, we plan for our initial model to be overly sensitive in order to ensure it activates if any danger is afoot. This will tax the collar's battery life, and is not a feature that we intend to keep for the entirety of the product's lifespan. Once we are confident in the basic construction of our collar, we will focus on fine tuning this model for efficiency and safety.

As for the Indoor Location and Fencing System, our advanced goal is to give this system the capability to differentiate between multiple pets and provide selective fencing capabilities for one of multiple pets. Furthermore, the sensors on the beacons can be made more robust, allowing for detection of the pet in a wider field of view and enabling their operation within open areas.

2.2.3: Stretch Goals

Our stretch goals for this project represent ideas that we would one day like to realize if times and money were not a constraint. These are features that, should our team choose to continue developing the SAFEPADS collar after graduation, would eventually see themselves added to the collar to make it stand out from the rest.

One area that we would like to further improve upon in the future will be the companion application. If we want our product to succeed in the market, we would have to port the app to as many platforms as possible, primarily iOS and Android devices. This would

require our team to learn new skills from the ground up, which is why we put it in the stretch goals. Furthermore, fully realizing the app's potential is something that our team would one day like to see accomplished. This means data tracking, professional UIs, marketing implementations, and so on.

We also plan to finalize and improve many of the collar's features. Some of the features we've thought of improving are the beacons, the training function, and the detection system. For the Indoor Location and Fencing System receivers our stretch goal is to provide more information to the user than just the pet's location. The sensors could communicate with each other in order to garner more information about the pet, such as its speed and activity. For the training function, we would include the ability to create and save certain regiments that the user can reuse as much as they like. This includes setting times in which the collar will direct the pet to certain areas and adjusting the intensity of the vibration based on the pet's behavior. Finally, for the predator detection system, our vision is to one day make the system robust enough to differentiate between different animals and assess their threat levels individually, therefore changing the collar's response to the threat. As an example, in a low danger situation, the collar would only send a notification to the user, while in a high danger one, it would deploy the defense mechanism. This would require further training of the model, as well as the collar knowing the size of the animal that it is being worn by. If our development goes smoothly, we plan on adding some of these features in order to make our product more appealing to the customer.

2.3: Project Objectives

To meet our goal of creating a defense system, our objective is to create a wide field-of-view camera system mounted on the collar that is integrated with image processing software. This camera system will be mounted on the back of the collar and feature a camera with an attached lens system that yields a wide field of view. The cameras will transmit the pet's surroundings to our image processing software, which we intend to use to determine if there are threats around the pet. To meet our goal of creating a deterrent system, we plan to implement an LED strobe light within a collimating lens housing that can flash brightly to frighten predators. To expand upon this system, we could also add a speaker that would play a loud sound at frequencies audible to native Florida predators.

Using the feed from the wide angle lens and libraries such as OpenCV, we will implement computer vision in order to automatically detect common predators, like birds of prey and coyotes. The collar will be able to automatically detect these creatures and deploy the appropriate deterrent, hopefully warding off any would-be attack on the pet.

To create the Indoor Location and Fencing System, an optical transmitter integrated in the harness that will send a signal to a freestanding receiver. This receiver will feature a lens system to collect light from a wide field-of-view such that a sufficient intensity falls upon it if the collar's angle or height changes slightly while its wearer is in motion. Light that passes through the lens system would then fall on a photodiode that would produce a signal to be sent to the software.

To create software to interface with the collar, our objective is to design and implement a Windows application that can transmit and receive information from the collar. This application will be the central hub for all of the collar's information, and will allow the user to control all of the collar's many features. It will use account services to save the user's data so that they can access their data on different devices. As far as the actual development goes, our team is new to creating applications. Our methodology is going to greatly depend on our research going forward, and is bound to change as we learn more about leading technologies. For now, however, we are planning on developing the application first for Windows using Python. Python's low complexity and image processing libraries would make it a great match for our project's needs, so it remains our group's first choice for a programming language. Our methodology behind this decision is explained in greater detail in section 3.20.1 of this paper. As a stretch goal, we eventually plan to port this application to iOS devices, which will require using Apple's native language, Swift. The plan to port to iOS is one that would increase our product's marketability, and keep it competitive with other similar products.

The collar will also feature a vibration that can be triggered from the app so the owner can get the pet's attention or correct undesirable behavior. This mechanism can be used concurrently with training and would require the owner to repeatedly use this feature as a correction so that the pet understands that a vibration means they did something they're not supposed to. The vibration would be implemented using a small solenoid or a DC motor embedded into the collar that converted a DC input voltage into mechanical energy.

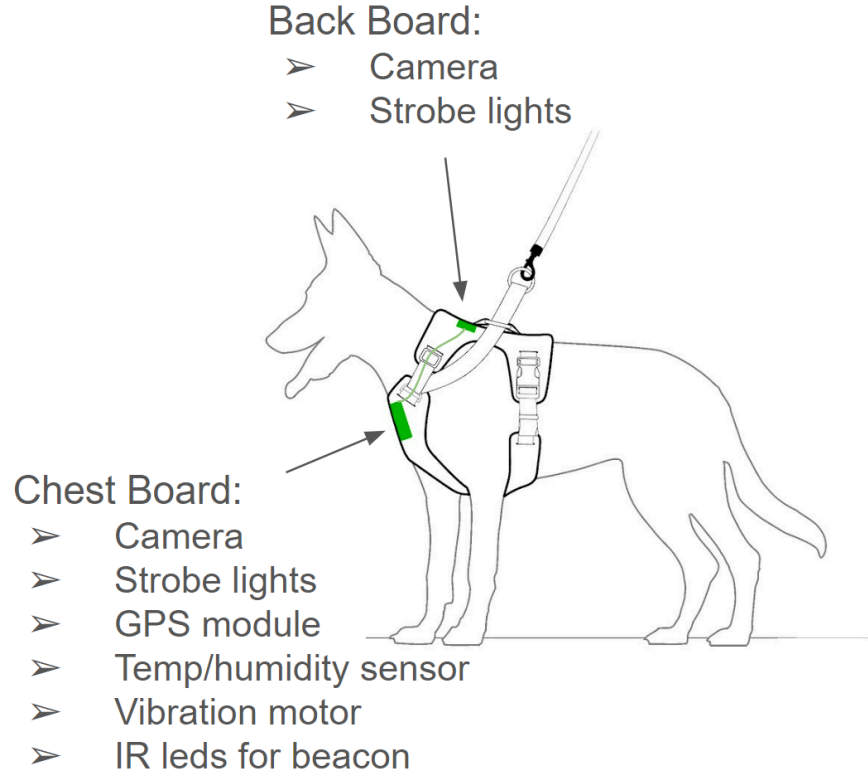
Below is a preliminary design draft of the collar, illustrating the placement of some key components and the overall scale of the product with respect to the collar size. There is the main box in the front of the collar that houses the PCB and the majority of the electrical components, and a peripheral box in the back of the collar that has the wide FOV camera and extra strobe lights and is connected to the main box using the connection cable. The main box is designed to be removable for charging without leaving the animal collarless.

3: Part Selection

Before we can get any farther into our project and its possible designs, we need to pick the best components for each part. We need to find the component options that are a balance of good quality and low cost; we want to optimize the performance of our project without compromising on our budget. For each component, we will look into the most common options and compare the most pertinent aspects of each one in order to deduce which option would work best for us. The comparisons and decisions for the most important of the components are outlined in the following sections.

The preliminary design for the collar based on the knowledge of what each section has to accomplish is pictured below. There is the front-of-collar portion and the back-of-collar portion.

Figure 1: Preliminary Design of Harness



3.1: Microcontroller Overview

Choosing the ideal microcontroller for our smart collar project, which integrates geofencing, temperature/humidity sensing, predator identification, and energy-efficient strobe light defenses, was a pivotal decision that significantly impacted the project's success. Our multifaceted collar demanded a microcontroller that could efficiently process sensor data, execute geofencing algorithms, and activate predator detection and defense mechanisms, all while operating within strict power constraints. Striking this balance between performance and power efficiency was crucial to ensure the collar's functionality in real-world scenarios.

In this comparative analysis, we will delve into a range of microcontroller options, examining their processing power, power consumption profiles, and compatibility with the collar's diverse functionalities. We will also consider factors such as ease of programming, community support, and cost-effectiveness to make an informed decision. By selecting the right microcontroller, we aimed to create a smart collar that not only meets its core objectives but also operates reliably and efficiently, ultimately enhancing the well-being and safety of the animals it's designed for.

3.1.1: TI-MSP430 and MSP432

The MSP430 microcontroller, which we have had hands-on experience with in previous classes, is a potentially excellent fit for our smart collar project. Since we have a solid

understanding of its capabilities, we can be sure to utilize the unique strengths of the MSP430 to best fit our project's needs.

The MSP430 is well known for its low power consumption capabilities which works well with our smart collar's power-efficient design requirements, ensuring that the device can operate continuously without having to recharge the battery frequently. The MSP430 also has a multitude of integrated timers and analog-to-digital converters, which will be instrumental in efficiently managing the input sensor data and executing time-sensitive tasks. Its compatibility with wireless communication modules, if required, can facilitate data transmission and remote control, although it doesn't have integrated WiFi or Bluetooth modules like other options listed in this section [16].

Our prior experience with the MSP430 microcontroller, along with its proven track record in low-power applications, means the MSP430 microcontroller is a frontrunner in our decision making process. By incorporating the MSP430, we can strike the right balance between functionality and energy efficiency, ensuring the collar performs optimally while conserving power resources, a crucial aspect of our project's success.

The MSP432, on the other hand, is based on a 32-bit ARM Cortex-M4 architecture, offering better performance capabilities. In contrast, the MSP430 employs a 16-bit RISC architecture, emphasizing ultra-low power applications. These families differ in their peripherals, development environments, and code compatibility. While both have strong community support, the MSP430 has a longer history and more established user base. Choosing between the two depends on project-specific requirements, with the MSP432 favored for higher performance needs and the MSP430 for ultra-low power consumption applications. Upon further research, the MSP432 has been discontinued and is unavailable for purchase. Therefore, only the MSP430 will be considered in this decision.

Unfortunately, the dimensions of the MSP family are more than a few inches in length and width, which would make fitting it on the collar of an animal a difficult ordeal. To accommodate for the size of the MCU, the rest of the collar would have to be bigger, which would be uncomfortable for the pet and could be a safety hazard if they can get their jaw around it or if it's too heavy and it fatigues their neck to hold it up.

3.1.2: Arduino Nano

For the purposes of the physical size constraints of the collar, the Nano was chosen for the comparison. Sara has had experience using the Arduino IDE which would make the Arduino Nano a potentially suitable choice for this project. However, when considering its suitability for a smart pet collar project, specific project requirements come into focus. The smart collar project entails geofencing, temperature/humidity sensing, predator identification, strobe light defenses, and low power consumption demands. While the Arduino Nano offers several advantages, it may not be the best fit for our particular needs.

Firstly, the Arduino Nano employs an 8-bit Atmega328P microcontroller [17], which may limit its processing power for real-time tasks like geofencing and predator

identification. These operations would benefit from more robust 32-bit microcontrollers with higher processing capabilities.

Secondly, power efficiency is crucial for a smart pet collar, as it directly affects battery life. While the Arduino Nano is energy-efficient, other microcontrollers like the MSP430 or ESP32 provide even lower power modes, which can be critical in extending battery life for prolonged usage between chargings.

Additionally, the smart collar project will require wireless connectivity for geofencing and data transmission features. Although the Arduino Nano offers modules that are compatible to handle WiFi connectivity or Bluetooth, other microcontrollers that are discussed in this section have these modules built into them already, making them a better contender.

In conclusion, while the Arduino Nano offers accessibility and versatility, the specific needs of the smart pet collar project, including geofencing, low power consumption, and advanced sensor integration, may be better addressed by microcontrollers with 32-bit architectures, lower power modes, and built-in wireless transmission capabilities. For these reasons, the Arduino Nano will be removed from consideration for our teams' microcontroller choice.

3.1.3: ESP32 and ESP8684

The ESP32 microcontroller is an exceptionally suitable choice for the development of our smart pet collar project. With its powerful 32-bit dual-core processor, the ESP32 offers ample processing power to handle real-time tasks such as geofencing and complex algorithms for predator identification, ensuring swift responses to changing conditions. It also has the ability to assign tasks to each of the cores, which allows for more efficient energy consumption and quicker response times compared to other microcontroller options listed here. One of the standout features of the ESP32 is its built-in Wi-Fi and Bluetooth connectivity [18], which simplifies communication with remote devices, servers, and mobile applications. This capability enables easy geofencing and data transmission, facilitating real-time tracking and monitoring of pets and therefore enhancing their safety.

Moreover, the ESP32's flexibility in interfacing with various sensors, including temperature and humidity sensors, streamlines the integration of environmental monitoring features into the collar, ensuring the pet's comfort and well-being. Its advanced power management features allow it to operate efficiently in low-power modes when not actively performing tasks, a crucial aspect for extending battery life, which is vital for a smart pet collar's continuous functionality.

The ESP32 benefits from a thriving community of developers and enthusiasts, resulting in extensive documentation, libraries, and open-source projects. This rich ecosystem can significantly expedite the development process and provide support for troubleshooting and enhancing the collar's capabilities. Additionally, its customizable form factor ensures

that the microcontroller can be seamlessly integrated into the collar's design, maintaining a compact and comfortable fit for the pet.

In summary, the ESP32 microcontroller's combination of processing power, wireless connectivity, sensor compatibility, energy efficiency, and community support positions it as an excellent choice for a smart pet collar project, empowering the creation of a feature-rich and reliable collar that enhances pet safety and owner peace of mind. Our team has little to no experience working with this microcontroller, however with the support of other developers online, the potential transition shouldn't be difficult.

In contrast, the ESP8684 has similar features with the WiFi and Bluetooth connectivity and sensor integration for the temperature and humidity sensors, however it has less processing power and may not be able to handle predator identification and all of the peripheral tasks that the collar will need to run intermittently. The ESP8684 also doesn't have the same level of power efficiency as the ESP32 and will lower the expected battery life of the collar. Therefore, the ESP32 would be a better choice for this specific collar.

3.1.4: Raspberry Pi

The Raspberry Pi offers a stark contrast to traditional microcontrollers like the MSP430, ESP32, or Arduino. It contains substantial processing power which would be suitable for the complex tasks involved in our project, including geofencing, predator identification, and data processing. It has built-in Wi-Fi and Bluetooth capabilities that make it well-suited for wireless communication, which is ideal for our project's needs. The Raspberry Pi also interfaces with various sensors, allowing for the incorporation of environmental monitoring features [19].

However, several drawbacks make the Raspberry Pi less ideal for a smart pet collar project. Firstly, its power consumption is significantly higher than that of other microcontrollers listed, making it unsuitable for designs where energy efficiency is critical, such as with our battery operated collar. Additionally, its larger size and more complex form factor might not align with the compact design typically desired for pet collars. Lastly, while the Raspberry Pi has extreme versatility and a wide range of applications, this may introduce unnecessary complexity for a project that can be efficiently managed by other microcontrollers that are specifically designed for low-power and real-time applications.

In summary, while the Raspberry Pi is an exceptional platform for a wide range of projects, its high power consumption, larger size, and complexity may not align with the specific requirements of a smart pet collar. Microcontrollers like the MSP430, ESP32, or Arduino are better suited for our type of applications, where we require low power consumption and a small overall size to fit it on a pet's neck. The choice between a Raspberry Pi and microcontroller should be made based on the distinct needs and priorities of the smart pet collar project. In this project, a Raspberry Pi board does not appear to be suitable to our needs.

3.1.5: Particle Photon

The Particle Photon is another potential option for our smart pet collar project due to its specific strengths in IoT (Internet of Things) and connectivity. Its built-in Wi-Fi capability is particularly advantageous, as it enables real-time geofencing and remote monitoring, allowing pet owners to track their pets' locations and receive alerts through our mobile app. Moreover, Particle's cloud platform integration simplifies device management, data storage, and remote control, providing a secure and efficient means of storing pet data and managing the collar's settings [20].

The Particle Photon's adaptability extends to sensor integration, allowing it to interface with a variety of sensors such as GPS modules, temperature and humidity sensors, and even predator detection sensors and cameras. This capability empowers the collar to collect and transmit relevant data to our mobile app. Unfortunately, the Particle Photon is not as power-efficient as some low-power microcontrollers, but there are careful power management strategies that can be employed to ensure a balance between performance and battery life. Furthermore, the Particle community offers extensive support, serving as a valuable resource for troubleshooting and accessing pre-built libraries and code examples.

In terms of size constraints, the Particle Photon will fit relatively well inside of the collar housing, but is not the smallest option presented. In summary, the Particle Photon's combination of connectivity, cloud integration, sensor compatibility, and community support positions it as a strong candidate for our smart pet collar project, ultimately enhancing pet safety and owners' peace of mind through real-time tracking and monitoring capabilities. However, it does not have all of the preferred characteristics we want in our microcontroller, and we don't have much room to compromise as the entire collar hinges on the performance of the microcontroller. Therefore, we will most likely proceed with a different option.

3.1.6: Microcontroller Final Comparison

Based on the above information, the final comparison of all of the microcontrollers can be summarized in the below table. As was discussed earlier, the main factors considered in microcontroller selection were size, the inclusion of a WiFi module, processing capabilities, power consumption profile, and price.

Table 2: Microcontroller Comparison

Component	Size	WiFi Module?	Num. of Bits	Bit Rate	Num. of Power Mode Options	Price
MSP430	7mm x 7mm	No	16	12Mbps	4	\$10
MSP432	9mm x	No	32	16Mbps	5	N/A

	9mm					
Arduino Nano (ATmega328 P)	7mm x 7mm x 1.2mm	No	8	2Mbps	4	\$12
ESP32	5mm x 5mm x 0.850mm	Yes	32	150Mbps (WiFi), 4Mbps (Bluetooth)	5	\$10
ESP8684	4mm x 4mm x 0.850mm	Yes	32	72.2Mbps (WiFi), 2Mbps (Bluetooth)	4	\$8
Raspberry Pi	7.75mm x 7.75mm	Yes	32	62.5Mbps	0	\$50
Particle Photon	14.60mm x 16.60mm	Yes	32	Unable to Find	0	\$19

Due to the processing capabilities and overall size of the ESP32 WROOM, we decided to move forward with that microcontroller. It has a 32 bit dual core that can theoretically manage the stress that our project will put on it, including predator detection and live GPS and geofencing. The ESP32 is also one of the smallest options we explored, which will work well with the small size constraints of the project. It has built in wireless connectivity which simplifies the transmission of data from the collar to the app for the user to look at in real time. The ESP32 also boasts 5 different low power modes that help us extend the amount of time in between charging, and has more low power modes than any of the other options. Overall, the ESP32 WROOM was a good fit for our purpose.

3.2: Temperature and Humidity Sensor Overview

One desired feature for the designed product is the ability to monitor the temperature and humidity of the environment. A temperature and humidity sensor can aid warning the pet owner when their pet has been in an overly warm or cold environment for an extended period of time. Once the pet has been in an environment that differs from a normal temperature, a notification will be sent to the pet owner notifying them before any harm befalls their pet. In regards to choosing the temperature and humidity sensors, certain parameters must be considered. One extremely important desired parameter is a small size and weight since the sensor will be located on a pet's neck. Additionally, the temperature sensor should have an accuracy of ± 2 degrees celsius and the humidity sensor should be able to determine the relative humidity with an accuracy of ± 10 percent. Furthermore, an extremely low power consumption is imperative since the sensors will

need to be powered by an extremely small rechargeable power supply. The budget also shows an allocation of four dollars for the humidity sensor and seven dollars for the temperature sensor indicating that a low cost may also be desirable. One factor that should be considered but is not imperative is a fast response time. Below is a collection of options that were explored for the purposes of our project.

3.2.1: DHT-11 and DHT-22 Temperature and Humidity Sensors

The first selection of temperature and humidity sensors to be considered are the DHT-11 and DHT-22 temperature and humidity sensors. The DHT series temperature and humidity sensors combine both sensors into a single device allowing it to obtain both measurements with a single device. They work by measuring the temperature when prompted to and then sending that information as a binary number over a single wire. The DHT-11 sensor has a low current consumption of 0.3mA when reading the environment's temperature and humidity and an even lower current consumption when in an idle state. Additionally, the DHT-11 sensor has an accuracy within the desired specifications with a temperature accuracy of $\pm 2^{\circ}\text{C}$ and a relative humidity accuracy of $\pm 5\%$.

Furthermore, the DHT-11 sensor has both a low cost of \$5 and takes up a small volume of 1023 cubic millimeters. The DHT-22 sensor has a greater accuracy when compared to the DHT-11 sensor with an accuracy of $\pm 0.5^{\circ}\text{C}$ for temperature and $\pm 2\%$ for relative humidity. Unfortunately, this greater accuracy comes at the cost of a larger current consumption of 1.5mA when reading the environment's temperature and humidity, a larger size of 1386 cubic centimeters, and a greater cost of \$10. The information presented here and additional information about the DHT-11 and DHT-22 temperature and humidity sensors can be found in the datasheets provided by Aosong Guangzhou Electronics Co. and Components101 [21], [22].

3.2.2: TMP36 Temperature Sensor

The next sensor to be considered is the TMP36 temperature sensor. The TMP36 temperature sensor determines the temperature with a linearly scaling output voltage. According to the sensor's datasheet by Analog Devices [23], the sensor increases its output voltage by 10mV for every 1°C increase in a linear fashion. This can be combined with an analog to digital converter in order for a microcontroller to determine an environment's temperature. The TMP36 temperature sensor has an accuracy of $\pm 2^{\circ}\text{C}$ which is within the desired accuracy range for the planned device.

Additionally, it has an extremely small size of 305.9 cubic millimeters and a low cost of \$3. It also has an extremely low current consumption of $50\mu\text{A}$ when operating. One downside is the TMP36 sensor does not include a humidity sensor so an additional sensor would need to be paired with this one in order to achieve the humidity sensing feature for the device.

3.2.3: LMT84 Temperature Sensor

The next sensor considered is the LMT84 temperature sensor. Information relating to the LMT84 temperature sensor can be found on the datasheet by Texas Instrument Incorporated [24]. The LMT84 sensor has many similarities to the TMP36 temperature

sensor but there are a few differences to consider. Like the TMP36 temperature sensor, the LMT84 sensor determines the temperature by outputting a voltage that scales linearly with the environment's temperature. However, the LMT84 temperature sensor output has a negative slope meaning that as the temperature increases, the output voltage decreases by about 5.5mV. Additionally, the LMT84 temperature sensor is very accurate with a typical accuracy of $\pm 0.9^{\circ}\text{C}$ which meets the project's desired temperature specifications. This sensor also features an extremely small size of 64.715 cubic millimeters and costs approximately \$2 to purchase. Finally, while idle, the sensor only consumes approximately 5.4 μA of current which would greatly improve the longevity of the project's power supply.

3.2.4: SHT31 Temperature and Humidity Sensor

The next sensor to be considered is the SHT31 temperature and humidity sensor. Sensirion provides a datasheet with information relating to this sensor that was used in obtaining relevant information [25]. The SHT31 sensor uses I2C communication in order to communicate its measured data with a microcontroller which differs from all the previous sensors methods of communication. The sensor has a temperature accuracy of $\pm 0.2^{\circ}\text{C}$ and a relative humidity accuracy of $\pm 2\%$ which satisfies the desired accuracy for this product. The sensor is especially accurate for the expected range of temperatures for the environment a pet will likely experience. Additionally it has an extremely compact size of 5.625 cubic millimeters. While reading, it has a relatively large current draw of 1.5mA but while not reading that number drops to about 1.7 μA allowing for a low power consumption as long as measurements are not being constantly taken.

Additionally, the sensor has a low cost of \$6. One downside of this sensor is it has a relatively long response time of 8s which is larger than most of the other sensors considered. Another thing of note for the SHT31 sensor is the availability of preassembled PCBs. Due to the size of the sensor, it would be difficult to test without it already being connected in a printed circuit board. The availability of this sensor in established PCBs would allow for easier testing of the sensor before incorporating it in this project's custom printed circuit board.

3.2.5: HIH-4030 Humidity Sensor

The next sensor considered is the HIH-4030 humidity sensor. The datasheet by Honeywell International Inc. provides important information that aids in the consideration of this sensor [26]. The HIH-4030 humidity sensor communicates temperature with a microcontroller unit by producing an analog voltage output that is proportional to the current relative humidity of the air. The voltage output increases by approximately 30.68 mV for every 1% increase in relative humidity. That voltage output can then be combined with an analog to digital converter to determine the relative humidity. It features an accuracy of $\pm 3.5\%$ when determining the relative humidity and has a low typical current consumption of 200 μAh . Additionally, it features a small size of 95.64 cubic meters.

Unfortunately, this sensor comes at a large cost of \$21. This sensor was considered due to the fact that there are not many humidity sensors available that do not come with a

temperature sensor also attached. A sensor like this one may be needed if one of the sensors that only measures temperature is determined to be the optimal choice for this project.

3.2.6: HDC2010 Temperature and Humidity Sensor

The last sensor to be considered is the HDC2010 temperature and humidity sensor which has information provided by the datasheet by Texas Instruments Incorporated [27]. The HDC2010 sensor features I2C communication in order to communicate the data it measures with the microcontroller unit. Additionally, it features an extremely small current consumption of 550 nA when temperature and humidity measurements are read every second. This is the lowest current consumption of all sensors considered. Furthermore, it has an extremely small size of 1.52 cubic millimeters which is also the smallest size of all temperature and humidity sensors currently considered and costs less than estimated with a cost of \$4.

One problem is that its extremely small size could pose difficulties when testing the sensor and it also has a longer response time when compared to some of the other sensors that were considered. Additionally, this sensor requires a supply voltage of less than 5V which deviates from what every other sensor requires and would therefore require a regulator in order to achieve its lower required potential difference.

3.2.7: Temperature and Humidity Sensor Final Comparison

As stated, the most important factors to consider when selecting a temperature and humidity sensor for this project are size and power consumption. Upon comparing all of the considered sensors, the sensor implemented in this project will be the SHT31 temperature and humidity sensor. The SHT31 offers one of the smallest sizes of all the sensors compared but unfortunately has a large power consumption. Due to the limited space a pet collar offers, size was prioritized over power consumption. Power consumption will instead be minimized by reading the environment's temperature less often. Additionally, the SHT31 temperature and humidity sensor offers the greatest accuracy. When viewing the sensors considered, it can be seen that the HDC2010 outperforms the SHT31 in every field considered. The reason the SHT31 was selected over the HDC2010 was due to the lack of readily available testing boards for the HDC2010. It would be impossible to easily test the two sensors due to the sizes of both the SHT31 and HDC2010 temperature and humidity sensors. Therefore, the SHT31s availability of established boards will allow for additional testing time before implementing it on this project's printed circuit board. The following table summarizes the obtained data of every considered temperature and humidity sensor.

Table 3: Temperature and Humidity Sensor Comparison

Component	Accuracy	Current Consumption	Size	Response Time	Price
DHT-11	±2°C and ±5% relative	0.3mA	15.5mm x 12mm x	10 s	\$5

	humidity		5.5mm		
DHT-22	$\pm 0.5^{\circ}\text{C}$ and $\pm 2\%$ relative humidity	1.5mA	14mm x 18mm x 5.5mm	2 s	\$10
TMP36	$\pm 2^{\circ}\text{C}$	50 μA	3.5mm x 4.6mm x 19mm	n/a	\$3
LMT84	$\pm 0.9^{\circ}\text{C}$	5.4 μA	4.3mm x 3.5mm x 4.3mm	0.7 ms	\$2
SHT31	$\pm 0.2^{\circ}\text{C}$ and $\pm 2\%$ relative humidity	1.5mA	2.5mm x 2.5mm x 0.9mm	8 s	\$6
HIH-4030	$\pm 3.5\%$ relative humidity	200 μA	4.17mm x 8.59mm x 2.67 mm	5 s	\$21
HDC2010	$\pm 0.2^{\circ}\text{C}$ and $\pm 2\%$ relative humidity	550nA	1.5mm x 1.5mm x 0.675mm	8 s	\$4

3.3: Global Positioning System

A global positioning system (GPS) is needed for this project in order to implement geofencing and location tracking. Geofencing will allow for protection of a pet in multiple ways. The first way is it can aid in keeping a pet within a designated area. The designated area will generally be a controlled area like a house and its surrounding area that can be considered safe from harm. Additionally, establishing a geofence and monitoring the pet's location will allow the user to know when their pet has left the established safe area. Additionally, once their pet has left the geofenced area, a device that causes a small amount of discomfort to the pet may be activated to encourage them to return to the geofenced area. Establishing a geofence can also aid in reducing the power consumption of the device. Many features of the device can be disabled while within a geofenced area due to that area being established by the user as a safe area. Power consumption can be significantly reduced by disabling features like the image recognizing camera and the predator defense mechanism since those features will not need to be utilized while within a geofenced area. Location tracking is also an important feature to monitor where a pet has gone during the day. Location tracking can help to monitor a pet's activity and provide important information if a pet were to go missing.

When selecting hardware for the global positioning system, the most important factor to consider is the size of the hardware. Due to the size limitations needed to successfully

implement a functional pet collar, it is important to keep the size of all selected hardware components to a minimum while still maintaining functionality. The second most important factor to consider when selecting the hardware for the global positioning system is the accuracy of the system. The specifications for the project indicate that the desired accuracy of the global positioning system is ± 5 meters. An accuracy less than this would be highly desirable but this accuracy ensures that the pet can not go a significant distance from the geofenced area without the pet owner being notified. A third important factor to consider is the power consumption needed for the selected global positioning system to operate. Due to the size of a pet collar, the room for a power supply will be extremely limited. The result of this is a need to minimize the power consumption of all hardware components in order to prolong the life of the battery. Additionally, it would be ideal to minimize the cost of the selected component. A lower cost allows for more funds to be allocated to other portions of the project or for additional funds if an error is discovered during testing.

3.3.1: PA1616D and PA1616S Ultimate GPS Modules

The first global positioning system module considered is the PA1616D ultimate GPS module. The information obtained for this analysis was found in the CD-PA1616D datasheet by CD Technology [28]. The PA1616D GPS module is able to communicate both the latitude and longitudinal coordinates of the device with an accuracy of ± 3 m which is within the desired specifications for the proposed smart pet collar design. Additionally, this GPS module sends information about the module's current altitude, the current time, and the speed at which the module is traveling. These features could be useful for providing a timestamp of a pet's location and for monitoring a pet's activity. The PA1616D GPS module supports both UART and I2C communication in order to communicate data with a microcontroller. Having multiple communication protocols allows for greater flexibility while designing the device due to some protocols having a limited number of microcontroller pins they can be used with. Additionally, while actively tracking the PA1616D uses 29 mA of current and the size of the module is 1715.2 cubic millimeters.

One downside of this GPS module is that setting up I2C communication would be difficult since no I2C address is given and setup requires firmware customization. This could pose problems due to the limited number of UART communication lines that are generally on microcontrollers. Additionally, this GPS module has a relatively large price tag at \$20.

Another option by the same company is the PA1616S GPS module which offers many of the same features with some slight differences. The PA1616S module offers the same length and width as the PA1616D but has a slightly smaller height allowing it to take up only 1203 cubic millimeters. Additionally, this GPS module utilizes less search channels as compared to the PA1616D which allows it to have a lower current consumption of only 20 mA when determining its location. This module also has an accuracy of ± 3 m which falls within the desired specification of the proposed smart collar design. Compared to the PA1616D, this GPS module has the exact same pin layout allowing it to send similar additional data like time and allowing it to have the same flexibility and

drawbacks. An additional difference in this GPS module is that this one costs \$25 which is slightly more when compared to the PA1616D GPS module. The obtained information for this GPS module can be found on the PA1616S datasheet by CDTechnology [29].

3.3.2: U-Blox NEO-M9N-00B GPS Module

The next global positioning system module considered is the NEO-M9N-00B GPS module. The information obtained for this analysis was found in the NEO-M9N-00B datasheet by u-blox AG [30]. The NEO-M9N-00B global positioning system is able to transmit its current position with an accuracy of $\pm 2\text{m}$. Additionally, it can send this information to a microcontroller using either UART, I2C, or SPI allowing for a large variety of options that could work with any microcontroller setup. Compared to the previous GPS module, it has a slightly larger power consumption since it requires 36mA when actively determining its location.

However, this GPS module has a size of 465.6 cubic millimeters which is a smaller size when compared to the PA1616D ultimate GPS module. Some downsides of this GPS module is there is greater complexity when integrating this module into a circuit due to the amount of communication protocols it offers. Additionally, this GPS module has a large financial cost of \$27.

3.3.3: Quectel L96-M33 GNSS Module

The Quectel L96-M33 GNSS Module is the next global positioning system considered for this project. The information obtained for this analysis was found in the L96 datasheet by Quectel Wireless Solutions Co. [31]. The L96-M33 is able to transmit its current position with an accuracy of $\pm 2.5\text{m}$. Additionally, it offers both UART and I2C communication capabilities. Unlike any other GPS module considered, the L96-M33 provides its I2C read and write addresses which are 0x20 for write and 0x21 for read which would help to immensely speed up testing of this module. Additionally, the L96-M33 module has the lowest current consumption of any GPS module considered so far with a current consumption of only 19mA while tracking its location. Furthermore, it has the smallest size of any module considered so far with a size of only 268.8 cubic millimeters.

Another unique feature of the L96-M33 module is it has a dedicated pin for enabling geo-fencing. This means that this module can indicate when a pet both enters and leaves a geo-fenced area with minimal configuration. The module also has additional low power modes to reduce power consumption which could be immensely beneficial for our project due to the limited available room for a large power supply. Finally, this module has the lowest cost of all modules considered with a financial cost of only \$13.

3.3.4: Global Positioning System Final Comparison

As stated, when considering the ideal GPS module for this project, the most critical things to consider were size, accuracy, and power consumption. It was originally decided that the Quectel L96-M33 GNSS module would be the most suitable GPS system for this project due to its small size, low power consumption, and high accuracy. However, the Quectel L96-M33 GNSS module is a surface mount device which means it would be

difficult to test without a dedicated development board or without making a printed circuit board to test it on. Due to this, the PA1616S GPS module was selected since it has an available development board that can be utilized to test the product before integrating it into the device. The PA1616S module offers a low current consumption of only 20 mA while actively tracking its location which is ideal due to the limited battery capacity of a portable device. Its accuracy also falls within the desired specifications of the device. For these reasons, it is clear to see why the PA1616S had to be selected for this project. The following table summarizes the obtained data of every considered GPS module.

Table 4: Global Positioning System Hardware Comparison

Component	Accuracy	Current Consumption	Size	Price
PA1616D	±3m	29mA	16mm x 16mm x 6.7mm	\$20
PA1616S	±3m	20mA	16mm x 16mm x 4.7mm	\$25
NEO-M9N-00B	±2m	36mA	15.9mm x 12.2mm x 2.4mm	\$27
L96-M33	±2.5m	19mA	14mm x 9.6mm x 2mm	\$13

3.4: Power Supply

A critical component in this project is the power supply of the system. In order for the system to function, an appropriate amount of voltage and current needs to be supplied to each component. Additionally, since a pet collar is being designed the power supply should be rechargeable in order to develop a portable device that minimizes the need to repeatedly buy external power sources like batteries. When determining which type of rechargeable battery to use, important parameters must be considered. First, a small size is desired since a large device might be too heavy for a pet to handle and could make the pet collar too bulky. Additionally, a large power capacity is desired since it would reduce the amount of times the collar has to be taken off the pet in order to recharge the power supply; having a larger power supply is one of the easiest ways to increase the operational time of the system. Another feature to consider is the typical output voltage of the power supply. Since the voltage will have to be regulated to conform with the operating voltage of multiple components it is ideal to have a power supply that outputs a slightly higher than that of the component that requires the greatest potential difference. On the other hand, if the output voltage is too great, the output efficiency will significantly decrease which would be a detriment to the user of the device since they would have to charge the device more often.

3.4.1: Lithium-ion Batteries

Lithium-ion batteries are a common choice for electronic devices and usually have an output voltage of 3.7V. According to the Clean Energy Institute at the University of Washington [32] Lithium-ion batteries have an extremely high energy density. This allows them to condense a greater amount of energy into a smaller area which is beneficial to this project due to the limited size that a pet collar can be. Another benefit of lithium ion batteries is their availability. Lithium-ion batteries are available in a variety of sizes which provides the opportunity to select the size of battery best suited for the project. Another thing to note about lithium-ion batteries is they have a greater efficiency when compared to other rechargeable batteries. Having greater efficiency allows these batteries to maximize the space they require and waste less of the energy stored within them. Another important thing to consider when viewing lithium-ion batteries is how they typically discharge. Lithium-ion batteries generally begin operating at a voltage above their listed operating voltage and then reach their operating voltage as they discharge. They maintain a constant voltage for a period of time until they reach near the end of their capacity, at which point the output voltage of the lithium-ion battery quickly drops to zero. This is beneficial since it is easier to maintain a constant output for the longest amount of time if the battery is operating near its listed output voltage for a longer amount of time.

3.4.2: Nickel Metal Hydride Batteries

Nickel metal hydride batteries are another option when selecting rechargeable batteries. On average, a nickel metal hydride battery outputs 1.2V but many can be combined in order to obtain higher output voltages. This may increase the difficulty of obtaining the voltage that many sensors require for optimal operation. When compared to lithium-ion batteries, they have a smaller energy density causing them to take up a larger amount of area to provide the same output. Nickel metal hydride batteries are also less energy efficient when compared to lithium-ion batteries which results in more of the stored energy being wasted. When comparing the cost of nickel metal hydride batteries and lithium-ion batteries, it can be seen that nickel metal hydride batteries cost less to provide the same capacity in mAh. Nickel metal hydride batteries also discharge in a similar way to lithium-ion batteries. Like lithium-ion batteries, they start outputting a voltage above what the battery lists and then it quickly drops to its operating voltage and maintains a steady state at that value. Once it reaches near the end of its capacity, the voltage output of the battery rapidly decreases to zero. Like the lithium-ion battery, this provides the benefit of having a longer usable period of time since the device will not be able to operate when the voltage drops to a certain level.

3.4.3: Nickel Cadmium Batteries

Nickel cadmium batteries are the final option of rechargeable batteries considered. Nickel cadmium batteries also typically output 1.2V but are generally combined in order to obtain higher output voltages. When compared to the other two types of rechargeable batteries, nickel cadmium batteries have the smallest energy density. This results in a larger battery being needed in order to obtain the same capacity as the other batteries considered. Nickel cadmium batteries are also less energy efficient when compared to lithium-ion batteries resulting in them having a smaller functional capacity. When

comparing the cost of batteries, nickel cadmium batteries sometimes have a higher cost when compared to nickel metal hydride batteries and a lower cost when compared to lithium-ion batteries. Nickel cadmium batteries also discharge similarly to both nickel metal hydride batteries and lithium-ion batteries which results in a similar amount of time they can be functionally used before dropping below a required output voltage.

3.4.4: Power Supply Final Comparison

The following table summarizes the data obtained regarding different available candidate rechargeable batteries. This data includes the typical voltage, energy density, and price of each type of battery discussed previously.

Table 5: Rechargeable Battery Comparison

Component	Typical Voltage	Energy Density	Price (400 mAh)
Lithium-Ion	3.7V	Highest	\$7
Nickel Metal Hydride	1.2V	Medium	\$2
Nickel Cadmium	1.2V	Lowest	\$1.5

Upon comparing the features of all the available rechargeable batteries, it can be seen that lithium-ion batteries would be the most beneficial battery type to use for this project. Lithium-ion batteries offer the greatest energy density and largest output voltage of all the rechargeable batteries considered. This would be largely beneficial due to the limited amount of space when building a pet collar. Having a greater energy density will also allow the collar to run for a longer amount of time before needing to be recharged. It can be noted that while the other batteries considered had a smaller cost, the specifications offered by lithium-ion batteries allow for the most optimal pet collar design.

3.5: Voltage Regulators

Voltage regulators must be incorporated into the project due to the various components and sensors that require different levels of potential difference to operate. Voltage regulators work by increasing or decreasing the output voltage supplied by a battery in order to achieve a desired output. Voltage regulators can be used to ensure that each component maintains a desired potential difference even in the face of voltage fluctuations caused by the battery as it slowly drains of energy. When determining what kind of voltage regulator to use, it is important to compare the efficiency of each option. When converting one voltage level to another, some energy may be lost as heat which could significantly reduce the functional use time of the device. Additionally, it is important to consider how voltage regulators may affect the power available to the circuit. Since energy can not be created out of nothing, if the voltage outputted by a battery is converted to that of a higher value, the total energy outputted by the circuit must remain the same or decrease. This could cause issues supplying an appropriate amount of energy to the project if the supply voltage is stepped up a significant amount.

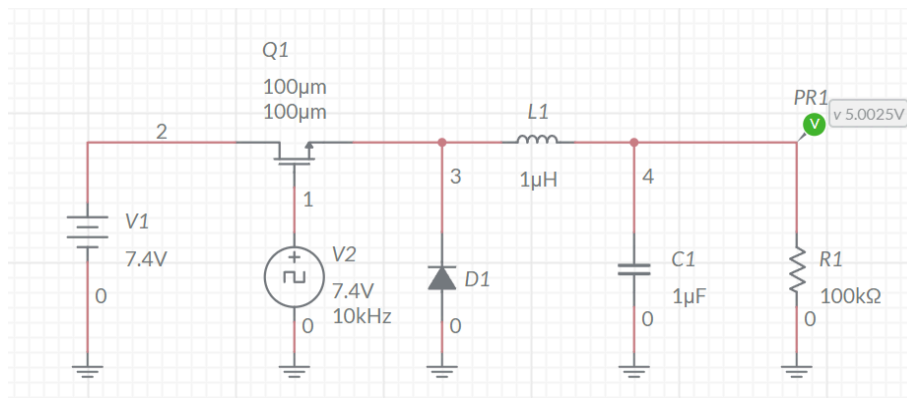
3.5.1: Linear Voltage Regulators

A linear voltage regulator takes a DC input voltage and converts that input voltage to a lower DC voltage. This regulation occurs by establishing a desired reference voltage in the circuit and then utilizing an operational amplifier to ensure the output has the same output voltage as the reference. By doing this, the circuit is able to maintain a constant output voltage even when changes in load impedance may occur. Since these regulators always convert the input voltage to a lower value, they can only be as efficient as the output voltage divided by the input voltage. When converting down in voltage, all the additional input power supplied to the circuit is lost as heat which can significantly impact the efficiency of the circuit. Additionally, the excess heat could cause damage to other components of the circuit depending on how much heat is generated. One benefit of linear voltage regulators is that they are affordable and easy to incorporate into a circuit. They also have a simple design when compared to other regulators and do not require the use of inductors which could add unnecessary noise to the circuit. Furthermore, linear voltage regulators are able to generate a constant output voltage which could be beneficial if components require an exact voltage to operate.

3.5.2: Switching Voltage Regulators

A switching voltage regulator takes an input voltage and either converts it to a higher or lower DC voltage. A switching voltage regulator operates in a slightly more complex way when compared to a linear voltage regulator. A switching voltage regulator generally operates with a clock signal turning off and on a MOSFET transistor in order to generate an average voltage at the appropriate level. The image below shows a simple design of the operation of a switching voltage regulator.

Figure 2: Switching Voltage Regulator



When the MOSFET transistor has a voltage applied to the gate, the inductor and capacitor are allowed to charge up allowing the load of the circuit to reach the desired potential difference. When power is no longer applied to the gate of the MOSFET transistor, the inductor and capacitor discharge allowing the load to maintain the same potential difference. By doing this, a switching voltage regulator is able to obtain a greater efficiency when compared to a linear voltage regulator since the battery does not

have to supply power 100% of the time. One downside of this approach is that the DC output of the regulator constantly oscillates slightly. Additionally, in order to maintain a near constant output, an inductor must be incorporated into the circuit which can add noise to the circuit. The need for an inductor may also pose a problem for this project due to the generally large size of inductors compared to other circuit components.

3.5.3: Voltage Regulator Final Comparison

When comparing voltage regulators, the most important factor to consider for this project is their efficiency at converting one voltage to another voltage. Due to the extremely limited power supply that will be available for the project, it is important to be as efficient as possible and therefore the switching voltage regulator is the best option for this project. While the switching voltage regulator may be harder to work with and includes an inductor, the ability for it to conserve some power when converting voltages provides it an edge over the linear voltage regulator even though it may slightly increase the size of the system and add noise.

3.5.4: Voltage Regulator Integrated Circuit Selection

Most of the chosen components can operate at a potential difference of 3.3V which indicates that a switching regulator that converts the input voltage to 3.3V will be required for the design. The operating voltage of a lithium-ion battery is typically 3.7V and 4.25V when fully charged meaning the chosen voltage regulator must be able to convert input voltages in those ranges down to the required operation voltage. Texas Instruments WEBENCH power designer [33] can be used to aid in obtaining the optimal switching regulator for this project by providing designs based on the stated input and output parameters.

When the desired input and output parameters are inputted into the WEBENCH power designer, the software outputs designs that fit those parameters and indicates the shown circuits efficiency, cost, and size. The most important parameters to consider for this project are the size and efficiency of the circuit since having a smaller size will allow greater room for other components in the design and having a greater efficiency will allow the battery size to be minimized. One thing to keep in mind though is that if the design is too small it may prove difficult to solder when the PCB needs to be constructed. Furthermore, minimizing the number of pins on the switching voltage regulator would be beneficial since it would allow a greater amount of space between pins when soldering.

3.5.5: TPS62867RQYR Buck Switching Regulator

When viewing designs that maximize these desired parameters, it can be seen that the TPS62867RQYR buck switching regulator would be an optimal choice for this project. The TPS62867RQYR regulator offers a 97.6% efficiency and only takes up an area of 4.16 square millimeters before other necessary components are added. This allows for a majority of the energy stored inside the power supply to be utilized and ensures that it can fit within the space of a pet collar. Additionally, the design only uses one 220nH inductor which minimizes the size the inductor must take up within the circuit. One downside of this design is that the integrated circuit it uses has nine pins meaning that it must be precisely placed when soldering. This could cause issues later on in the project due to the necessity of this component's successful operation in order for every component in the

device to work. The TPS62867RQYR integrated circuit also costs a large amount of money at \$2.53 which may unnecessarily increase the cost of the project.

3.5.6: TPS564257 Synchronous Buck Converter

The TPS564257 synchronous buck converter would also be an ideal choice to integrate into our project's design. Compared to the previous switching regulator considered, the TPS564257 has a far simpler design. This voltage regulator utilizes only six pins which would allow for the device to be more easily soldered onto a printed circuit board due to each pin having a greater amount of distance between them. Another benefit of this integrated circuit is that it only takes up an area of 1.33 cubic millimeters which would aid in reducing the size of components on the pet collar. Additionally, this voltage converter is the most affordable of all, only costing \$0.62. Some downsides of this integrated circuit are that the design given by WEBENCH power designer only offers a 93.8% efficiency which would result in the battery being drained faster. Additionally, the design requires a larger 3.3 μH inductor which would increase the size of the complete design. Furthermore, even though the integrated circuit is smaller, the complete circuit requires more components than the previous design making this integrated circuit take up a larger amount of space.

3.5.7: TPS62823DLC Step-Down Converter

A balance between the two designs is the TPS62823DLC step-down converter. This integrated circuit utilizes eight pins in order to achieve the desired output voltage. Additionally, it has an efficiency in between the efficiencies of the two designs at 95.2%. This allows for a relatively simple design while still allowing for most of the lithium-ion batteries capacity to be utilized. The TPS62823DLC offers a relatively small size of 3.09 cubic millimeters and provides a decent amount of distance between each of the device's pins. One benefit of the design provided by WEBENCH power designer is it only uses a 470 nH inductor which is incredibly small. This greatly minimizes the size that must be dedicated to the inductor when implementing this circuit. Furthermore, the design given utilizes very few components which would further decrease the size this circuit takes up. This integrated circuit can also be purchased for only \$1 which would greatly minimize the cost when implementing it onto the finished project.

3.5.5: Voltage Regulator Integrated Circuit Final Comparison

The following table summarizes the data obtained for the comparisons between different available switching voltage regulator integrated circuits. Upon comparing different switching voltage regulator integrated circuits, it was decided to use the TPS564257 synchronous buck converter. This integrated circuit was chosen due to its simple design and low cost. Even though this design has the lowest efficiency of all the integrated circuits analyzed, it was deemed a necessity to choose the easiest circuit to solder onto the printed circuit board. The reason for this is because having a functional voltage regulator is required in order to ensure the proper operation of every other component. Having to solder less pins will greatly speed up the soldering process and will ensure that this important component is correctly integrated into the finalized design.

Table 6: Voltage Regulator Integrated Circuit Comparison

Component	Efficiency	Number of Pins	Cost	Size
TPS62867RQYR	97.6%	9	\$2.53	1.6mm x 2.6mm x 1mm
TPS564257	93.8%	6	\$0.62	1.3mm x 1.7mm x 0.6mm
TPS62823DLC	95.2%	8	\$1.00	1.6mm x 2.1mm x 1mm

3.6: Power Management Integrated Circuit

In order to ensure the battery is charged to an appropriate level and to extend the usable life of the battery, a power management integrated circuit should be included in the design. A power management integrated provides an important role in the fact that it can ensure that a battery is being charged with the optimal amount of current and cut off the supply of energy to the circuit when the battery is fully charged. It is able to carry out these features by monitoring the voltage level of the battery and acting as a constant current source while the battery is charging. Most batteries start at a voltage that is above their typical output voltage, in the case of lithium-ion batteries, this voltage is around 4.2 to 4.25V. When the power management IC determines that this potential difference has been reached, it is able to reduce the amount of power being supplied to the battery which increases the safety of the device and limits wasted energy. The desired features for an effective power management integrated circuit are a regulation voltage of 4.2V and a small size due to the size limitations required when building a pet collar.

3.6.1: Microchip Technology MCP73811/2T-420I/OT

In order to accurately obtain information for the MCP73811T-420I/OT integrated circuit, its datasheet by microchip technology was utilized [34]. The MCP73811T-420I/OT charge management controller provides a 4.2V voltage regulation which is optimal for the selected lithium-ion battery. Additionally, it allows the selection of a charge current between 85 mA and 450 mA enabling it to effectively charge batteries that are over 170 mAh in capacity. The charge management controller ensures an operation of providing a constant current until the regulation voltage of 4.2V is met, at that point the controller switches its mode of operation to a constant voltage mode to ensure that the circuit is not over charged. Additionally, the specified charge management controller includes a thermal shutdown within the design to end charging if the temperature of the device exceeds a significantly large temperature. A final benefit of this charge management controller is its affordable price of only \$0.69 and its small size of only 7.254 cubic millimeters.

3.6.2: Texas Instruments BQ25101YFPR

In order to accurately obtain information for the DQ25101YFPR integrated circuit, its datasheet by Texas Instrument Incorporated was utilized [35]. The BQ25101YFPR single

cell lithium-ion battery charger integrated circuit provides a regulation voltage of 4.2V. Additionally, this integrated circuit allows input voltages from -0.3V to 30V which allows it to work with a wide range of chargers. This integrated circuit also provides a range of output currents between 10 mA and 250 mA allowing it to work with batteries with extremely small capacities which could provide a benefit for this project. The BQ25101YFPR also implements various additional protections into its design including thermal regulation, overvoltage protection, and short circuit protection which could aid in making the device safer for users. The battery also applies different stages depending on the current charge of the battery to ensure the battery is not overly charged and to allow the battery to have a greater usable lifespan. This integrated circuit also comes at an extremely small size of 0.73 cubic millimeters which would be beneficial in reducing the area it needs within the smart collar. One downside of this integrated circuit is it costs \$1.75 which is over double the price of the previous integrated circuit.

3.6.3: STMicroelectronics STC4054GR

In order to accurately obtain information for the STC4054GR integrated circuit, its datasheet by STMicroelectronics was utilized [36]. The STMicroelectronics STC4054GR battery charger integrated circuit also provides a 4.2V regulation voltage to ensure lithium ion batteries reach the appropriate charge level. This integrated circuit allows a selection of the desired charge current up to a maximum of 800mA which allows it to charge a wide range of lithium ion battery sizes. Additionally it can handle input voltages from -0.3V to 10V allowing it to work with most chargers. Compared to the previous integrated circuits considered, the STC4054GR features an extremely simple design requiring only one external capacitor to operate effectively. Like the other integrated circuits considered, this IC completes charging in multiple stages where it first acts as a constant current source and becomes a constant voltage source over time to increase the usable life of the battery. This IC also comes at a relatively small size, only requiring 5.104 cubic millimeters of space. Unfortunately, when compared to the other integrated circuits considered, this one costs the most at \$2.01.

3.6.4: Power Management Integrated Circuit Final Comparison

The following table summarizes data obtained when comparing different power management integrated circuits. The MCP73811/2T-420I/OT was chosen due to its affordable cost and due to it meeting all of the required needs for the design. When comparing all of the designs, all the integrated circuits were approximately equal in size only differing by a few cubic millimeters. Additionally, each integrated circuit is able to provide the appropriate regulation voltage. The MCP73811/2T-420I/OT wide range of output currents and affordable cost will allow for great configurability and will allow for the purchase of multiple components which will aid in testing in the event that one of the integrated circuits breaks.

Table 7: Power Management Integrated Circuits Comparison

Component	Regulation Voltage	Dimensions	Price
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MCP73811/2T-420I/OT	4.2V	3.1mm x 1.8mm x 1.3mm	\$0.69
BQ25101YFPR	4.2V	0.5mm x 1.61mm x 0.91mm	\$1.75
STC4054GR	4.2V	1.1mm x 1.9mm x 2.9mm	\$2.01

3.6.5: Power Management Integrated Circuit Changes

Due to increased current needs while designing the project, it was determined that the battery size would need to be increased and thus the battery would need to be charged at a faster rate. To accomplish this, the MCP7381/2T-420I/OT was replaced with the MCP73833 from microchip technology. The MCP73833 features a programmable current like the MCP7381/2T-420I/OT but is able to charge at a rate of up to 1A. It has a relatively simple implementation in the circuit and only requires a couple of resistors and a thermistor to implement. It also maintains a small size making it desirable for our project. For these reasons, it was chosen to replace our original power management integrated circuit.

3.7: Indoor Location and Fencing System Overview

A desired feature in this project is an Indoor Location and Fencing System. This system will allow the collar user to detect when their pet has passed a given location in their home, thus allowing them to track their pet's movement between locations where the system is installed. Furthermore, an option available to the user will be to automatically turn on the training vibration upon passing the point-of-installation, so that the system also serves as an invisible fence that can deter pets from entering a room or other space. This system will operate using a freestanding optical receiver with a transmitter attached to the pet's collar to detect when a pet has passed the point-of-installation. The system should accurately detect the collar passing the point-of-installation at speeds of 2 miles per hour or less with a 90% accuracy, and it should not report that the collar has passed when it is not present. The system will also be able to uniquely identify which pet has passed a point-of installation and which point-of-installation the collar has passed if receivers are in use by a single user. As is true with other components in our system, the transmitter components must be of a small size and weight since they will be on the pet's neck. Another feature that is desirable is a fast response time so that the collar can be detected if it passess by the point-of-installation at higher speeds.

3.8: Infrared Transmitter Light Source Overview

Choosing a suitable transmitter light source will be crucial to the functioning of the indoor supplementary location system, as this component will be solely responsible for generating the pulsed optical signal at the point of installation which will provide information to the receiver. The chosen light source must be eye-safe and emit light within the aforementioned wavelength range of 900 nm to 2000 nm for reasons discussed in Chapter 9. It also must be operable at approximately 13°C to 30°C, so that it may work as intended within homes in a variety of climates. Furthermore, it must be capable of producing light of sufficient irradiance (power per unit area) to be received by the chosen photodetector. It is also preferable for the light source to be of a small size to facilitate

fitting the transmitter easily on the collar, though a larger emission area would reduce the system's vulnerability to misalignment. It also is preferred that the light source have low power consumption to facilitate cost-effective use. Two technologies that were considered for this light source were laser diodes and LEDs.

Furthermore, the selection of a suitable light source was revisited in Senior Design 2. While a light source with a smaller emission angle was sought originally to facilitate collimation, this design failed. Testing revealed that collimation of light from the transmitter light source was not possible or practical, and the emission angle of the original light source even without collimating lenses was too narrow to yield a spot incident on the receiver large enough to be robust against misalignment. Thus, LEDs with a larger emission angle ($> 60^\circ$) and a comparable irradiance to the originally selected LED were investigated, and a suitable revised candidate was chosen.

3.8.1: Laser Diode Overview and ML925B45F

Laser diodes utilize a semiconductor material that lases when supplied with adequate electrical current. That is, they emit coherent light, which is light that is nearly monochromatic light with waves identical in phase. Because of the coherence of the light that they emit, a beam from a laser light source can be made to travel highly directionally. That is, the beam can propagate for long distances without a change in beam size. This characteristic offers the potential for the transmitter light source to achieve a high irradiance, as it can concentrate the output power into a narrow beam. This high irradiance would be advantageous for our application as it would ensure that the photodetector receives the signal when the system is properly aligned.

However, there are some disadvantages to using a laser diode in this project. A drawback of using a laser diode is that laser light is often not eye-safe, especially at high output powers. Thus, in order to remain within our health and safety constraints, the choice of laser diodes would be thus be restricted to those of wavelengths considered so the choice of laser diodes would be greatly restricted to those that emit wavelengths of lower risk to eye safety, which are generally agreed to be those longer than $1.4 \mu\text{m}$, and would have to be operated within acceptable exposure limits per IEC 60825-1 [37]. Furthermore, laser diodes in an eye-safe wavelength range from leading manufacturers are quite costly. The least expensive laser diode longer than $1.4 \mu\text{m}$ sold by Thorlabs, one leading supplier of optical components, costs \$56.48 [38], while the least expensive laser diode from Newport, another leading supplier of optical components, costs \$100 [39].

Much of the utility of laser diodes comes from the narrow spectral bandwidth (a few nanometers) of the light that they emit. However, this narrow spectral bandwidth is unnecessary for the application, as photodetectors can utilize light from a source with much wider spectral bandwidth than that produced by laser diodes and produce an electrical signal of similar integrity given the dissimilarity of the wavelength to be emitted by the light source with the wavelength of typical indoor ambient lighting.

Still, if a laser diode were to be used, Mitsubishi's ML925B45F would be a good candidate. It emits 5mW of optical power at a peak wavelength of 1550 nm with a spectral bandwidth of 1.5 nm. It's beam divergence is 25 to 30 degrees, depending upon

orientation during measurement, and is operable at temperature ranging from -40°C to 85°C. It consumes 33 mW of power (1.1 V * 30 mA) under typical operation. The diameter of the emitting facet is 1 mm, while the device has a diameter of 5.6 mm and a thickness of 3.3 mm [40].

3.8.2: LED Overview

LEDs also utilize a semiconductor material to emit light. However, they emit incoherent light. That is, they emit light that has a larger spectral bandwidth than the nearly-monochromatic light emitted by a laser source, and the waves are not in phase, which makes the light source less directional. Thus, light emitted by an LED cannot propagate as a collimated source for as long as a laser source without loss due to divergence.

However, the advantages of using an LED in this project over a laser diode are great. LEDs have a much better eye-safety profile than laser diodes, as they are generally accepted to be eye-safe at visible and infrared wavelengths [41]. There is also an abundance of inexpensive LEDs available on the market (under \$10 per light source), making them a more cost-effective solution for this project. Furthermore, while the spectral bandwidth of LEDs is not as narrow as that of a laser, there are still LEDs available with a spectral bandwidth (~50 nm) narrow enough that most incident light could be transmitted through commercially available bandpass filters that transmit a spectral bandwidth of similar size or longpass filters that block visible light that would both serve to remove environmental noise from ambient light. Furthermore, light of the aforementioned spectral bandwidth in the required wavelength range will not undergo significant chromatic dispersion in NBK-7 (the refractive index changes by 0.015 from 900 nm to 2000 nm), which is the material of most cost-effective optical components for this wavelength range [42].

3.8.3: IR333-A

One LED that would be suitable for this project is EVERLIGHT's IR333-A. Its peak emission wavelength is 940 nm with a spectral bandwidth of 45 nm. Like the ML925B45F laser diode, it is operable at -40°C to 85°C. Its typical output irradiance when supplied with a current of 100 mA (the manufacturer's recommended maximum for continuous wave use) is 85 mW/sr. The approximate output power of one LED can be calculated knowing that the FWHM viewing angle of the LED within the manufacturer casing is 20°, and the solid angle in sr, Ω , of a spherical cap subtending an angle 2θ is:

$$\Omega = 2\pi (1 - \cos\theta)$$

Thus, the LED's emission subtends approximately $\Omega = 2\pi (1 - \cos(10^\circ)) = 0.095$ sr, and it emits approximately 8.11 mW (0.095 sr*85 mW/sr) of optical power when supplied with 100 mA of current. While this amount of optical power is higher than the ML925B45F laser diode, it is important to consider that there will be more loss of power during propagation if an LED is used than if the laser diode is used.

Like the ML925B45F laser diode, the IR333-A LED is small in size, with a diameter of 5.9 mm and a thickness of 8.6 mm. Its typical power consumption when supplied with a 100 mA current is 140 mW (1.4 V *100 mA) [43].

3.8.4: OED-EL-1L1

Another LED that would be suitable for this project is Lumex's OED-EL-1L1. Like the IR333-A LED, the OED-EL-1L1's peak emission wavelength is 940 nm with a spectral bandwidth of 45 nm. It is operable at temperatures between -25°C to 85°C. Its typical output irradiance when supplied with a current of 100 mA is 120 mW/sr. Given that the FWHM viewing angle of the LED within the manufacturer casing is also 20° it emits approximately 11.4 mW (0.095 sr*120 mW/sr) of optical power when supplied with 100 mA of current.

The diameter of this device is 5.9 mm, and it is 8.7 mm thick. Its typical power consumption when supplied with a 100 mA current is 140 mW (1.4 V *100 mA) [44].

3.8.5: OED-EL-1L2

After it was determined that the transmitter LED's emission angle needed to be larger, Lumex's OED-EL-1L2 was considered as a suitable revised LED choice for this project. The OED-EL-1L2's peak emission wavelength is 940 nm with a spectral bandwidth of 45 nm. It is operable at temperatures between -25°C to 85°C. Its typical output irradiance when supplied with a current of 50 mA is 60 mW/sr, but it could potentially yield more output irradiance if supplied with the maximum safe current of 100 mA. The FWHM viewing angle of the LED within the manufacturer casing is 60°, so its emission subtends approximately $\Omega = 2\pi (1 - \cos(30^\circ)) = 0.84$ sr. Thus, it emits approximately 50.4 mW (0.84 sr * 60 mW/sr) of optical power when supplied with 50 mA of current.

The diameter of this device is 5.9 mm, and it is 8.7 mm thick. Its typical power consumption when supplied with a 100 mA current is 120 mW (1.2 V *100 mA) [45].

3.8.6: L1I0-A940090020000

Another suitable revised LED choice for this project is LUXEON's L1I0-A940090020000. The peak emission wavelength of this LED is 950 nm, and its bandwidth is 36 nm. It is operable at temperatures between -40°C to 125°C. Its typical output irradiance when supplied with a current of 100 mA is 74 mW/s (interpolated from the current-irradiance relationship given in the datasheet). The FWHM viewing angle of the LED within the manufacturer casing is 90°, so its emission subtends approximately $\Omega = 2\pi (1 - \cos(45^\circ)) = 1.84$ sr. Thus, the LED emits approximately 136 mW (1.84 sr*74 mW/sr) of optical power when supplied with 100 mA of current.

The diameter of this device is 5.9 mm, and its thickness is 8.7 mm. Its typical power consumption when supplied with a 100 mA current is 290 mW (2.9 V *100 mA) [46].

3.8.7: Transmitter Light Source Final Comparison

The following table summarizes the specifications of the transmitter light sources considered for this project. Since all potential transmitter light sources compared were of a similar size and operate within an acceptable temperature and wavelength range, power consumption, maximum output irradiance, and cost were the primary factors first weighed in choosing an LED.

Table 8: Transmitter Light Source Comparison

Component	Emission Wavelength	Emission Angle	Typical Output Irradiance, $I_f = 100 \text{ mA}$	Power Consumption ($I_f = 100 \text{ mA}$)	Price
ML925B45F *measurement taken with $I_f = 30 \text{ mA}$	1500 nm \pm 0.75 nm	25-30	23.35 mW/sr*	33 mW*	\$56.48
IR333-A	940 nm \pm 22.5nm	20	85 mW/sr	140 mW	\$0.75
OED-EL-1L1	940 nm \pm 22.5nm	20	120 mW/sr	140 mW	\$0.43
OED-EL-1L2 *measurement taken with $I_f = 50 \text{ mA}$	940 \pm 22.5nm	60	60 mW/sr*	120 mW	\$0.57
L1I0-A9400900200 00	950 nm \pm 36 nm	90	74 mW/sr	290 mW	\$4.06

In balancing high maximum output irradiance, low cost, and power efficiency, it was originally decided that the OED-EL-1L1 would be used. However, upon testing this LED and discovering the Indoor Location and Fencing System was not sufficiently robust against transmitter light source misalignment, the selection of a suitable light source was revisited in Senior Design 2. Given that the photodetectors received sufficient optical power during testing when the system was perfectly aligned, an LED with a wider emission angle ($> 60^\circ$) and comparable irradiance to the OED-EL-1L1 was sought. Furthermore, with the selection of other components, the previous requirement for low power consumption became more definitive. Specifically, the maximum possible current consumption for the LED was limited to 146 mA. The OED-EL-1L2 was ultimately chosen given its relatively high irradiance at 50 mA, low cost, and larger emission angle.

3.9: Photodetector Overview

To convert light incident on the receiver into light into an electrical signal that can be processed, utilizing a photodetector is necessary. The chosen photodetector should have a high responsivity, or ratio of current output to optical power input [47], as it must be able

to convert input light into an electrical signal of sufficient amplitude to facilitate a high signal-to-noise ratio. Furthermore, the chosen photodetector should have an acceptably fast rise time and fall time, so that the pulses of optical signal from the transmitter light source are distinguishable from each other, and the transmitter light source used can be uniquely identified by the frequency of pulses produced. It should also have minimal dark current, or current through the photodetector in the absence of light [48], such that the signal has less noise. It is also preferable that the photodetector have a large active area so that the system is more robust against misalignments. Two technologies under consideration for this application are the photoresistor and photodiode.

Photoresistors, also referred to as photoconductors, are fabricated from semiconductor materials whose resistance decreases when exposed to incoming light [47]. Therefore, an incoming optical signal can regulate the electrical current passing through the photoresistor and the voltage drop across the resistor, facilitating the conversion of this optical signal into an electrical signal conveyed through variation in current or voltage, provided that an external voltage is applied to the resistor.

In this project, using photoresistors would be advantageous in that they can provide high levels of photoconductive gain. That is, they can be quite sensitive to incoming light [47]. However, a disadvantage of employing a photoconductor in this project is that they have limited ability to respond to high frequency modulation. The photocurrent yielded in response to a modulated optical signal is generally proportional to:

$$\left(1 + \frac{e^{j\omega t}}{1 + j\omega\tau} \right)$$

Here, ω is the angular frequency of the modulated optical signal, t is the time in seconds, and τ is the carrier recombination lifetime, which is a property determined by the semiconductor material used. Furthermore, the response time of a photoresistor is slower than that of a photodiode, which makes it less suitable than a photodiode to detect high frequency signals [47]. Knowing this, if a photoresistor were used in this project, a modulated optical signal from the transmitter light source would be limited to lower frequencies where the photoresistor could provide sufficient output photocurrent. The response of a photoresistor is approximately logarithmic to incident irradiance [47], which makes it less suitable for this application, since its response to low levels of environmental noise would be larger proportionately than its response to higher levels of light from the incident optical signal produced by the transmitter light source. Additionally, while photoresistors in general are inexpensive and widely available, photoresistors with a peak sensitivity near 940 nm do not appear to be widely commercially available.

On the other hand, photodiodes are fabricated from semiconductor PN or PiN junctions which produce a current and/or voltage when exposed to light. Despite a lesser responsivity than photoresistors in many cases, photodiodes are generally better suited to high frequency applications than photoresistors, as they have faster response times and do

not experience the same attenuation of photocurrent amplitude as a photoresistor in response to a high frequency signal. They can operate in either photovoltaic mode or photoconductive mode. In photovoltaic mode, no bias voltage is applied to the photodiode, which is connected to a load with high impedance. The output photocurrent in this configuration is a logarithmic function of the incident irradiance, which would yield similar challenges to those present if the photoresistor was used. However, in photoconductive mode, a reverse bias voltage is applied. The output photocurrent in this configuration is now a linear function of the incident irradiance, which would be much more suitable for this application, since the response to the incident optical signal produced by the transmitter light source would be larger proportionately than the response to environmental noise [47].

Given its linear response to incoming light and its superior ability to respond to high frequency signals, the photodiode in photoconductive mode would be best suited to this application. Furthermore, to make the signal easier to detect, the photodiode could be placed in a circuit where its output is connected to a transimpedance amplifier—a common photodiode circuit configuration [47]. This transimpedance amplifier would serve to convert the photocurrent to a voltage with sufficient gain for usability.

3.9.1: VEMD2704

One photodiode that may be suited to this project is the VEMD2704 from Vishay Semiconductors [50]. This photodiode is a silicon surface mount PiN photodiode. The responsivity given for this photodiode is $1.17 \mu\text{A}$ given an incident irradiance of 0.1 mW/cm^2 . To facilitate comparison with other photodiodes, this value was converted into units of A/W knowing that the active area of the photodiode is 1.51 mm^2 , yielding a responsivity of 0.78 A/W . The measured dark current with a reverse bias voltage (V_r) of 10 V is 0.03 nA , and the measured rise time and fall time with $V_r = 5 \text{ V}$ are both 70 ns .

3.9.2: SFH 203 PFA

Another photodiode under consideration is OSRAM's SFH 203 PFA [51]. This component is a PiN photodiode housed in through-hole packaging. Its responsivity of 0.62 A/W was measured by the manufacturer using 850 nm light. However, the component's relative sensitivity at 940 nm is approximately the same as that at 850 nm , so its responsivity at 940 nm can also be taken as approximately 0.62 A/W . The measured dark current at $V_r = 20 \text{ V}$ is 1 nA . During comparison with other photodiodes, where this measurement was taken with $V_r = 10 \text{ V}$, it should be noted that the dark current increases with reverse bias voltage, so the dark current at $V_r = 10 \text{ V}$ is most likely less than the measured value. The rise time and fall time of this photodiode are both 5 ns when $V_r = 20 \text{ V}$, though this measurement is most likely inaccurate at 5 V , which was the reverse bias voltage used during this measurement for all other photodiodes under comparison. The active area is 1 mm^2 —the smallest active area of the photodiodes considered.

3.9.3: BPW 34 S

The BPW 34 S, which is a silicon surface mount PiN photodiode manufactured by OSRAM, may also be a suitable option for this project [52]. The responsivity given at 850 nm is 0.62 A/W . Knowing that this photodiode has 90% relative spectral sensitivity

at this wavelength while the relative spectral sensitivity at 940 nm appears to be 97%, the responsivity at 940 nm was calculated to be 0.67 A/W. The measured dark current with $V_r = 10$ V is 2 nA, and the measured rise time and fall time with $V_r = 5$ V are both 20 ns. The active area of the photodiode is 7.02 mm².

3.9.4: SFH 2200

The SFH 2200 is a silicon surface mount PiN photodiode, manufactured by OSRAM, which may be suitable for this project [53]. Its responsivity at 940 nm is 0.7 A/W. The measured dark current with $V_r = 10$ V is 1 nA, and the measured rise time and fall time with $V_r = 5$ V are both 40 ns. Like the BPW 34S, the SFH 2200 has an active area of 7.02 mm².

3.9.5: Photodetector Final Comparison

The following table summarizes the specifications of the photodetectors considered for this project. As was stated earlier, the main parameters of importance to consider in choosing a photodiode are responsivity, rise time and fall time, active area, and dark current.

Table 9: Photodiode Comparison

Component	Responsivity at 940 nm	Rise Time ($V_r = 5$ V)	Fall Time ($V_r = 5$ V)	Dark Current ($V_r = 10$ V)	Active Area	Price
VEMD2704	0.78 A/W	70 ns 5V	70 ns	0.03 nA	1.51 mm ²	\$0.83
SFH 203 PFA *measurement taken with $V_r = 20$ V	0.62 A/W	5 ns*	5 ns*	1 nA*	1 mm ²	\$1.00
BPW 34 S	0.67 A/W	20 ns	20 ns	2 nA (10 V reverse bias)	7.02 mm ²	\$1.13
SFH 2200	0.70 A/W	40 ns	40 ns	1 nA	7.02 mm ²	\$1.39

All of the photodiodes under comparison are incredibly cost-effective and do not show a significant difference in cost since a large volume will not be needed. The SFH 2200 was chosen since it balances a relatively high responsivity, fast rise and fall time, and low dark current in comparison to the other photodiode candidates. Furthermore, it has the largest active area of the photodiodes under consideration, which will facilitate the detection of a signal should it be incident on the receiver off-axis.

3.10: Filter Overview

A filter will be needed in front of the receiver's photodetector to absorb or reflect ambient light (especially from visible indoor light source) in front of it that would otherwise contribute environmental noise to the optical signal received by the photodetector. Specifically, the filter must block (that is, have a transmittance close to 0%) light of wavelengths from 450 nm to 750 nm, as these are the most commonly emitted wavelengths by indoor light sources, though it would be preferable that the filter block the transmission of wavelengths up to approximately 900 nm in order to block as much environmental noise as possible while having high transmittance of light at wavelengths within the spectral bandwidth of the transmitter light source to the photodetector.

It is also preferable that the filter is thin so that it can be easily implemented into the system. Furthermore, having a thinner filter would minimize the longitudinal shift of the location of the focal point on the photodetector due to the refraction of transmitted light.

In an ideal setting, the chosen filter should have the most regular surface possible, as poor surface quality would cause unanticipated scattering of light and irregular diffraction patterns that could cause loss of the optical signal at the receiver. Surface quality is communicated by manufacturers as a scratch-dig specification. The first number in the specification indicates the width of surface scratches in 10ths of a micron, and the second number in the specification communicates the maximum diameter of digs in the surface in 100ths of a millimeter [54]. However, keeping in mind our manufacturing constraints, it is likely that the filter surface will obtain additional scratches beyond those it had at the time of manufacture, since we are not capable of assembling our project in a cleanroom environment. Also, components with a lower scratch-dig specification are much more costly than those with more tolerance than scratches and digs. To balance this preference for high surface quality with these other factors, a filter with a scratch dig specification of 80-50 or lower will be allowable, as this specification is considered acceptable for commercial use in low precision applications [55].

Two technologies under consideration for this application are bandpass filters, which only transmit light within a specific wavelength range, and longpass filters, which only allow the transmittance of light longer than a specified wavelength.

Utilizing a bandpass filter would be the most effective option in blocking environmental noise as it would limit transmitted wavelengths to the narrow spectral bandwidth produced by the transmitter light source. However, these filters are extremely costly. Bandpass filters that meet the criteria for this project appear to cost \$85 at minimum from reputable manufacturers [56], [57]. On the other hand, while a longpass filter would transmit most light of wavelengths longer than the cutoff wavelength, which would create the possibility of environmental noise from additional infrared light sources, indoor light sources primarily emit visible light. Thus, the cost-savings from using a lowpass filter greatly outweighs the slight additional reduction in noise that would be attained by using a bandpass filter.

3.10.1: SCHOTT RG850

One filter considered for this project was the SCHOTT RG850 from Edmund Optics [58]. This filter is a colored glass longpass filter with a cut-on wavelength of 850 nm. At wavelengths within its passband, which includes wavelengths within the 920 nm to 960 nm range, the transmittance is 97%, while its transmittance between the wavelengths of 400 nm to 750 nm is approximately 2%. The filter is 1 mm thick and its scratch-dig specification is 60-40.

3.10.2: 850FAP2500

Another filter that was considered for this project was Knight Optical's 850FAP2500 [59]. This filter is an acrylic longpass filter with a cut-on wavelength of 850 nm. Its transmittance between the wavelengths of 920 nm to 960 nm is around 92%, while its transmittance between the wavelengths of 400 nm to 750 nm is 0%. The filter is 1 mm thick. However, after speaking with the manufacturer to confirm this, the scratch-dig specification was not measured for this filter or any of the other acrylic filters manufactured by the company, making this a less viable candidate due to the unknown nature of this specification.

3.10.3: 5CGA-850

Newport's 5CGA-850 filter was also considered for this project [60]. This filter is a colored-glass alternative longpass filter with a cut-on wavelength of 850 nm. Its transmittance between the wavelengths of 920 nm to 960 nm is around 95%, while its transmittance between the wavelengths of 400 nm to 750 nm is 0%. The filter is 1.1 mm thick and its scratch-dig specification is 80-50.

3.10.3: HOYA IR85N

Between the first and second semesters of senior design, the filter initially chosen and received was lost, stolen, or otherwise misplaced. However, the loss of this filter gave the team the opportunity to reconsider the desired filter specifications with more knowledge of the system before ordering another. It was determined that using a filter with a diameter larger than the original 12.5 mm diameter would enable easier assembly of the system, as there would be more tolerance for misalignment of the filter with respect to the photodetectors as well as reduction of the filter aperture diameter due to its mount. However, none of the previous filter candidates were available with a larger diameter at a reasonable price point. Therefore, more filter candidates were sought out. The HOYA IR85N [61] was found to be a viable candidate. This filter is a colored glass longpass filter with a cut-on wavelength of 850 nm. At wavelengths within its passband, the transmittance is 97%, while its transmittance between the wavelengths of 400 nm to 750 nm is approximately 0%. The filter is 1 mm thick and has scratch-dig specification of 60-40. It is available with a diameter of 25.4 mm.

3.10.4: Filter Final Comparison

The following table summarizes the specifications of the longpass filters considered for this project. Due to space constraints, the cut-on wavelength is not listed, as it is 850 nm

for all considered filters. All filters initially compared were longpass filters of a similar thickness and cut-on wavelength. Thus, as was discussed previously, cost, acceptable surface quality, and transmittance in the desired stopband and passband are the most important factors to consider in deciding which filter will be used.

Table 10: Filter Comparison

Component	Diameter Considered	Thickness	Passband Transmittance (Approx.)	Stopband Transmittance (Approx.)	Scratch-Dig Specification	Price
SCHOTT RG850	12.5 mm	1 mm	97%	2%	60-40	\$32.00
850FAP2500	25 mm	1 mm	92%	0%	Unspecified	\$25.16
5CGA-850	12.7 mm	1.1 mm	95%	0%	80-50	\$38.00
HOYA IR85N	25.4 mm	1 mm	97%	0%	60-40	\$44.00

While the 850FAP2500 would be the most cost-effective option, its lack of a surface quality specification makes it unclear whether the product's surface is regular enough to be acceptable for this project. Thus, the SCHOTT RG850 or 5CGA-850 would be a better option for this project when considering this specification.

In using a lowpass filter as opposed to a bandpass filter, it is accepted that a minor level of environmental noise there may be received by the photodetector during operation. Therefore, while no transmittance in the stopband region is ideal, the miniscule level of transmittance in the stopband provided by the SCHOTT RG850 would still be acceptable for this project. This consideration in combination with its cost-effectiveness, superior surface quality, and superior passband transmittance compared to the 5CGA-850 made the SCHOTT RG850 the most suitable initial choice for this project.

However, given that the SCHOTT RG850 filter was lost between the first and second semester of work on this project, there was an opportunity to reconsider the choice of filter to be used in the final product. After initial prototype testing, it became clear that using a filter with a 12.5 mm diameter for this project would be difficult, as there would only be a 1 mm tolerance for centering this size filter on the active area of the photodiode panel, and some of the filter's aperture may also be covered by its mount, further decreasing this alignment tolerance. Therefore, it was decided that a filter with a larger diameter would be ordered. Since a SCHOTT RG850 filter was not available with a larger diameter and the other candidates would have been costly to order with at a larger diameter (Knight Optical's shipping cost would have more than doubled the order cost for the 850FAP2500 with 25 mm diameter), additional filter candidates were considered. The HOYA IR85N was found to have similar specifications as the SCHOTT RG850 and was available with a larger diameter of 25.4 mm at a reasonable price.

3.11: Collimating Lens (Indoor Location/Fencing System)

In the initial design of this system, a collimating lens was considered to prevent light from the transmitter light source from diverging so that a sufficient amount of power can be directed towards the receiver. While the collimating lens was later removed from the design, the following section includes the considerations made when choosing this collimating lens:

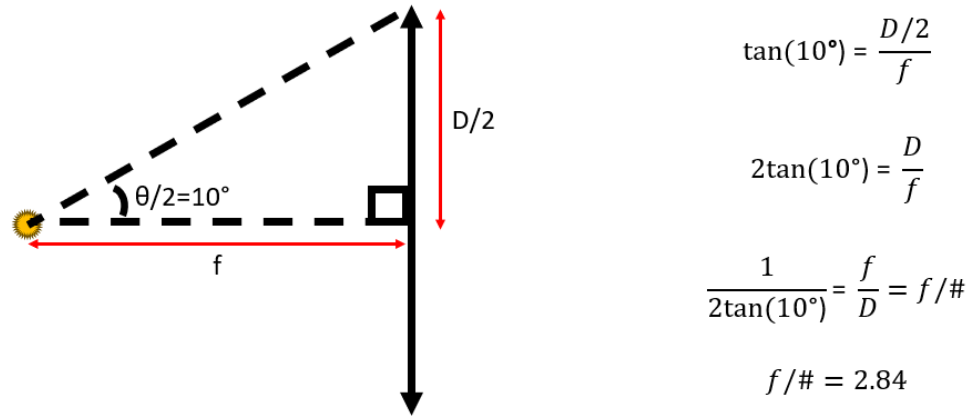
In a collimating lens system, the light source to be collimated is placed at a distance from the lens system equivalent to its focal length, which produces an “image” of the light source at infinity. That is, it causes light to propagate such that it does not converge or diverge, and instead, its propagation can be modeled as rays that travel parallel to one another. It is important to consider that ideal collimation could only occur when using an infinitesimally small light source in a setting where diffraction is not present. However, given that the minimum distance of propagation for light from the transmitter is 1 m, some level of divergence is still acceptable.

Important for this system is using a lens system with approximately the correct f-number ($f/\#$) in order to collimate as much light as possible from the transmitter light source. The $f/\#$ of a lens is the ratio of its focal length to its diameter. Knowing that the light source will be placed at the focal length of the lens and given the viewing angle of the light from it, the $f/\#$ can be calculated to ensure that light subtending the entire viewing angle is collimated by the lens.

Given that the viewing angle of the lens is 20° , the required $f/\#$ can be calculated trigonometrically as shown in Figure 7, where f is the focal length of the lens and D is the lens diameter.

Given this calculation, the collimating lens should be of an $f/\#$ close to 2.84. However, given that a lens of this exact $f/\#$ is not likely to be commercially available, and the diameter necessitated by this project is on the order of the size of the transmitter light source’s packaging diameter, a lens with a lower $f/\#$ than that calculated is acceptable, since a lower $f/\#$ would correspond to a larger lens diameter, which would ensure that the most possible light would be captured.

Figure 3: Calculation of Minimum Collimating Lens $f/\#$



Even though it reduces the ideality of the collimation by increasing the size of the light source with respect to the lens, a shorter focal length (ideally under 1 cm) should be chosen rather than a longer one to reduce the transmitter size so it can easily be mounted on the wall/collar. Furthermore, using a shorter focal length with a fixed f -number results in a reduced lens diameter, which would also help reduce the transmitter size. Furthermore, the material of the chosen lens should also have a high transmittance at 940 nm so that light from the transmitter source can propagate through it, and it is preferable that the lens be thin for easy implementation into the system. Given these requirements, lens types considered for this application include the spherical biconvex lens, the spherical plano-convex lens, and the aspheric lens.

Spherical biconvex lenses are lenses with two convex spherical surfaces with equal radii of curvature, while spherical plano-convex lenses are lenses with one convex spherical surface and one flat surface. Biconvex lenses perform with minimum aberrations when the object to image ratio, also known as the conjugate ratio, is close to 1:1 and are suitable for applications where the conjugate ratio is between 1:5 and 5:1. Meanwhile, plano-convex lenses perform with minimum aberration when the conjugate ratio is outside of the range between 1:5 and 5:1, which is the case in this application. Since there is no significant difference in cost between spherical biconvex and spherical plano-convex lenses, the spherical plano-convex lens would be the better choice from these two options [62], [63].

Another lens type considered for this application was an aspheric lens with an appropriate focal length. These lenses do not have a constant radius of curvature on each surface, and, instead, have a radius of curvature that changes with distance from the optical axis. Through this structure, using an aspheric lens corrects for spherical aberration, which results in collimation of better quality [64].

Spherical lenses have the advantage of being more cost-effective and readily available than aspheric lenses in materials that transmit the appropriate wavelength range. Furthermore, while reducing the presence of spherical aberration would help improve the quality of collimation, it is accepted that the collimation from the chosen lens will not be ideal, and, when the light is ultimately focused on the photodetector, the spot does not have to be diffraction-limited (that is, the maximum physically possible resolution) or aberration-free, since this is not an imaging application. Rather, this collimating lens combined with the receiver lens system simply serve to direct as much power from the transmitter light source as possible onto the active area of the photodetector surface. Still, both plano-convex and aspheric lenses of comparable cost will be considered, as they both have the potential to perform their function well.

3.11.1: LAF0607

One collimating lens considered for this project was the LAF0607, which is an uncoated plano-convex aspheric lens manufactured by Knight Optical [65]. The lens is manufactured from Schott B270 glass, which has a transmittance of around 92.5% at infrared wavelengths. Its center thickness is 2.9 mm. Its effective focal length is 5.9 mm and its diameter is 6.8 mm. Thus, this lens has an $f/\#$ of 0.87, which is much less than the maximum allowable $f/\#$ of 2.84.

3.11.2: 45-077

Another collimating lens considered for this project was one of Edmund Optics' TECHSPEC uncoated spherical plano-convex lenses, such as the 45-077 [66]. Many lenses in this product line with acceptable focal lengths and $f/\#$'s, including this lens, are manufactured from Schott N-SF11 glass. At 940 nm, N-SF11 glass has a transmittance of around 87% [64]. The 45-077 lens has a center thickness of 2.5 mm. Furthermore, it has an effective focal length of 6 mm and a diameter of 6 mm, from which it can be calculated that it has an acceptable $f/\#$ of 1.

3.11.3: KPX510

Like the 45-077, the KPX510, which is manufactured by MKS Newport, is an uncoated spherical plano-convex lens composed of Schott N-BK7 glass [67]. This glass has a transmittance of around 90% at 940 nm [68]. The KPX510 has a center thickness of 5.38 mm, which is much larger than those of the other candidate lenses. The effective focal length of the lens is 6.4 mm and it has a diameter of 6.35 mm, giving it an $f/\#$ of approximately 1.

3.11.4: Collimating Lens (Indoor Location/Fencing System) Final Comparison

The following table summarizes the specifications of the collimating lenses considered for use in this project's indoor location system. As discussed earlier, each candidate lens' transmittance at 940 nm, effective focal length, $f/\#$, center thickness, and price was considered.

Table 11: Collimating Lens (Indoor Location and Fencing System) Comparison

Component	Lens Shape	Approximate Transmittance at 940 nm	Effective Focal Length	f / #	Center Thickness	Price
LAF0607	Aspheric Plano-Convex	92.5%	5.9 mm	0.87	2.9 mm	\$19.81
45-077	Spherical Plano-Convex	87%	6.0 mm	1	2.5 mm	\$26.00
KPX510	Spherical Plano-Convex	90%	6.4 mm	1	5.38 mm	\$17.00

The LAF0607 was originally chosen given its high transmittance at 940 nm, its short focal length/acceptable f/#, and its apparent cost-effectiveness compared to the next best candidate: the 45-077. While the KPX510 costs less than the LAF0607, the large center thickness compared to similar lenses is a downside given that it would increase the difficulty of mounting the lens securely in the system. Furthermore, its aspheric shape is also advantageous, given its correction for spherical aberration, since it can be obtained at a cost comparable to spherical lenses with otherwise similar specifications. However, the shipping cost for this lens was so exorbitant that it would have doubled the price of the order, so the 45-077 was chosen in the end.

3.12: Receiver Lens System

A lens or lens system is necessary in front of the receiver photodiode so that light from the transmitter LED can be directed towards it even if it is not directly incident on the photodiode. This will be the case in most instances, as the animal wearing the collar is expected to be in motion when it passes the point of installation, and the spot where light incident on the receiver lens system will move on the receiver in the direction of the animal's motion while also potentially exhibiting movement normal to this direction of motion due to the animal's gait.

Thus, to fulfill this function, it is necessary for the lens system to have a wide field of view, with a minimum angular field of view of 90° being the initial decided specification for the system.

To calculate the necessary effective focal length of the lens system, it must be ensured that light refracted by the lens system is incident on the active area of the photodetector. Thus, the following equation for a lens system's angular field of view in terms of the sensor size should be used:

$$AFOV = 2 \times \arctan\left(\frac{H}{2f}\right)$$

Where AFOV is the desired angular field of view, H is the sensor size, and f is the focal length. It is important to note, though, that this calculation does not account for aberrations caused by the lens system as well as the size of the system's aperture, which may limit the field of view.

Given that the chosen photodetector's active area is a square with a side length of 2.65 mm and the desired angular field of view is 90° , the focal length of the lens system should be 1.33 mm or shorter if one photodiode is used.

Achieving this focal length would not be possible for this system, as the thickness of the filter, which must sit between the lens and photodiode, is 1 mm, and the thickness of the area between the photodiode and the chip packaging is 0.45 mm, so the minimum possible focal length would be 1.45 mm.

However, it is possible to use multiple photodetectors in a panel in order to increase the maximum acceptable focal length. For instance, if three of the selected photodiode were placed next to each other, the maximum acceptable focal length would be 5.325 mm, which is much more practically attainable. While this configuration would result in some blind spots in the system due to the space taken by the photodiode packaging, the impact on the system's overall performance would be minimal, since it is physically impossible for the animal wearing the collar to appear such that the transmitter light is only incident upon the blind spot without passing the rest of the receiver, which is active over the majority of the desired field of view, as well as the edge of the field of view.

Simulation in Zemax is required to determine the optimum focal length of the lens system used, given that light from it must also pass through a filter and the photodiode packaging, and commercially available parts must be compared to simulation results. Furthermore, the system must be compact, so that the entire indoor location system receiver can be mounted on a wall or doorway easily, and it must be cost-effective, so that multiple receivers can be easily produced. Given these requirements, four families of technologies that were considered to fulfill this purpose were fisheye lens systems with a meniscus lens front element, ball lenses, half-ball lenses, and hemispherical Fresnel lens arrays.

3.12.1: Multi-Element Fisheye Lens Systems

A common means of obtaining a wide field of view, particularly in imaging systems, is a multi-element fisheye lens system. These systems typically have a field of view larger than 120° , and commonly include a negative meniscus lens as a front element. They also utilize multiple lens groups, comprising a total of at least five or six lens elements (but usually more), to correct aberrations while maintaining this wide field of view [69], [70].

While this type of system has the advantage of attaining a 180° field of view with acceptable resolution for imaging applications, there are great disadvantages to this type of lens system. The use of many elements to reduce aberration in this system is not entirely necessary for this aspect of the project, since it is not an imaging system, but

would be quite costly and difficult to assemble. It is also likely that this lens system would be too thick to work well in this application.

3.12.2: Ball and Half-Ball Lenses

Half-ball lenses are another possible option to incorporate into the lens system for this project. Along with ball lenses, they are commonly used to couple light into fibers and sensors over a wide field of view and at a short focal length [71]. They have also been successfully utilized in early wide-field-of-view imaging applications to achieve a field of view of approximately 90° before the development of modern fisheye imaging lenses, making them a promising candidate [72]. They would also be more compact and cost-effective than multi-element fisheye lens systems, even if one or two other elements are added to the system to increase the field of view further.

Ball lenses share many of the advantages of half-ball lenses. Given their spherical geometry, an advantage they have over half-ball lenses is that they theoretically are able to focus light incident normally on the sphere omnidirectionally. That is, their optical axis can be any axis passing through the diameter of the sphere, which renders them useful in cases where light isn't incident normal to the rest of the system. However, to take full advantage of this capability, mounting the lens in order to have as much of it exposed as possible may be difficult.

In both cases, as spherical lenses, both half-ball and ball lenses are subject to spherical aberration as well as other aberrations such as field curvature and vignetting that cannot be easily corrected without using multiple lenses. However, given that this is not an imaging application, correcting these aberrations is of limited importance compared to designing a system that collects light from a wide field of view that is cost-effective and compact.

3.12.3: Hemispherical Fresnel Lens Array

Another possible technology for the receiver lens system is a hemispherical Fresnel lens array. These lenses are comprised of multiple circular or polygonal Fresnel lenses, which are thin surfaces that use concentric grooves to refract light, arranged in a dome shape. They are commonly marketed for use in passive infrared sensing, as this dome configuration can easily be placed over a sensor to direct incident light towards it from a wide field of view.

Many of these systems boast an extremely wide field of view, with one leading manufacturer of these lens arrays, Fresnel Factory, boasting products with a field of view of up to 140° [73]. Furthermore, the three-dimensional, hemispherical configuration of many flat Fresnel lenses, which each focus light to a chosen point, makes this option less vulnerable to movement of the focal point across the sensor. Furthermore, this configuration makes the ideal focal length calculated using the angular field of view equation irrelevant, since this trigonometric calculation assumes the use of a lens system where the position of the lens system with respect to the photodetector remains constant regardless of light's angle of incidence.

However, some challenges would be present in implementing a hemispherical Fresnel lens array in this project. Most commercially available hemispherical Fresnel lens arrays are marketed for use in the mid-infrared wavelength range, so determining the feasibility of their use with 940 nm light would require consultation with the manufacturer to obtain the material's transmission spectrum at this wavelength as well as information about the amount of change in the given focal length due to chromatic aberration. Additionally, given the three dimensional configuration of the lens array, it would be difficult to simulate its use in Zemax without assistance (such as a Zemax file of the lens) from the manufacturer.

3.12.4: Final Receiver Lens System Comparison

The following table summarizes the information that was discussed above. It compares the different types of receiver lens systems and their respective advantages and disadvantages. The advantages and disadvantages considered relate to field of view, cost, size, and ease-of-use within the project.

Table 12: Receiver Lens System Comparison

Technology	Advantages	Disadvantages	Relative Price
Multi-Element Fisheye Lens System	<ul style="list-style-type: none"> • Widest potential field of view 	<ul style="list-style-type: none"> • Costly and challenging to assemble • Not compact 	High
Half-Ball and Ball Lenses	<ul style="list-style-type: none"> • Most compact • For ball lenses, omnidirectional optical axis 	<ul style="list-style-type: none"> • Vulnerable to aberrations • Challenging to mount 	Lower
Hemispherical Fresnel Lens Array	<ul style="list-style-type: none"> • Dome-shaped geometry conducive to use with sensors • Extremely cost-effective (for mid-infrared applications) 	<ul style="list-style-type: none"> • Challenging to simulate • Unknown commercial availability for near-infrared applications 	Lowest, for mid-infrared applications Unknown for near-infrared applications

Given the above information about each possible lens/lens system that could be used, a ball lens is the first choice given its relatively compact size, its theoretically omnidirectional optical axis and short focal length (which contributes to the system's achievement of a wide field of view). However, after determining the optimum focal length for this lens and comparing it to commercially available lenses, a half-ball lens could also be used if necessary. This is especially true if it is determined that the addition

of other optical elements would further enhance the system, as they are more compact than ball lenses.

3.13: Strobe Light

The strobe light is the primary defense system for the smart pet collar. The strobe light implemented into this collar will have to be confined and compact to fit into a pet collar, while also maintaining an effective illumination. A predator is usually blinded by a bright light source, and the implementation of the strobe light will ensure that this happens. When a bright light is shined onto a predator it usually disrupts their natural surroundings causing them to be disoriented [74]. This will usually scare them off, and in this case scare them away from a pet. Strobe lights available on the market can come in small sizes, with some of the smallest strobe lights having dimensions of 4" L x 3.5" W x 1.5" H [75]. These strobe lights are cost effective and have prices ranging from about ten to twenty dollars [75],[76]. There are many commercial strobe lights that are intended to be put onto bikes. These would be something feasible for the smart pet collar, however they are still too big to be put onto the collar. Since there is limited space on the pet collar the strobe light must be small and not have housing that takes up a lot of space. The width of the light must especially be minimized so that the collar can be thin enough for a pet.

Figure 4: Image of a commonly made strobe light design.



Many strobe lights sold on the market have shapes that are not conducive for a pet collar. They are mainly a hexagonal shape which can be seen in the figure above. This particular strobe light has clips that can be hooked onto the desired object. Other strobe lights can be attached to an object by Velcro. For this to be feasible for a pet neither of these options would work for a pet collar. If the animal is running around the movement from this could loosen the strobe light and risk the strobe light falling off which could be hazardous for the pet. Another common strobe light shape is a projector style. This would not work for the pet collar because it does not have a feasible way to attach to the pet collar. This makes the projector style an unsuitable choice for our projects' needs.

The strobe lights that are commercially available on the market are not suitable to go on a pet collar as-is. Due to the size, shape, and functionality constraints of the particular

strobe light needed for the pet collar, there proves to be a necessity for a unique strobe light design.

The strobe light will need to be small enough to fit on the pet collar. The width of the strobe light must be thin, so the pet collar is not unreasonably bulky. To achieve this, the strobe light set up will be configured into the pet collar. This will significantly reduce the size of the strobe light because any extra housing will not be a factor for size. This can therefore minimize the size of the strobe light and be easily implemented into the pet collar. If the pet collar acts as the housing for this strobe light, then the risk of the strobe light falling off is eliminated. The strobe light will need to have a relatively fixed position so there is no risk of losing the light or blinding the pet in case the light falls off. This can be done by having the pet collar be attached to a harness for the animal. If the collar is attached to the harness the likelihood of the collar moving is much less. This will ensure the strobe light stays in place and will not blind the animal. The effectiveness of the strobe light being able to blind a predator approaching the pet will also be much more likely. This will ensure the defense mechanism can be effectively executed.

The strobe light will need to have functionality within the app and work on the same electrical configuration as the rest of the collar. By implementing the strobe light into the pet collar, it will ensure the strobe light can work effectively with the app and be able to be powered by the rechargeable battery inside the pet collar. This will be an important aspect in the defense mechanism for the pet collar.

The strobe light design would consist of a LED, collimating lens set up, and a reflector. This configuration would be set inside the collar and be wired to the electrical wiring inside the collar. The LED will be set in between the lens and the reflector. The reflector will be under the LED and the lens will be located above the LED. The reflector is used to direct the light from the LED to the desired direction. The lens is then used to focus the light from the reflector and then illuminate the desired location.

3.14: LED

When designing the strobe light, trying to limit power consumption will be an important factor. There are many other things in the collar that will need power, and to preserve the longevity of the battery the power consumption is a factor that needs to be optimized. All these benefits will help in making the strobe light optimal for the implementation into the pet collar. The working space is also something that needs to be optimized. Since the pet collar cannot be extremely large, as it needs to go around a pet's neck, the strobe light cannot take up a lot of room.

The bright white light will be more visible at night and better at scaring off predators. Bright lights are a good deterrent to scare away predators. These bright lights often disorient animals because it causes a disruption to an animal's natural surroundings, which will encourage the animal to flee from where the pet is once the strobe light goes off. LEDs are some of the best types of light to do this. LEDs are energy efficient which will also contribute to better power consumption for the pet collar. This makes an LED the best type of light source to use in the strobe light. They are among the most common to use because of their energy efficiency and effectiveness.

The brightness of the LED is something that is important to consider when designing the strobe light. Lumens indicate the total amount of visible light the LED will emit. The average amount of lumens produced by an LED ranges from 75-110 [77]. Since this is not an extremely high number of lumens overall, one LED will not be sufficiently bright. Therefore, the strobe light will have multiple LEDs implemented to achieve an effective brightness. The LEDs will be put in parallel so that there is enough voltage to be supplied to the LEDs.

For our design of the strobe light, we considered four kinds of LEDs which are Through-Hole LEDs, Surface Mount LEDs, Bicolor LEDs, and High Power LEDs.

3.14.1: Through-Hole LEDs

Through-hole LEDs consist of an LED with two legs that fit through holes that are then soldered onto a circuit board and then can be integrated into an electrical circuit. [78]. Through-hole LEDs are one of the most common types of LEDs and they have applications where the LED needs to be physically robust. This can include things like outdoor lighting and automotive lighting.

3.14.2: Surface Mount Device LEDs

Surface Mount device LEDs are LEDs that can be mounted on a PCB. These LEDs have no wiring and are soldered onto SMD pads [79]. These LEDs are compact in size, which is beneficial for the strobe light design because there is only a limited amount of space to utilize. These LEDs are highly efficient in terms of lumens per watt, and they provide a broad light beam. These LEDs use less power and can produce the same amount of light as other LEDs. These are therefore better when using battery powered devices. SMD LEDs are used in a variety of applications including backlighting, medical devices, automotive, consumer electronics, and industrial, and advertising.

3.14.3: Bicolor LEDs

Bicolor LEDs can produce multiple color temperatures [78]. These LEDs include at least two different wavelengths that are contained in one discrete addressable LED package. The packages offered by these LEDs can produce a single color, pulsed color, or blend the two wavelengths for another constant color [79]. While this is an important feature for some LEDs the strobe light design does not need to have a colored LED. These LEDs are used in medical applications, treatment and therapy applications, sensing, imaging, and communication.

3.14.4: High Power LEDs

High Power LEDs produce a very high light intensity that can be up to 100 lumens per light watt. [78] These LEDs have a much higher power consumption because of this and therefore have a higher current than most other LEDs. These LEDs produce more thermal energy because of the high current and therefore require cooling technology that is built into their design in the form of component cooling and heat dissipation. These LEDs have applications in industrial and outdoor lighting.

3.14.5: Final LED Comparison

The SMD LED has the best voltage, lumens, and wattage for the strobe light design. While it does not have the smallest size, the benefits from having a high brightness with minimal power consumption is more important when considering the design of the strobe light. The LED that will be used is the SMD LED based on the properties of this LED. This LED is the best kind of LED to use in strobe lights. These lights are a good tool to use when trying to optimize things like power consumption and working space [85]. The SMD LED is helpful in minimizing the space used. The voltage that this LED produces is conducive to our project as the power supply will be able to supply this voltage to the LED.

The below table summarizes the information presented about LED types. The specifications being looked at for the LEDs are the wattage, voltage, brightness, dimensions, and beam angle. The wattage is important to consider because this value indicates what kind of power consumption the LED will have. An LED with a very high wattage would not be ideal because it would take up a lot of power. The power consumption is a constraint for the pet collar because the battery life needs to be elongated. The voltage is important because a voltage of 3.3V and under is supported by the smart pet collar design. If the voltage is too high the voltage that is able to be supplied will not produce a sufficient brightness. The voltage of the LED needs to be at or around 3.3V to maximize brightness. The brightness is an important factor as the strobe light needs to produce a very high brightness in order to be effective in the design. Brightness is measured in lumens. A higher lumen value indicated a higher brightness. A strobe light has a typical brightness of 300 lumens per watt, so the total lumens produced will need to be around this value for the final design. This will be achieved by implementing multiple LEDs at a sufficiently high brightness. The dimensions are important based on the size constraint of the pet collar. Since multiple LEDs are being implemented an LED design that will take up a lot of space will not be ideal. LEDs are typically very small but since the design will require multiple dimensions will be an important factor to consider. The beam angle is important because this represents how much the light will spread. This value is measured in degrees. This value determines what kind of reflector will be used, or if any it is needed at all. The beam is not spreading past a certain angle then the reflector is not necessary or will need to be adjusted. A beam angle that is very large will require a reflector in order to capture as much light as possible. A beam angle that is lower may require a round reflector as opposed to a flat one in order to capture as much light as possible.

Table 13: LED Comparison

Component	Wattage (W)	Voltage (V)	Brightness (Lumens)	Dimensions	Beam Angle (Degrees)
Through Hole LEDs	0.192	3.2	11	37.36 mm	360°
SMD LEDs	1	3.6	110	15 mm	120°

Bicolor LEDs	0.066	3.3	40 - 65	2.5mm x 1mm x 0.7mm	130°
High Power LEDs	1	3.6	100	20mm x 8mm x 6.6mm	140°

3.15: Lens

The lens used in the strobe light will be made of glass and have a collimated lens design to focus the light from the reflector. A collimated lens can convert divergent beams of light into parallel beams of light [80]. This is necessary for the strobe light design because the light produced by the LED will transmit more power and produce a brighter beam, which will be more effective for this design with a collimating lens. This type of lens is necessary for our design because when the LED is lit up the light beams will be divergent. This means they will go in any random direction. The reflector is useful because it can reflect beams that do not reach the collimating lens back to the lens. The strobe light design will use the reflector to then reflect these divergent light beams onto the lens. Once the light beams reach the lens the lens will convert these divergent beams into parallel beams, or collimated beams, and focus the light once it exits the lens. For our project we will need a single collimating lens to achieve an efficient strobe light. This is because the strobe light needs to remain small, and the LED is a smaller light source, meaning only a single lens will be necessary to collimate the light. Smaller light sources require only one lens because there are less divergent beams that need to be collimated.

The LED has a certain beam angle, which will affect the F-number ($f/\#$) of the collimated lens. The $f/\#$ measures the light-gathering ability in an optical system [81] This value is defined as the ratio of the focal length of the camera lens to the diameter or the aperture being used. To find a $f/\#$ that is suitable for the LED, the $f/\#$ needs to be calculated based on the beam angle. This is done through the following equation:

$$\tan(\theta) = \frac{1/2 D}{f}, \text{ where } D = 1.73 \text{ cm}$$

To obtain our calculation, the full width half max (FWHM) of the beam angle was used. The FWHM is the width of the spectral peak at half the maximum amplitude. The FWHM of the SMD LED selected is 60 degrees. A focal length of 0.5 centimeters was used of the f value. The focal length is the distance at which a lens will focus light from a lens. The $f/\#$ that was found was 0.289. This value was found by dividing the focal length by the diameter. For this $f/\#$ to be possible for our project, it would require getting the lens made, instead of finding a lens on the market. This is because the $f/\#$ is super specific and not common for lenses. This would result in having this lens made which would be very costly and possibly very time consuming. This would not be conducive for the project, as the project has a limited budget and limited time. To negate this challenge the diameter of the lens can be manipulated to two centimeters for a $f/\#$ of 0.25. This $f/\#$ is more commonly found in lenses available on the market.

The best kind of lens to use for a strobe light design is a positive bi-convex spherical lens. A bi-convex lens comprises two convex surfaces in a spherical form with some radius of curvature. These types of lenses are best for collimating divergent light beams, which will be ideal for an LED. There are various types of glass used for these lenses. The types of glass that will be considered for the strobe light are N-BK7, UV Fused Silica, CaF₂, and ZnSe. N-BK7 are ideal glasses for finite imaging applications. UV Fused silica are ideal for UV to near infrared applications. CaF₂ are ideal for finite imaging applications that require a high transmission in the infrared and ultraviolet ranges.

When selecting the glass type several factors need to be considered. These are the wavelength range, refractive index, abbe number, and the available focal lengths. The wavelength range is important because the lens needs to be conducive for the wavelength being emitted from the LED. This wavelength would be around 450 nanometers to 460 nanometers, as this is typical wavelength of a white LED. The refractive index is important to consider because it measures how light is bent inside of the medium. This is an important factor to consider because it determines how well a lens can focus light. A high refractive index is important because it is more efficient in letting light pass through.

The Abbe number represents the light dispersion of a lens. This value measures the quality of the lens, as it is used to determine the ability of a lens to have a uniform scattering of light [82]. A higher abbe number is usually more desirable, as a higher abbe number indicates a better optical performance. The focal length is also important because the strobe light must be set up in such a way to achieve a certain focal length. This value is important because the strobe light will need to have a small configuration, so the focal length of the lens cannot be too large to account for this.

All lens prices are for a diameter of $\phi 1$, which is a unit given by Thorlabs, and a focal length of 50 mm, as determined by the equation. For lenses that came uncoated, this option was chosen because uncoated lenses can retain most of their clarity with little effect on the transmission of light. Uncoated lenses work roughly the same as coated and uncoated lenses are more cost effective. For the strobe light the uncoated lens will operate sufficiently.

Below is a table comparing the different glasses commonly used for lenses. The specifications being looked at are the wavelength range, refractive index, abbe number, available focal lengths, and the price. The wavelength range needs to be considered because it has to be able to transmit the wavelength output from the LED. The LED emits white light which has a wavelength around 450 nanometers (nm). The refractive index is important to consider because this value determines the bending of light when passing from each medium. If the refractive index is too high then the light will not be able to efficiently pass through the lens. The abbe number is important because this value is a measurement of a material dispersion. Dispersion would not be ideal in this situation because a high dispersion would produce an unfocused beam that as a result could not produce a sufficient brightness for the strobe light. A higher abbe number indicated a lower dispersion value. The focal length is important to consider because the strobe light design has a focal length that was calculated to be 2 centimeters for an ideal design. This means the lens being used has to facilitate this value. The price is also important to

consider because it needs to fit into our budgetary constraints. A lens with an unreasonably high price would not be ideal if the specifications between two lenses are similar.

Table 14: Lens Comparison

Glass	Wavelength Range	Refractive Index	Abbe Num.	Available Focal Lengths	Price
N-BK7 (Uncoated)	350nm - 2.0 μ m	1.515 at 633nm	64.17	10mm - 1.0m	\$24.92
UV Fused Silica (Uncoated)	185nm - 8.0 μ m	1.460	67.82	10mm - 1000nm	\$110.36
CaF ₂ (Uncoated)	0.18 μ m - 8.0 μ m	1.428	94.99	15mm - 200mm	\$208.47
ZnSe	7 μ m - 12 μ m	2.403 at 10.6 μ m	20 - 1000	15mm - 200mm	\$342.54

The glass that will be chosen for the collimated lens will be N-BK7. This is because this glass covers the wavelength of the LED chosen, has a suitable refractive index and abbe number, includes the focal length needed, and it is extremely cost effective. This glass is also the most common for many optical applications and is used for applications like the strobe light design. This lens will ensure the light is focused and the strobe light is able to produce bright and directed beams.

3.16: Reflector

A reflector is a type of optical device that can redirect incident light back onto the incident surface [83]. The purpose of the reflector in the strobe light is to direct the beams of light from the LED onto the collimating lens. The beams of light that do not reach the lens will be redirected onto the reflector. The reflector will then direct these beams onto the collimated lens. The finish of the reflecting surface is what enables the light to be redirected [83]. This will require a reflector that is relatively small to minimize the total size of the strobe light. Using a reflector is important because without it there would be significant loss of light inside the strobe light structure. The reflector ensures that most of the light is being used in the strobe light design and produces a significant illumination. Without a good illumination the strobe light may be ineffective in scaring off predators.

While there are many different types of reflectors, the one best suited for the strobe light would be either a parabolic reflector or a mirror. These reflectors are useful in catching and reflecting divergent light beams. There are several factors that lead to considering these two, which are economic, utility, size constraints, and functionality. This reflector will act as essentially a second collimating lens without having to develop a complicated

and expensive collimating lens design. This will also ensure the strobe light will be kept minimal in size. The shape of the reflector is an important factor to consider.

Parabolic reflectors, which are usually mirrors, are reflectors where a cross section through an optical surface has the shape of parabola [82]. Parabolic reflectors can reflect incoming rays of light onto the same focal point. This could be helpful in the strobe light design because the divergent light rays need to be collimated and assist in focusing the light onto the desired focal length. Another benefit of using a parabolic reflector is these reflectors are achromatic which means the principal operation does not have refraction [82]. Refraction involves light being deflected while passing through interfaces between different mediums. This is generally undesirable because light is being lost.

One subset of parabolic reflectors is off-axis reflectors. These reflectors have a focus point that is outside of the incoming beams [84]. This can sometimes require eliminating certain parts of the mirror. These reflectors are made for a certain angle of incident and will work for angles that are entering at angles close to the angles of incidence. While off axis reflectors may be more practical, they can be very difficult to align. This can be difficult to achieve and hard to maintain. If the reflector somehow loosens and moves the whole design could be thrown off. Parabolic reflectors are typically used when a beam needs to be tightly collimated or to collimate a tightly focused beam [84]. This is needed if the beam divergence is strong. This can be helpful for LEDs because it produces divergent beams, however the divergence of these beams is not necessarily extreme. This is useful in high harmonic generation, laser material processing, and fluorescence microscopy [84]. When the beam divergence is small, this can still be useful if the reflector is used far away from the center. These applications are telescopes, laser scanner systems, and spectrometers [84]. This does not apply for the strobe light design because the reflector will be close to the light source due to the size constraints.

Mirrors are a type of reflector that can have a relatively flat design, which can be useful in the dog collar as something containing a lot of depth may not be feasible with the final design of the strobe light. Mirrors are typically used when the angle of reflection is equal to the angle of incidence [85]. Metal-coated mirrors would be most useful in the strobe light design. A metal-coated mirror contains a glass plate with a silver coating on the back side. This type of design has very low absorption losses for visible light, which is what is being used, in the silver layer. This is ideal in the strobe light, as it will maximize the luminescence from the LED, as very little light will be lost due to absorption. This type of mirror is generally used as a household mirror. This is beneficial because it ensures that the light will be reflected and not lost. The Silver mirror that is behind glass has a reflection factor of 80-88 percent [86]. This is more than sufficient for the strobe light. Mirrors are typically low in cost, especially types of household mirror. This is important to consider as some reflectors can cost hundreds of dollars. The reflection inside the strobe light does not necessarily have to reach total internal reflection (TIR). This means light is completely reflected into a medium, and in this case would be the collimating lens. A mirror will give a reflection that is high and achieving TIR is not something that is necessary in the strobe light. The reflectance of the parabolic mirrors and the Plano mirrors is high, around 95%-97% [84]. This proves to be a good reflectance for the strobe light to function appropriately.

Below is a comparison of different reflectors discussed above. The specifications being looked at are the reflectance, dimensions, wavelength range, reflected focal length, and the price. The reflectance is important because most of the light being shined needs to be reflected in order to obtain a bright strobe light. The dimensions are important because of the size constraints of the pet collar. The total size of the strobe light needs to be kept as small as possible to facilitate the other components being implemented. The reflector therefore has to fit into these size constraints and remain relatively small, while also keeping a sufficient size to encompass the other components of the strobe light. The wavelength range is important because the LED will output a fixed wavelength that needs to be reflected by the reflector. If the wavelength range of the reflector is outside the wavelength of the LED then it will not be suitable for the design. The LED will output a wavelength around 450 nanometer (nm), so the reflector needs to be able to reflect light at this wavelength. The reflected focal length is an important factor because this represents the distance from where the mirror is to where the reflected light rays converge. This value needs to be considered because it shows the focal point of the light and is determinant of the overall brightness of the light. The price needs to be considered because of the budget constraints for the project. The reflector needs to be cost effective to fit into the budget constraints.

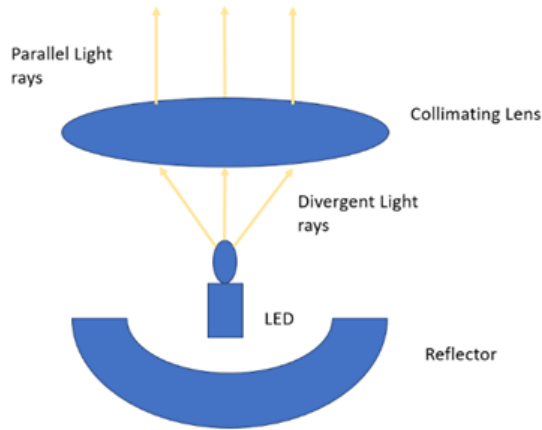
Table 15: Reflector Comparison

Component	Reflectance	Dimensions	Wavelength Range	Reflected Focal Length	Price
½” 90° Off-Axis Parabolic Mirrors	95%	12.7mm x 18.8mm	450nm - 20µm	50.8mm	\$160.71
45° Off-Axis Parabolic Mirrors	97%	25.4mm x 21.8mm	450nm - 20µm	50.8mm	\$225.94
Round Protected Silver Mirror	97%	12.7mm x 6.0mm	450nm - 2.0µm	N/A	\$34.48
Square Protected Silver Mirror	97%	12.7mm x 12.7mm x 6.0mm	450nm - 2.0µm	N/A	\$36.41

All the reflectors have a good reflectance and mostly follow similar specifications. The only main difference is the price points of these. The round protected silver mirror and square protected silver mirror are significantly cheaper than the off-axis parabolic mirrors. The off-axis parabolic mirrors have some difficulty in the design aspect, as they can be very difficult to align. These reasons make the Plano mirrors much more attractive options. Between the square and round mirrors, the round mirror may fit better in the design. This is because it is not as limiting in the size requirements. The round mirror can

be manipulated better to fit inside the collar than the square one. The round protected silver mirror, therefore, will be chosen as the reflector for the strobe light design.

Figure 5: Preliminary strobe light optical schematic for understanding of functionality.



The design that is discussed above will ensure that the strobe light acts as a good defense mechanism in the case there is a predator around a pet. The optical design of the strobe light ensures that the light will follow the correct path and produce a good illumination. An optical schematic of this design can be seen in the figure. This schematic depicts the light rays going from the LED to the lens and coming out of the lens as parallel beams. When light comes out of all angles from the LED it will be directed onto the reflector which will then redirect these beams onto the lens producing these same parallel light rays. The design depicted in the figure will be like the design that will be used for the collar and will be housed inside of the collar. The components will be placed relatively close together. The reflector will be right underneath the LED and the lens will be placed about half a centimeter from the LED to achieve the desirable focal length. This design is most suitable for the pet collar and mimics a typical design schematic of a strobe light.

3.17: Wide FOV Camera Design

The smart collar will contain a camera to detect predators. This camera design aims to accomplish the following: a wide field of view (FOV), a clear identification of hot bodies that emit around 9.5 micrometers of light, a compact size, a frame rate around 1-10 frames per second, and a large depth of view. A field of view is the range or extent of the visible area. A wide FOV would entail a very large visible area. This is necessary in the camera design because to detect a predator the camera needs to capture a large amount of area. The clear identification will work in conjunction with image processing software. A compact size for the camera is necessary because the collar serves as a size constraint and for the camera to be implemented onto the collar, it must have a compact size. The frame rate is important to consider because the frame rate is the frequency at which frames from the camera are displayed. A very low frame rate would result in a blurry or unreadable picture. For a surveillance camera a good frame rate is 10-15 frames per second [87]. Making a frame rate this high however can increase storage costs by a significant amount

[85] Our goal will be between 1-10 frames per second. A frame rate between this range will still produce a readable image, and this will negate the storage costs from a high frame rate. A large depth of view is needed because to detect predators from a distance and give the owner enough time to protect their pet, the camera needs to be able to pick up images from far away. A depth of view is the distance between the nearest and farthest objects in a landscape that will still appear clear in an image [88]. The camera will serve as the detection aspect for the defense mechanism. This feature will work with the strobe light to complete the defense mechanism system. The camera will be a part of the detection system and the strobe light will act as the deterrent system. This system will consist of a CMOS camera with a wide-angle lens design implemented into this camera. The camera with the implemented lens design will then be attached to the collar.

This design proves necessary because the field of view of most cameras on the market are not suitable. The camera system should have a field of view of almost 360°, with our goal being 300°. This is because to protect a pet the entire surrounding of the pet needs to be visible. There will be some limited visibility because of how the collar is positioned with respect to the pet's head. The pet's head may get in the way and limit a small portion of the field of view. To achieve a field of view around 360°, potentially three cameras would have to be purchased. This would be very expensive and therefore not cost effective.

Another issue with these cameras is the visibility at night. The field of view at night would not be as good, and this would prove a more important feature considering human visibility is also limited at night. If the visibility at night is limited it could still put a pet in danger. Most cameras are also designed to be stationary. The pet will be moving around at unpredictable speeds, to be able to account for this, multiple cameras would have to be field tested. This would not be feasible because of cost and time constraints.

3.17.1: CMOS Camera

For this design, a CMOS camera is the most suitable. A CMOS, or complementary metal-oxide-semiconductor, camera uses an image sensor to register visible light as an electronic signal [89]. The electronic signal is then recorded to an internal memory or a device that is remotely connected [89]. The reason for this is because CMOS cameras develop high quality images, have a low power consumption, and have application in security surveillance [90]. The use of CMOS cameras in security surveillance is relevant because the camera will essentially be acting as a surveillance device, as the camera will need to monitor if there are predators that put a pet in danger. A high-quality image is desirable because, to serve as a detection system, the camera needs to produce an image that is readable for the pet owner. The low power consumption is desirable because the collar will be operated from a battery, so only a finite amount of power can be provided to each element.

Overall, a CMOS camera is the most suitable for this system. CMOS sensors have many different applications. A main application is security. CMOS sensors are good for surveillance and security. This is because they can capture high-quality video and images in a variety of different lighting, including low-lit [90] This makes them useful when monitoring different environments and identifying any potential threats to an area [90].

CMOS sensors can also be applied to manufacturing. These sensors can inspect products for defects, measure the dimensions of products, and monitor the line of production [89]. The ability of the sensor to capture images at great speeds makes them useful when trying to inspect products moving at a fast pace [89]. CMOS sensors are also used in the medical field. They are used in medical imaging technologies because they can capture high-quality images in small spaces and at varying angles [89]. This can be helpful when diagnosing and treating medical conditions [90]. This demonstrates the usefulness of CMOS sensors, as they have a vast variety of applications that have helped improve upon many different industries. The versatility of this sensor makes it particularly useful. The security application is especially helpful when it comes to implementing this sensor into the smart pet collar.

There are multiple different types of CMOS sensors. The three main types of CMOS sensors will be analyzed. The types of sensors are basic CMOS, backside illuminated CMOS, and stacked CMOS. The main differences between all these types of sensors are the configurations of the components. This is important because moving around these components can change the way an image is processed. While this can help specialize certain CMOS sensors to the corresponding application, each type of CMOS can still be applied to roughly the same applications. These are still important to note because of the complexity some of the CMOS sensors entail.

3.17.2: Basic CMOS Sensor

A basic CMOS is an improved version of a CCD sensor. The CMOS sensor can produce better quality images and uses less current and voltage when operating. This is something that is ideal for the smart collar, as low power consumption is an important aspect of this project. The high image quality is also beneficial when detecting a predator, as stated before. A basic CMOS consists of a photodiode, amplifier, and output circuit [91]. The way an image can be produced is light comes into contact with the photodiode and turns this into an electrical charge. This electrical charge is then amplified and processed by the output circuit [89]. The output circuit then transforms these electrical signals into digital signals which are then processed as an image using the digital signals.

3.17.3: Backside illuminated CMOS Sensor

A backside illuminated (BSI) CMOS has components arranged differently than the basic CMOS [90]. The different arrangement of these components can enable practical advantages. This type of CMOS has a f-stop that is better for image noise [91]. This can help in creating a clearer image. A f-stop controls how much light is allowed to hit a sensor from the aperture opening. This is desirable when trying to achieve a clear image as the aperture remains small. This can be undesirable when trying to achieve a wide FOV. With a smaller aperture opening it reduces the FOV because more of the lens is being exposed and light can enter the lens at a wide range of angles [92]. The BSI CMOS can produce an image that has better quality than a basic CMOS. This is because the sensor in the sensor is placed opposite of the imaging components [92]. This, therefore, produces a much sharper and clearer image.

3.17.4: Stacked CMOS Sensor

A stacked CMOS sensor combines multiple layers of imaging components into one unit [90]. These sensors have imaging components that are separated into multiple layers. Each of the layers in these sensors has a dedicated function. This improves upon the efficiency of the use of space inside the sensor [92]. The configuration used for this sensor improves the performance and functionality of the sensor [91]. This sensor can maintain a complex and compact design. This sensor adds more components than a basic BSI CMOS, which adds to the image quality. This type of CMOS has an effective use in high-end photography equipment. This is because the images produced are very high quality, making it highly effective for this application.

The following specifications will be investigated for the camera: required voltage, resolution, shutter type, pixels, dimensions, and price. The required voltage is investigated because our battery supports a voltage of up to 3.3V. This means any components used have to have a voltage at or under 3.3V. This restraint makes the required voltage important to consider. The resolution is important to consider because the resolution tells how many pixels can be captured in a single image capture. These measurements are usually in the unit of megapixels, MP, which signifies how many millions of pixels are being recorded. This value is important because it refers to the sharpness of the image. A higher resolution would result in a sharper image. Shutter type is important because the shutter is the component of the camera that can open and close to control the light being directed onto the sensor or film. This is a determinant of the exposure time. The exposure time determines the brightness of an image produced by the camera. The type of shutter is important to the image being developed, as it determines the brightness. The shutter type is also important depending on the reason for imaging. Some shutter types are better for imaging still objects, and some are better for imaging fast moving objects. The pixels are important to consider because the pixels record light being directed into the camera. From this the pixels are then also responsible for building a visible image. Each pixel represents an individual sensing area that is able to capture light. A greater number of pixels can produce a better image, and therefore, is important to consider. The dimensions of the camera is important because of the size constraints of the pet collar. A smaller camera is more ideal to put into the collar because it can maximize the total space. A smaller camera will allow for more room to work with when it comes to the other components being put into the collar. The price of the camera needs to be considered because of the budget constraints of the project. Two cameras need to be put into the collar and the total cost of this still has to remain cost effective. A camera that has ideal specifications while also maintaining a low price will need to be pursued in the final design.

Table 16: Camera Comparison

Component	Required Voltage	Resolution	Shutter Type	Pixels	Dimensions	Price
Mega 5MP SPI Camera Module	3.3V	5 MP	Rolling	2592 x 1944	33mm x 33mm x 17mm	\$34.99

Arducam for Raspberry Pi Camera	Variable	8 MP	Rolling	4608 x 2592	25mm x 24mm	\$22.99
Arducam 64MP Camera Module for Raspberry Pi	Variable	64 MP	Rolling	9152 x 6944	25mm x 24mm	\$59.99
OV5640 Camera Board	3.3V	5 MP	Rolling	2592 x 1944	35.70mm x 23.90mm	\$25.99

The camera being picked will be the OV5640 Camera Board. This camera is a raspberry pi camera and will be the best fit for the lens system being investigated. The lens system being investigated requires a OV5640 camera with a resolution of 5MP, which can be further explored in the sections below. These are the exact specifications of the camera chosen and therefore the best option. The price for this camera is economical, as two cameras will need to be purchased to facilitate this design. This camera has high performance and fits the specifications needed for the lens design, so it is, therefore, the most ideal camera to choose.

3.18: Lens Design

The CMOS sensor will have a lens design implemented into it. The CMOS sensor proved the best to facilitate something with a wide FOV. The lens design being used will be one that prioritizes the maximum FOV. This is because to detect predators the camera will need to be able to cover a large distance all around the pet. To implement a FOV of 300°, two lens and CMOS sensors will be implemented into the collar. One camera design would not be sufficient because it would not be feasible for one camera to have a FOV that stretches over a 300-degree view. There will be one camera placed on the front and one camera placed on the back of the collar. This will cover a 300° FOV with these two cameras combined.

There are different types of lens designs that can produce a wide FOV. Two of the most commonly used lenses with wide FOV are fisheye lens designs, zoom lens design, and wide angle lenses. These are used in a variety of applications when a wide FOV is needed. This can include things like security cameras and Go Pros.

3.18.1: Fisheye Lens Design

A fisheye lens design is a common lens design when trying to achieve a very wide FOV. This lens design can produce an FOV of up to 180°. A fisheye lens is a spherical surface that can image onto a flat surface. Commercial fisheye lenses have a negative and positive lens group so that resolution can be maximized [93]. This lens design is typically used to achieve a FOV of 180 degrees. These cameras can capture curved panoramic images [93]. There are different kinds of fisheye lenses which include a circular fisheye lens and a full frame fisheye lens. A circular fisheye lens can capture light from a full

180° in all directions. This lens can project a complete hemispherical or curved panoramic image into the camera sensor [93]. A full-frame fisheye lens can project the hemispherical image to the sensor's full array of pixels. This stretches beyond the sensor's image producing screen.

This type of lens does limit the FOV some but not significantly [94]. The issue with these lenses is there is a distinct distortion in the image captured. This is due to the nature of lens shape. This lens does not try to fix the curvature from the lens and shows what is seen throughout this whole lens [94]. While the distortion for these lenses is present it does not take away from the quality of the image which makes it a good contender for a wide FOV camera.

3.18.2: Zoom Lens Design

The zoom lens entails motorized lenses that can shift the focal length of a lens. This lens system can have a wide variety of focal lengths. A smaller focal length produces a large FOV so this can be useful when trying to achieve a large FOV because the focal length can be minimized. These lens systems contain a focusing group, a variator group, a compensator group, and a master group [95]. The focusing group can focus the image by moving back and forth. The variator group can vary the magnification of the focusing group and is the most pivotal in changing the focal length [95]. The compensator group helps in focusing the lens as the focal length is being adjusted. This will move with the variator but will not move as much as the variator [95]. The master group corrected the field aberrations [95]. All these different lens groups work together to create a clear image as part of the lens system is moving. This type of lens design has application in security. This is because if something is detected the threat can be zoomed in and out of which can make identification of what is happening clearer.

3.18.3: Wide Angle Lens

A wide-angle lens has a focal length ranging from 16-35mm [96]. These lenses can capture a wide FOV with minimal distortion in the image. These lenses typically have an FOV of around 65°, which is just outside the FOV of the human eye of 60° [96]. Putting multiple of these lenses in conjunction with each other can create a FOV wide enough for the purpose of the pet collar. These lenses can still have some distortion and can produce distortion in the subject of an image. This, however, is not a concern for the pet collar as the image does not have to produce a pristine image, only one that is clear and can provide an identification of a predator.

Some security cameras can produce a very wide FOV with minimal distortion using wide angle lenses coupled with other lenses. The Reolink Duo camera, for example, can capture a 180-degree image [98]. This is done by placing two lenses across from each other, one on the left and one on the right so that this wide FOV is captured. While a wide-angle lens may not produce the widest FOV, it can still be effective in producing a wide FOV.

3.18.4: Final Lens Comparison

Ultimately a lens design like the fisheye lens design or wide view lens design would prove the most ideal for this camera. Both of these can be viewed in the figures below. The first figure denotes a fisheye lens design and the second figure denotes a wide view lens design. These will mimic the final lens design explored during the design and testing phase.

This is because it can produce the widest FOV. This will prove to be a more cost-effective outcome than trying to do more than one lens design containing multiple lenses. An example of a fisheye lens is shown in figure 2. To achieve this lens design, making a lens would prove to be very expensive. This is because of the size of the lenses. Lenses that can accommodate the size of the camera being used on the collar would need to all be very small and a lens system consisting of approximately six to eight different lenses. Creating this lens system would require making custom lenses for each of the lenses in the system. For this to be done it would be very costly, a rough estimate would be around five thousand dollars. This is way outside the budget of the project. This would also be very time-consuming as well and many not be able to fit into the time constraint of the project. The best solution to this issue while still getting the desired product would be to purchase a premade lens system found in either a lens kit or different wide field of view technology. After purchasing the premade lens system, the focal length, curvature, thickness, and refractive index would be tested for the lens to characterize each lens. The refractive index measurement would be used to find the approximate glass type of each lens. The chromatic aberrations would also be explored in the testing. All this information would then be used to reconstruct the lens system to fit the needs of our lens design. Purchasing a premade lens kit proved to be the best option. The lens kit provided had 10 different lenses with FOV ranging from ten to two hundred degrees. The lenses in the lens kit were all M12 lenses. This kit provided enough lenses for preliminary lenses to explore how each lens system was made and what these entailed. While the lens system could range drastically for the different FOV it would be able to give an idea of how these systems were tested.

Figure 6: Fisheye lens design. Arrow denotes direction of propagation

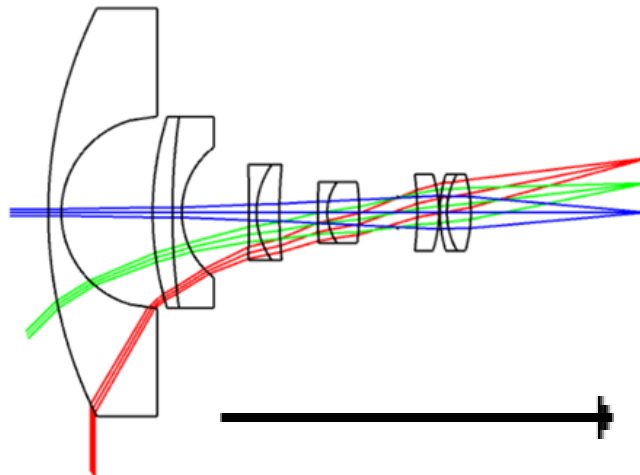
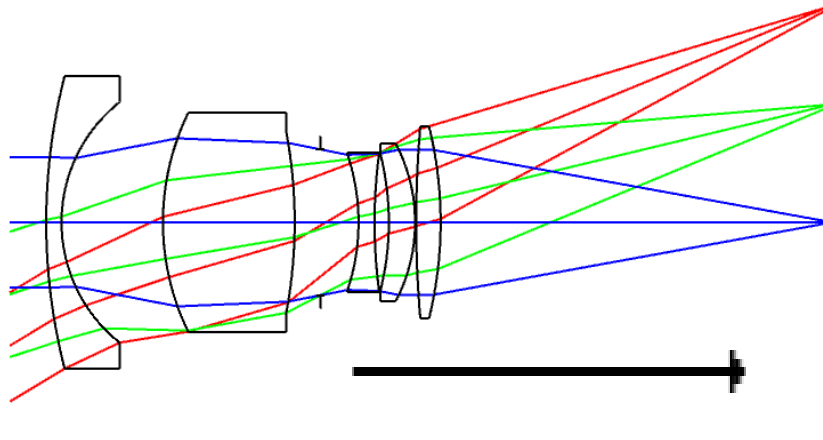


Figure 7: Wide Field of View camera design with arrow to show direction of propagation.



3.19: Vibration Motors

There are a few different types of components that could've been used to create a vibration for the correction component in the collar. We will explore the overall subtypes and also compare specific component options from each one.

One of the most common types of vibrating electro-mechanical components is aptly named vibration motors, or vibro-motors. These are the types of vibrations found in smartphones, video game controllers, and other electronics that require haptic feedback. They're generally affordable and versatile, which would make them a good fit for our project. They're designed with a weight attached to the shaft of the motor which causes a vibration when the motor spins. They come in both coin and linear types.

Another type of vibration component is the piezoelectric transducer. These use the piezoelectric effect, which is the phenomenon that a mechanical pressure can create electrical charges in specific materials, to create vibrations. These are often used in buzzers and for the same type of haptic feedback devices as listed previously.

The next electromechanical component to be considered is a solenoid. There are multiple different types, the most common ones being a rotary solenoid and a linear solenoid. They generally have a metal plunger that is resting inside a coil, and when an electrical current is applied to the coil, it generates a magnetic field that pulls or pushes the plunger based on the field direction. Due to Sara's previous experience using solenoids, we originally wanted to use one for our collar, however we've decided that the plunger would create too many potential problems and a different type of vibration would be better suited for our project. The small size of the solenoids that would fit inside the casing of our collar would also likely not be enough mechanical force to be effectively felt by the animal, thus rendering the vibration useless.

More specific types of vibration motors are linear resonant actuators (LRAs) and eccentric rotating mass (ERMs) motors. They're less common in consumer electronics

but are becoming more popular due to their precise and more realistic haptic feedback. LRAs consist of a mass attached to a spring and a voice coil. When an electrical signal is applied to the coil, the mass is moved back and forth at its resonant frequency. This is what creates the vibration. ERMs have an unbalanced mass attached to a rotating shaft which creates vibrations when the motor spins. LRAs and ERMs are both compact in size and would make a good fit inside the smart pet collar as there are no external parts that could get dislodged or affect other circuitry. They also can be adjusted in intensity by increasing or decreasing the applied voltage to make the vibration more or less intense, respectively. For these reasons, our project will only look at LRA and ERM type motors for the vibration component of the collar.

Below are a few options for possible components we could've used in our smart pet collar project. We will explore vibro-motors, ERMs, LRAs, and a solenoid.

3.19.1: Vybronic's Z-Axis LRA Coin Vibration Motor

This device generates a vibration in the Z-axis, which is perpendicular to the surface of the component. This orientation ensures that the generated vibration energy is directed towards the user's skin, enhancing the overall haptic experience. In contrast, other types of coin ERM vibration motors produce vibrations parallel to both the coin's face and the user's skin.

For haptic feedback applications, achieving fast rise and fall times is paramount to deliver an optimal user experience. Vybronic's LRAs excel in this regard, offering rise times up to 10 times faster and fall times up to 2 times faster than standard coin-type ERMs. Their straightforward internal construction not only ensures high reliability but also an exceptionally long operational life when compared to brush ERM coin vibration motors. This makes them an excellent choice for devices with limited battery capacity. For example, Vybronic's VG0832012 model draws a mere 19 mA at 0.6 V while producing a substantial vibration G force of 0.55 G_{RMS} .

To drive these LRAs effectively, an AC signal at the device's resonant frequency is required. For this specific model, the resonant frequency is at 140 Hz to 300 Hz. This model also has low power consumption, which is good for our project because we have a limited battery and need to conserve power as much as we can.

The information for this component was found in source [99].

3.19.2: Adafruit 1201 Vibration ERM Motor

The 1201 ERM motor is another contender for the vibrating component of our project. Sara already has one, so it would be beneficial if this is the component we decide on selecting. That decision remains to be seen until after further research is conducted.

The motor has an overall small stature at a 10mm diameter and lightweight, near weightless design. This makes it an ideal fit in the small size of the pet collar without weighing it down or hurting the animals' neck for extended wear times. It also is known

for its low power consumption, drawing a maximum of 5V while still delivering a substantial 11000 RPM.

The 1201 also has a very simple design, a total of one positive and one negative wire, which will make integrating it into our PCB very simple and ensure that the component is reliable in the long run. Although the axis of vibration is not specified, it's unlikely to be in the Z-axis like the previous example is, which means it will potentially be harder for the wearer to feel with less input voltage. Thus, this component will have to draw more power to deliver the same amount of force as other options.

The 1201 remains a possible candidate for our purposes, but considering all of the listed characteristics, it may not be the best fit for our needs.

The information for this component was found in source [100].

3.19.3: SparkFun Electronics Solenoid Push

This solenoid is a linear solenoid which involves a metal arm that extends out from the body. When a voltage is applied, the inside of the solenoid creates an electromagnetic force that pulls or pushes the arm to create mechanical movement. While solenoids can be used to create vibrations, it's not their primary purpose, and won't be as efficient or powerful as other options listed on the document.

Additionally, the arm is not held in the body of the solenoid and can be fully removed if there is no power applied, which is not ideal for the inside of a collar that may be turned around in any orientation. The vibrating component needs to be stable in the event that the pet wearing the collar is rolling around or if the owner takes the collar off the pet. If the owner has to maintain the upwards orientation of the collar to prevent the solenoid from falling apart, the design isn't intuitive or efficient. The solenoid could potentially be positioned so that the arm doesn't have the space to fall all the way out, however that would mean that the arm is still hitting against another component in the collar. This would eventually deteriorate the quality of the components and potentially break the collar in the long run. It could also become a safety hazard if the components that break expose live voltage to the animal wearing the collar.

The size of the solenoid is also not ideal for our project. The solenoid is long and would take up valuable space in the collar, which has strict size constraints as it is in order to fit on a pet's neck comfortably. Overall, a solenoid is not the ideal choice for our purposes, and we will move forward with a LRA or ERM motor which is specifically designed for vibrating without any parts sticking out.

The information for this component was found in source [101].

3.19.4: Kingstate KPEG130 Piezoelectric Transducer

Piezoelectric transducers are used in a wide variety of applications, including welding and cleaning. They also are extremely precise and can be controlled by the input voltage, which is one of the requirements that we want for our project.

This specific option also has a large stature at a 30.2mm diameter, easily the largest option thus far. Unlike the solenoid, there are no components that are sticking out that could potentially damage the rest of the circuitry, and it has more of an efficient vibration mechanism. It does, however, require more voltage than the other component options, which would mean it isn't as power efficient which is a necessary requisite for our collar.

Unfortunately, this type of component also includes a loud, high-pitched tone that continuously plays when the buzzer is given power. This tone is not part of our requirements and actually could pose a danger to the animal wearing it, as it might be in a frequency that is harmful to their hearing. Due to this, and the overall size of the transducer, we moved forward with a different option.

The information for this component was found in source [102].

3.19.5: Final Vibration Comparison

Below is a table listing some key characteristics of the above components. As was discussed earlier, these key characteristics include operating voltage, dimensions, inclusion of adjustable intensity levels, and price. The chosen component is highlighted in yellow.

Table 17: Vibration Final Comparison

Component	Operating Voltage	Dimensions (diameter x height)	Adjustable Intensity?	Price
Vybronic Z-Axis LRA Coin VM (VG1040003D)	0.14 V - 3.54V	10mm x 4mm	Yes	\$3.71
Adafruit 1201 Vibration ERM Motor	2V - 5V	10mm x 2.7mm	Yes	\$1.95
SparkFun Solenoid	2V - 5V	4mm x 20mm	Yes	\$5.50
Kingstate KPEG130 Piezoelectric Transducer	4V - 28V	30.2mm x 7.5mm	Yes	\$2.27

The Adafruit 1201 ERM Vibrating Motor was chosen due to its small size and optimal operating voltage. Solenoids are too impractical due to their physical design, and piezoelectric transducers make a potentially harmful noise that overshadows their utility, therefore the choice was narrowed down to the LRA coin and ERM motor. Due to the

operating voltage being a good range for the voltage the motor receives, the Adafruit 1201 motor was chosen.

3.20: Software Design Overview and Methodology

To tie all of the collar's features together, we will wirelessly connect the onboard microcontroller to the user's phone through an application. The application will give the user control over all of the collar's features and access to all of the collar's collected data.

3.20.1: Programming Languages

Programming languages are used to instruct hardware on how to behave. These languages have their own syntax, rules, capabilities, strengths, and weaknesses. Since there are plenty of different languages out there, deciding on the right one for us is a very important first step as we tackle the software design in this project. Before deciding on a programming language, we must define some terms that relate to our decision making methodology:

High vs Low Level Languages: A language is said to have a "level" associated with it, usually simply divided into being either high or low. Low level languages tend to be faster for the computer to process, but more difficult for the programmer to write, as they directly reference addresses and computer instructions. High level languages are much easier to understand on the human side, as their syntax is very close to english. However, high level languages lose out on speed, memory requirements, and power consumption, since the instructions must first be translated into machine code for the computer to run them.

IDE Availability: Integrated Development Environments (IDEs) are applications that allow developers to develop new software more efficiently. These applications boast a great number of quality of life features, such as syntax checking, IntelliSense, debugging, and more. As such, picking a language that has a useful IDE would make the software design flow much smoother for us.

Image Processing Availability: Since our project relies heavily on computer vision, choosing a language that provides good support for this type of project is crucial. Computer vision, especially when moving into the realm of image processing, is still new in the grand scheme of technological history. This will be one of the main deciding factors when it comes to languages.

Prior Experience: This simply means the team's experience with the language.

When taking everything into consideration, we arrive at four main candidate languages: Java, Python, C, and Swift. These languages all have native libraries for image processing, which is one of the most important things regarding our decision. We also already have experience in these languages, as they are the most commonly taught languages at UCF, our university. Additionally, they all have plenty of documentation and online resources which we can reference throughout the project. Below is a table comparing these four languages in terms of the aforementioned parameters.

Table 18: Programming Language Comparison

	Programming Language			
	Java	Python	C	Swift
Level	High	High	Low	High
Speed	Low	Low	High	Mid
Power Consumption	Low	High	Low	Mid
IDE Availability	Yes	Yes	Yes	Yes
Ease of Production	Mid	High	Low	Mid
Image Processing Support	Yes	Yes	Yes	Yes
Readability	Low	High	Low	High
Experience	Yes	Yes	Yes	No

Of these three languages, Python is definitely our first choice. Although C has the superior speed, it is the lowest level language of the ones we considered. This makes it the one that would be the most complicated to develop for, as we would have to manually deal with memory assignment and put the most effort into making sure the code is readable for the reviewers. Java seems like a step up, but does not provide enough positives to justify its use. While being generally easier to read and develop than C, effort would still need to be made to ensure proper readability. Furthermore, it is a very slow language that takes up a lot of power due to being high level [103]. We also considered Swift, Apple’s native language, solely for developing our companion application for iOS devices. However, the team has no experience with Swift, and have decided to move the iOS release of the app to a stretch goal.

All of these considerations leave us with Python as our language of choice for the collar. Python is a simple, high level language that is great for image processing and application development. Its low complexity makes it the easiest language to develop for, and there are many IDEs that support it. This does not mean that Python is the perfect language, however. By choosing Python as our language, we are sacrificing speed and power efficiency, which are going to be two major hurdles that we must contend with for the rest of the project. The power efficiency will fall to the hardware design, while the speed will require extra effort on the software side to ensure efficiency.

3.20.2: Application Development

The companion application is very important for the user’s experience with the collar. Nowadays, it is standard practice to include some sort of smart connectivity with your products. The most popular smart collars on the market currently all come with companion apps, so developing our own was necessary for breaking into this market. In order to be competitive, our app must include a variety of features already made standard

for the market, as well as the additional features that come with our collar. The app features account services, which are used to keep track of a user's unique data. These accounts are password-protected in order to keep the user's data secured. The user will be able to pair multiple collars to their account, and keep track of each collar's data individually. For each collar that the user has registered, they will be able to see their pets location information, the temperature and humidity around the pet, access the onboard camera, and set up geofences.

As a proof-of-concept, the application was first developed as an executable to be used on our PCs. We used the ESP32's built-in Wi-Fi functionality to transmit the data wirelessly to our devices. Developing this app for smartphones will remain a stretch goal for now, as making sure the collar work is our first priority with this project. Once the collar and application is developed, we will include a mock UI for smartphone devices as well.

3.20.3: Image Processing

One of our collar's capabilities is its threat detection system. The collar is outfitted with a wide angle cameras, which will provide a live feed of the pet's surroundings. Using this live feed, we trained our own computer vision model to detect anomalies in the pet's environment, and possibly trigger the deterrent system. For this, we will be training a computer vision model using OpenCV and TensorFlow in Python. The model will be trained on publicly available image libraries, which will be properly credited for their assistance in the training.

Our goal for our computer vision model is for it to be able to accurately detect birds of prey, such as hawks, and large dangerous animals, such as coyotes and boars. Eventually, we would also like to extend this model to detecting more elusive predators, such as snakes and large cats. Once the collar detects a possible predator, it will automatically engage the strobe lights in order to fend it off. This will also send a notification to the user's phone through the application, informing them that their pet might potentially be in danger.

With image processing comes a few possible problems, but the most pressing one will be accuracy. With a camera that has such a wide field of view, the images captured will be significantly distorted. Our first step will be to use OpenCV to digitally transform the images into straightened versions, so that the model will have an easier time processing them. Though the images will look mostly normal to a human eye after the transformation, there may still be small imperfections due to the camera's resolution that could confuse a computer model. In order to address this, we will conduct a long debugging process where we will test the model's accuracy out in the world. During this debugging stage, whenever the model detects what it believes to be a predator, it will provide us a snapshot of what it detected. There, we can manually review if its detection was correct or not. This debugging feature is one that might prove useful to include in the finished product, allowing the model to continuously train itself with user-reviewed data. This tactic aims to correct false positives, but it neglects the more dangerous problem that is false negatives. If the camera fails to detect a predator that is actually there, it could cause the pet to fall victim to a preventable attack. Fixing this will require a more

intensive approach, as the only solution would be to manually review hours of footage and spot the animals ourselves, and then relaying the newly marked footage back to the model. This would be incredibly time consuming, which is why we intend to add a second layer of detection to our model. Instead of only relaying back whenever the model is sure there is a predator, our vision model will additionally mark whenever it spots an “anomaly” in the environment. This should be much easier for the model to do, as spotting moving bodies against backgrounds should be fairly simple for a well-trained model. Then, all we have to do is categorize the anomalies as dangerous or harmless, and train the model off of those labeled images. This approach aims to nullify the false negative issue by forcing the model to report everything it sees, essentially trading in false negatives for false positives. This might cause the deterrent system to fire at times where there are no predators, however we believe that, when it comes to a pet’s safety, we would much rather our collar be more sensitive than it needs to be.

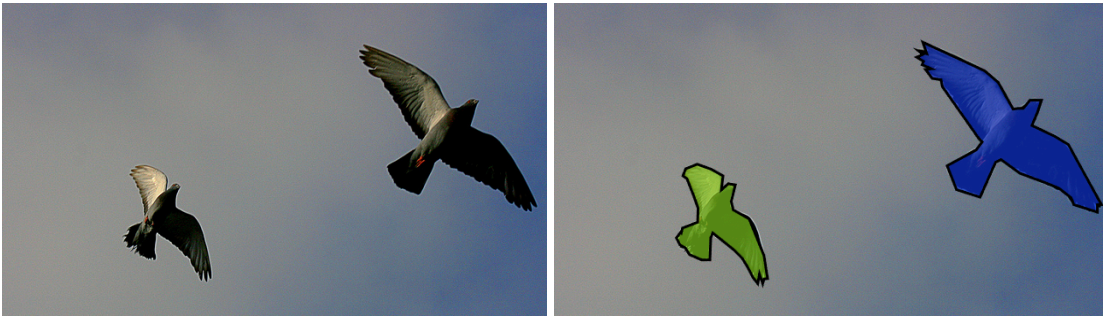
3.20.4: Dataset Selection and Training

Our goal for our collar is for it to be able to discern predators from a live video feed. For this to work, our model must be able to separate moving bodies from the background of the feed and categorize them correctly, which will require training. In order to begin training our predator detection model, we must first find a proper dataset to train it with. Selecting the correct dataset to use is crucial to our success, as the accuracy of our model is going to completely depend on the data it is being fed. As such, we must take great care in researching and selecting the proper dataset to use.

A dataset refers to a library of images compiled from multiple sources. These libraries contain thousands of images portraying various objects and animals which are designed to be used for machine learning projects. These images contain labels that a machine learning program can understand, and thus learn what the images contain. Having data like this is the only way that we can teach our collar to see, but our team lacks the resources to create our own, which means we must find publicly available datasets online.

One of our first looks at a possible dataset was the Common Objects in Context (COCO) dataset. This image library contains over 200,000 labeled images of common animals and objects [104]. When it comes to working on a video feed around a pet, we expect the pet to be surrounded by common things such as people, trees, other pets, doors, cars, and so on. The COCO dataset would then be perfect for understanding these day to day objects, as it was specifically created to train models to detect common images. It achieves this by providing images that have been curated for quality, accuracy, and lack of bias.

Figure 8: Unlabeled vs Labeled Image



Adapted from [104]

Above we see the difference between an unlabeled and labeled image. Since the computer cannot innately understand images the way a human can, these labels are the only way it can understand what exactly it is looking at. To a computer program, images are simply arrays of numbers describing the color values for each pixel on the screen. By labeling data, we give context to the numbers the computer sees. This allows the model to begin learning the shapes and colors usually associated with common objects, which will eventually allow it to look at completely new images and make inferences as to what the image contains. Now that we have labeled data, we can start creating a model that uses this data to see.

In order to utilize this data, we must decide on a model to use. For this task, our team has decided to use Python's OpenCV library. The OpenCV library is one of the most powerful image processing libraries available to python, and it comes equipped with many useful tools for accomplishing our task. Additionally, OpenCV comes equipped with the capability of running Neural Networks, which eases the complexity of the project significantly. For the beginning of this project, we are going to be using OpenCV's Deep Neural Network. OpenCV's DNN module is a centralized neural network, meaning that it comes pre-trained with proper weights, making it easy to set up and start from. Using this model, we can begin our work towards fine-tuning the weights and creating a proper predator detection system.

4: Standards and Design Constraints

4.1: Standards

Standards are documented specifications for products, services, and other processes that explain in detail how and why they should be designed, manufactured, or performed. It's important to follow a standard so as to maximize safety and efficiency. There exist standards for many different areas, including but not limited to: product, process, industry, performance, safety, environmental, national, international, government, and voluntary. Not every project requires standards from every section, and some will be more pertinent than others. For example, the Department of Defense has its own set of standards called Military Standards (MIL-STDs) which would be useless to the candy manufacturing industry.

For the purposes of our project, the applicable standards are product standards, industry standards, and performance standards. As we also have a mobile application, we must also take into consideration information security standards. Below, we will explore these areas more in depth.

4.1.1: Product Standards

Product standards specifically define the criteria of products' characteristics and properties, in order to ensure that all of the same products have consistent quality. Common areas of product standards involve specifications of characteristics, quality assurance, safety, and reliability [105].

In the case of our project, we adhered to the product standards that are related to wireless communication technology and data security, as our collar includes the use of location tracking and collecting data on the app for the owner's benefit. The standards involved are from organizations such as IEEE and Bluetooth SIG, as well as some standards set by the Global Positioning System (GPS).

For the data security in the app, we need to reference standards like ISO/IEC 27001 to protect our users' data. The ISO27001 is a recently updated standard that includes detailed documentation as to how to apply security measures to any product or business that deals with protected information [106]. It's most helpful in protecting information confidentiality, integrity, and availability (CIA).

A related document that is more applicable to healthcare technology, cloud hosting, and security, is the SOC 2, which is actually a voluntary compliance standard. A voluntary standard is one that businesses can opt-in to adhere to in order to demonstrate their commitment to quality [107]. This can instill a sense of trust in customers that will encourage them to entrust their data with our project.

4.1.2: User Interface Standards

Related to the wireless communication technology and security that was discussed above, the application that we must design must also follow certain software development guidelines. As our application is only compatible with computers as a proof-of-concept, we must comply with User Interface/Experience (UI/UX) design standards.

The central idea to these standards is the concept of predictability. Users should be able to understand how to use most of the features without having to read a manual or look it up. These include locations and imagery for common actions such as undo, save, exit, and search options. The user needs to feel comfortable using the application and know what to expect from the interface. To that point, it is also important that the UI is efficient and intuitive so as to avoid frustration in the user [108].

On top of that, an effective UI design should give the user the power to identify and recover from errors with only the interface [108]. Users should not feel pressured to contact a developer to resolve any problem they have; the interface itself should provide clear instructions, guidance, error messages, and solutions to ensure self-sufficiency.

4.1.3: Humane Animal Welfare Standards

In regards to the corrections function that we have decided upon, we must be aware of standards for animal welfare and humane treatment. Humane animal treatment is a fundamental concept that deals with the ethical and compassionate treatment of animals and avoiding unnecessary or cruel harm or pain. Shock collars are a commonly used training tool that apply an electrical shock to the neck of the animal wearing it, as controlled by the human, and can vary in intensity. Shocking the animal can lead to anxiety, stress, and physical pain, which can then lead to even more aggression from the animal as they don't understand what is happening to them [109]. Shock collars can even cause burns to the animals' skin. Vibrations offer a humane and pain-free method of "punishment" to mark undesirable behaviors in the animal wearing the collar, and have no physical side effects besides getting their attention.

Due to those, we have decided to use vibrations instead of a shock component. These standards are recommended by organizations such as the American Veterinary Medical Association (AVMA) as well as the American Humane Society.

4.1.4: Lithium-Ion Battery Standards

One of the most dangerous items of an electrical circuit is the power supply source which if left unchecked, could cause fires or even explosions within the circuit. In order to minimize the risk of utilizing lithium-ion batteries, many standards have been developed in order to protect consumers.

Lithium-ion batteries include protection circuits in their design in order to minimize risk during their use. One such standard that emphasizes the inclusion of safety in the design of lithium-ion batteries is the International Electrotechnical Commission's IEC 62133 standard [110]. This standard lists necessary components needed to ensure the safe construction of a lithium-ion battery and includes common problems a battery might encounter while in use. In response to some of these common problems, lithium-ion batteries include protection circuits to help protect against overcharging the battery, overheating as a result of a battery short circuit, and overly discharging a lithium-ion battery. Lithium-ion batteries also utilize a fuse in their design in order to stop the flow of electricity in the case where the current draw from the battery becomes too large. By doing this, lithium-ion batteries are able to turn themselves off before the circuit overheats which would result in a fire.

Lithium-ion batteries also include necessary standards needed to ensure they can be safely transported. The International Electrotechnical Commission lists standards that should be followed during the transport of lithium-ion batteries in their document IEC 62281 [111]. This document lists common tests and conditions all lithium batteries should be able to go through including differences in temperature, impacts that may occur during shipping, a puncture in the battery, slight shifting in the packaging, and vibrations the battery may experience. Having these requirements ensure that a lithium-ion battery is able to safely reach a desired destination without causing harm to those who are transporting the material. Additionally, these requirements ensure that when a lithium-ion

battery is built into a system, that system has similar protections against similar things that may occur like slight shifting in a pet collar.

We ensured that we are adhering to energy efficiency and safety standards set by the Institute of Electrical and Electronics Engineers (IEEE). The specific standard that addresses rechargeable batteries is called IEEE 1625, and it applies specifically to lithium-ion and lithium-polymer batteries that are used in a variety of portable devices. IEEE 1625 addresses evaluation procedures for performance, charging and discharging requirements, safety requirements, and physical characteristics of the battery itself.

4.1.5: Internal Communication Standards

In order to ensure multiple devices are able to communicate with each other, numerous communication standards have been created. Standards like universal asynchronous receiver and transmitter (UART), serial peripheral interface (SPI), and inter-integrated circuit connectivity (I2C) are universally used across numerous sensors and devices allowing for them to be easily implemented and utilized in a variety of projects.

One communication standard that was utilized in this project is the I2C communication standard. I2C allows multiple devices to be connected to a single communication bus. In order to transmit data, a wire communicates the address of the device that it wants to send information. In return, the specified device sends the requested information. This process is done through the use of two wires, the serial clock and serial data wires. Most microprocessing units and many sensors on the market utilize the I2C communication standard which allows for the portability of many sensors across different projects.

The Universal Asynchronous Receiver and Transmitter standard (UART) was also utilized in this project. UART is a communication standard that utilizes wires and a clock signal in order to transmit information one bit at a time between devices. The rate of transmission is dependent on the baud rate that is set when programming the device. In order to receive the transmitted data, the receiving device is set up to read the transmitted data at an equal baud rate. The UART standard, unlike I2C, only allows a single device to be connected to the communication bus of the device which ensures that a single bus is entirely dedicated to communicating with a single device. UART was utilized in this project in order to transfer code onto the selected microprocessor chip.

4.1.6: Data Standards

When it comes to storing user data, there are certain standard terminologies that allow different systems to communicate with one another without mixing up the information. The software development side of this project relies on basic data type standards for gathering and identifying information. Data types such as integer, boolean, and string were used in all areas regarding programming. Additionally, our database makes use of the standard schema SQL for defining relationships between our stored data.

As part of regular operation, SAFEPADS collects GPS location data and video data that could potentially capture the user, the user's family, and the user's house. It is therefore very important that we treat this data very carefully and adhere to as many national

standards as possible. Although we do not have plans to sell user data to any extent, it is still important to be aware of these standards. Regulations such as the Electronic Communications Privacy Act (ECPA), Children's Online Privacy Protection Act (COPPA), and the California Consumer Privacy Act (CCPA) are all regulations that have been created in order to regulate what kinds of data companies are able to collect, and what they can do with said data. Pertaining to us, we mostly have to worry about the user being aware that the collar is collecting video recordings and that children may be captured on video. In order to adhere to regulations regarding this, we must ensure that the users give their express consent to being recorded. Additionally, if the user has any children, they must also have access to and control over any recordings that contain their child, as per the COPPA. Failure to adhere to these standards could see us facing legal repercussions for violating the user's privacy [112].

On top of making the user aware of the data being gathered, we must also ensure that the data can only ever be seen by intended parties. Since our product could possibly gather incredibly sensitive data, we must ensure that this data is kept as safely as possible. Any user data that the collar gathers must be password protected and encrypted, and must be stored in such a way that only certain users on the network are able to access it. Failure to properly secure this data could be catastrophic for both us and the user. If there were to be a data leak, third parties would be able to gain access to the user's location and potentially what their house looks like. In order to address this privacy concern, we must make sure that once the video data is captured and used for training/predator detection, the data must be deleted completely. We do not need to keep all the video taken from the camera, only those moments that could potentially be used to better train our predator detection model. If the data does not contain valuable training information, or if it contains sensitive details such as the user or their family, it can be deleted to ensure user privacy and safety. By adopting this practice of deleting video data that has already been used, we can avoid any possible problems arising from improper management of the data.

4.1.7: LED Standards

In order to promote eye-safety, this design opts for LEDs instead of laser diodes as light sources. However, it is still important to keep in mind that, while LEDs are generally considered to be safe for viewing with the naked eye, especially in comparison to light from lasers, they are not inherently without eye safety and other safety risks in the case of improper use.

One standard particularly pertinent to this project is IEC 62471. This standard outlines potential photobiological hazards for incoherent light sources, including LEDs, and defines exposure limits and safety classifications for these sources [113].

While the contents of this standard were not accessible by the team, and compliance information was not available from most producers of suitable LEDs for this project, one article was found with relevant information regarding this standard. Per the article, while exposure to visible LED sources at high powers is made safer due to the instinctual responses of blinking or averting one's eyes upon exposure, these responses are not protective against infrared sources, which highlights the importance of adhering to safety

standards when using them. The article states that for exposure times greater than 1000 seconds, the maximum permissible exposure of the lens/cornea to a source with a wavelength of 940 nm, the wavelength utilized in our project, is an irradiance of 100 W/m², and also includes a graph relating exposure time to permissible exposure limit. Furthermore, for exposure times greater than 10 seconds the maximum permissible skin exposure to a 940 nm LED source for a period 3.6*10³ W/m². In compliance with these standards, all 940 nm LEDs used emit light at a lower irradiance than these limits at a reasonable viewing distance and exposure time, as they present the potential for continuous exposure [114].

This project also adheres to common sense precautions to promote LED safety. These precautions include powering the LED at a voltage and current no greater than that intended by the manufacturer, and refraining from incorporating design elements that focus the LED light into a small, high-irradiance spot in a location accessible for viewing with the naked eye by both the animal on which the collar is placed and those who may view the collar. We also advise users to refrain from purposely staring directly at the LED lights within our product for long periods of time or attempting to touch one's eye to the LED to further promote eye safety.

4.1.8: IEEE 802.11 Wireless Communication Standard

One important requirement for this project is the ability to wirelessly communicate and transmit data to an external device and therefore the IEEE 802.11 wireless communication standard has great importance to this project. The IEEE 802.11 standard establishes a set of requirements to ensure that wireless devices utilizing the standard can communicate with one another. One way they ensure communication with a wide variety of devices is by creating standard frequency bands that are utilized for transmitting data. The frequency bands specified by the IEEE 802.11 standard are most commonly the 2.4GHz frequency band and the 5GHz frequency band. The 2.4GHz frequency band is utilized because it provides longer data transmission ranges and is able to penetrate common obstacles found within a house like walls and furniture. The 5GHz frequency band is utilized because the higher frequency is able to provide faster data transmission rates but is not able to achieve the same ranges and object permanence as the 2.4GHz frequency band. By standardizing the use of select frequency bands, devices are able to know what frequencies to search and transmit with and are able to filter out unnecessary noise from frequencies used for other purposes. The IEEE 802.11 standard also includes rules for modulation and demodulation of a transmitted signal. One of these is the utilization of orthogonal frequency division multiplexing where data is transmitted over closely spaced frequencies in order to increase the rate of data transfer. The IEEE 802.11 standard also utilizes direct sequence spread spectrum (DSSS) to increase a signal's bandwidth and reduce interference with other signals.

The IEEE 802.11 wireless communication standard can be further divided into different versions that have various benefits and drawbacks associated with them. The ESP32 microcontroller, which has been chosen to be this project's microprocessing unit, allows the utilization of 802.11b, 802.11g, and 802.11n. A document by Tektronix goes into detail on what different versions of the 802.11 standard offer [115]. The 802.11b standard

operates in the 2.4GHz frequency band and offers data transfer rates of up to 11 megabits per second. This standard only utilizes DSSS to transmit data which can result in slower speeds compared to some of the more advanced versions of the IEEE 802.11 communication standard. The 2.4GHz frequency would be useful for obtaining a larger range the smart pet collar can be utilized within and the speed of 11 megabits per second would be enough to enable video streaming from the device. The 802.11g standard also operates within the 2.4GHz frequency band but incorporates orthogonal frequency division multiplexing to obtain a maximum data transfer rate of 54 megabits per second. Using the 802.11g standard would offer the same frequency benefits as the 802.11b standard but would also provide more data transfer allowing for better video quality and faster transmission of data. The 802.11n standard operates in both the 2.4GHz and 5GHz frequency bands which allows it to provide both a wide range of coverage and fast data transmission speeds. The ESP32 microprocessing unit only utilizes the 2.4GHz frequency of this standard and allows for transmission speeds up to 150 megabits per second which would be more than required for an efficient transmission of data.

Adhering to the IEEE 802.11 standard is important for this project to ensure that the created prototype is able to communicate with a wide variety of devices. Utilizing this standard also ensures that the created device will have an efficient transfer of data. Furthermore, this standard ensures that the created device generates data that is able to be read by a receiver and ensures that data transferred to the device will be readable.

4.1.9: Video Surveillance Standard

Although there aren't any specific laws prohibiting the act of recording video, there still exist certain privacy and consent regulations to be aware of [116]. The regulations differ slightly in public places compared to private, such as bathrooms and changing areas. Due to the nature of putting cameras on animals, it is impossible to prevent the animal from wandering into a place that would be considered private where privacy and consent laws become more defined. In Florida specifically, however, video surveillance is allowed in public spaces and consent is not required.

4.2: Design Constraints

Design constraints refer to the limitations to a products' design that must be taken into consideration when developing something. These constraints can come from various areas and help define the boundaries within which the product design must exist. Common types of design constraints are budget, time, resources, and space constraints. The applicable constraints that our project faces are discussed below.

4.2.1: Economic Constraints

While this project is sponsored, the amount of funding we receive from our sponsor is limited. Thus, the components that can be included in our project are limited to those that are affordable within the budget our sponsor provides and any additional funding provided by our team members out-of-pocket. As a result, we had to balance affordability with performance for all components. This is especially the case with optical components, as lenses and other optical components from leading manufacturers can range from relatively affordable to extremely expensive.

Additionally, our capacity to experiment with various components in our design is constrained by budgetary limitations. Given our inability to order and test a multitude of components through trial and error, we needed to be thorough in our calculations and simulations throughout the design process to ensure that most, if not all, of the components we order are those necessary to create a functional product.

4.2.2: Manufacturing Constraints

Given that we have limited access to professional manufacturing facilities, numerous manufacturing constraints affected the execution of this project. One notable challenge stems from the compact size of our product. Knowing that a significant portion of our project required manual assembly, we ensured that small optical components remained large enough for manual assembly with enough precision to create a working product. Furthermore, we also selected electronic components meticulously, giving preference to smaller options of applicable components (i.e. chip resistors instead of through-hole resistors) and also troubleshooting the PCB layout to ensure the design is as compact as physically possible. These choices made the end product difficult to assemble due to the nature of soldering by hand instead of by a precise machine. Since it was necessary to build a bigger product with larger components for easier assembly, the project featured additional solutions to support the weight of these components, such as extra straps that distribute the weight of SAFEPADS comfortably on its wearer. Wiring and cable management were also a factor considered when assembling the finished product, and careful planning early on to ensure efficient routing and prevent clutter was crucial to the final design.

Another challenge that we faced due to our lack of professional manufacturing facilities is that we were forced to assemble the optical components incorporated in this project outside of a cleanroom environment. Ergo, we were mindful of maintaining cleanliness to the greatest extent possible by cleaning optical components throughout the assembly process and by choosing components that are not particularly vulnerable to damage.

Furthermore, manufacturing constraints affect our ability to make a durable housing for the collar components. Certain materials, like metal, are impractical for us to utilize because our team lacks the necessary equipment and expertise, despite their superior durability in safeguarding our components. Thus, we limited our choice of housing materials to those that can be easily 3D printed and to pre-made parts.

Because we are not manufacturing many of our components, we also must consider supply-chain issues that occur outside of our control, such as shortages or shipping delays. To minimize the potential impact of such situations, we had to ensure that components to be purchased were received in a timely manner. Furthermore, we strived to order selected components as early as possible in order to prevent the possibility that they may become unavailable later. Nevertheless, we must be cautious to strike a balance between managing this manufacturing constraint and managing our economic constraints by thoroughly considering the necessity of the parts that we order rather than over-ordering parts that end up unused.

4.2.3: Health and Safety Constraints

Given that our project was conceived with the intent of promoting the health, safety, and wellbeing of pets, minimizing negative health and safety impacts of our product on both pets and their owners is one of our priorities. We made every effort to securely house electronic and optical components to eliminate any opportunities for pets to chew on them or accidentally ingest them. We also strove for this housing to protect the electronics from water, which could pose a hazard for electric shock if it entered the system. We also avoided exposed live wires either, as this would create a high probability of electric shock hazards. Additionally, it's crucial for the collar to fit snugly to prevent animals from getting their jaws caught underneath it or having the collar become snagged by objects during their daily activities.

Additionally, electrical components are known to output heat when being utilized. Since electrical components are unable to use all the supplied energy with one hundred percent efficiency, some heat generation in the device is inevitable but it is important to minimize how much heat the device produces. An excess amount of heat could cause discomfort toward a pet. Additionally, if too much heat is generated by the device, it could result in burns which would cause unnecessary pain to the pet and would also result in legal issues due to the harm the product caused to an animal. Due to this, every effort was made to efficiently use all the energy within the power supply, which minimizes the amount of heat generated by the device.

There are also constraints that our optical systems must adhere to in order to minimize health and safety risks. The strobe light source on our product must be directed away from the eyes of the pet wearing it so that it fulfills its intended purpose of disorienting a potential predator without jeopardizing the pet by disorienting it or interfering with its vision. It must also only turn on for a short time period as needed, so as not to scare the pet wearing it more than is necessary to protect its life.

The Indoor Location and Fencing System must also utilize a transmitter light source that is eye-safe. While it is not advised to look directly at bright light sources, pets and small children cannot be expected to know this. Thus, they must be able to look at the light source from a close distance for a short time period safely. Using LEDs or laser sources which are deemed eye-safe ensures adherence to this safety requirement.

Furthermore, the light source used in the indoor supplementary location system transmitter should not impact the circadian rhythm of people or pets. There is a dearth of studies examining the impact of infrared light exposure on circadian rhythm in both people and animals. Still, a 2022 study found that daily prolonged (3 hour window) direct exposure in the morning to a light source emitting at a wavelength of 850 nm did not affect sleep circadian rhythm in humans, so they are extremely unlikely to suffer from indirect exposure to a similar light source [117]. Similarly to humans, the range of wavelengths dogs can see is confined to the visible region, so it can be reasonably inferred that short-term exposure to an infrared light source would not affect their circadian rhythm [118]. However, photoreceptor pigments in cats' eyes do appear to have

some sensitivity to light of wavelengths as long as 900 nm, particularly in dark conditions, so a wavelength longer than 900 nm was used to minimize the probability that the transmitter light source would affect the circadian rhythm of cats [11].

4.2.4 Time Constraints

This is not a project that we had unlimited time to complete. Due to the nature of this course, our group needed to meet certain deadlines and complete the design before a predetermined date. This means we do not have the privilege of changing our timeline as the project progresses, and we must adhere to certain deliverables over the course of the semester. Failure to comply with these time limitations could result in serious delays to the overall development of the smart collar, and could potentially jeopardize our performance in the course. Failure to complete the course would in turn have serious repercussions for every group member, as it would delay their graduation and potentially cost us real world opportunities. Due to this, each group member is dedicated to keeping an organized workflow schedule and working together to stay on top of deadlines.

Another timing related constraint is that of lead time and delivery times for our electrical components. As previously mentioned, our group does not have access to any manufacturing facilities for our components, so all of them were ordered from and delivered by providers. Although it is not as serious as during the Covid-19 pandemic, we are still experiencing extended lead times for most electronic components. In some cases, we are still seeing over 8 weeks of expected lead time for boards, power supplies, and basic electrical components. Running into a situation where we are unable to find a necessary component already in inventory could be potentially devastating to our project's timeline [120], [121], [122]. To mitigate this risk, our team has been proactive in ordering materials and done extensive research to find in-stock suppliers.

Ordering components early does not completely guarantee our safety, as the ordered materials could become damaged due to the nature of our project. Since our collar is meant to be used by animals in outside conditions, damage to the prototypes was considered to be a pertinent risk. If components become damaged beyond repair, our team would have no recourse but to order replacement components. This was a particularly dangerous time-related risk, as we had no way of knowing which components are going to need replacing until they have already broken, which could be deep into development. For this risk, we planned to monitor the market of components and remain aware of any components becoming scarce. Once we ordered all of our necessary components, we planned to set aside a portion of our budget for preemptively ordering replacements for components that we believed could become easily damaged during the testing of our prototypes.

4.2.5: Environmental Constraints

Throughout the project, our team faced multiple environmental design constraints. This is mainly due to the unpredictability of a pet's movement as well as what is encountered when the pet is outside. The environment design constraints include image processing at high speeds, different outdoor climate conditions that affect image processing and the strobe light effectiveness, brightness of the strobe light, different things blocking the

camera that could limit the field of view, and accurately portraying a pet's indoor location.

When the pet is moving at fast speeds the image processing will need to keep up with these movements and give accurate images of the pet. To fix this issue, we have to use a sufficient frame rate to capture a relatively clear image. Since the collar cannot remain in a fixed position on the pet the camera may bounce around or get moved when the pet is moving. This will affect the image being processed because the image processing will have to account for the speed of the animal and the movement of the camera, and it provides a heavy constraint on the effectiveness of the camera due to these environmental factors.

Many different environmental factors will impact the quality of the camera picture. When the pet is outside things like rain, cloudy conditions, and darkness are things that could make the camera ineffective in developing a clear picture that can be provided to a pet owner. The image processing of the camera picture will have to account for this as well as still considering the different motion of the pet and camera.

The camera that is put on the pet will also need to have a wide enough FOV to curate an image that is accurate of the pets' immediate surroundings. This resulted in needing to put in more than one camera to achieve a sufficient FOV. There are different things that could block the camera which would limit the field of view. This could be the pet's head getting in the way depending on where the collar is positioned. Different things the pet encounters could also limit the field of view.

The strobe light must be bright enough to scare away predators during the day and night. This means the strobe lights need to produce a bright enough illumination so these predators can be scared off during the day as well. The strobe light is installed in the collar which means the light may get moved around when the pet is moving. This would pose an environmental constraint because depending on where the collar is the strobe light may be ineffective in scaring off a predator or even risk blinding the pet. The collar must remain as fixed as possible on the pet to avoid these risks.

The Indoor Location and Fencing System needs to provide accurate information from within a certain location in a home. The signal may get feedback if there are other signal sending devices located within a house. If the pet is moving at very fast speed, the signal may not be able to transmit fast enough for the receiver to pick up on the location of the pet. The receiver must also differentiate between instances of signal receipt in order to detect whether the pet is entering or leaving a room, which may not be able to be deciphered depending on how the signal is processed.

All of the collar's gathered data needs to be transmitted back to the app for storage and display. This data is transmitted to the collar using wifi signals. When the pet is outside, it is likely to exit the range of any accessible wifi networks, meaning that the user would lose live access to many of the collar's features. In order for the data from the collar to remain accurate, we would need the collar to store the data that it gathers while outside wifi range and upload it once it returns to a familiar network. However, in order to keep

the pet safe, the collar must still continue to function autonomously when outside of wifi range. The collar must still be able to monitor the pet's temperature, humidity, position, and still be able to engage the defense mechanism if necessary. This means that not only will the collar be storing data for later upload, it will also be needing to actively process and use this data without being connected to the network. For this to work, the processing needs to be happening on board the collar, which will also tax our battery life. The collar can't just go off the grid once it's outside either, as it still needs to send alerts to the user if anything bad is happening to the pet. In the event that the pet is too far away to communicate with the user's registered device, it must still be able to ping the user and display the pet's GPS location using the on-board GPS chip. This restriction will mostly apply to pets that are allowed to free roam, such as outdoor cats. In the event that the collar is running low on power and the pet is still far away from the house, the collar will need to shut down some non-vital features in order to conserve battery life and allow the GPS to remain operational until the owner retrieves their pet.

4.2.6: Social Constraints

The social constraints that this project may encounter is the theoretical willingness of a customer to invest in a multifaceted collar. The average pet owner may be apprehensive to pay for an expensive pet collar when there are many collars that they presume will be fine for their pet. The smart pet collar may only be marketable to certain clientele. This clientele would be pet trainers, as it is a good tool to train pets, and people of the upper and upper-middle class. The cost of a pet is already expensive, and some may find a pet collar of this cost to be essentially not necessary for the health and wellbeing of their pet. While the smart collar offers many innovative and beneficial features, some may deem it as unnecessary. Pet collars on the market can be very costly, many costing hundreds of dollars. Many pet owners may not be looking for a collar with all the features of a smart pet collar. The main concern of pet owners is tracking their pet and there are much simpler solutions to this problem, including a microchip being put into the pet, an Apple Air Tag, or other devices that have GPS tracking. These solutions are much cheaper and therefore more attractive to pet owners. If people are looking for just one feature the smart pet collar has, it will pose a challenge to make the smart pet collar seem more attractive to these customers.

Our smart pet collar offers a vibrating mechanism that assists in geofencing for pets. Using this mechanism, however, requires training the pet. In theory, this sounds like something that is attractive to pet owners, but some pet owners may not feel that this is worth the cost. If they are paying the hundreds of dollars to purchase this collar and then still must train the pet, the time and cost of this may not seem worth it to a customer.

Additionally, the created product may allow for pet owners to monitor their pet from remote locations. The inclusion of cameras, indoor and outdoor geofencing, and vibrations allow users of the product to monitor and discourage their pets from doing certain actions even when they are not at the same location as the pet. Every day, people are paid to monitor pets when homeowners are away to ensure the pets do not participate in undesirable activities like sitting on the couch or scratching furniture. The inclusion of technology to monitor and discourage pets actions could result in pet sitters losing their

jobs due to their no longer being a need to monitor pets throughout the day. As a result, people who are employed to monitor pets may be left with a diminished amount of pay each day which could make people dislike the product. This could lead to decreased sales of the product if it ever went into production due to the displeasure with the jobs it is displacing.

5: ChatGPT and Similar Platforms

The emergence of the large language model (LLM), which includes ChatGPT, is a major technological breakthrough that will have lasting impact on many facets of modern life. LLMs are a type of neural network (NN) which specializes in language processing. Models like this are trained on massive amounts of data and are able to generate new text when prompted. They are also able to follow conversations, make predictions based on information, summarize content, and complete many other advanced text-based problems. This is, of course, all dependent on the model's robustness. Although these tools are very powerful and constantly getting better, there is still a ways to go before they achieve human levels of authenticity and adaptability. While they are able to pour over sources and answer complex questions in a fraction of human time, they lack the ability to scrutinize their own findings and double check their work.

Currently, the two most powerful and popular LLMs available for free to the public are ChatGPT 3.5 and Bing Chat. Both of these platforms are language models that were trained on large amounts of data and are capable of completing most language-related tasks asked of them. Though they share these similarities, there are still some key differences between them that are important to acknowledge before moving forward.

An LLM is only as good as the data it's trained on, so understanding where the model's knowledge comes from is necessary for assessing its value to our project. Although the models do not divulge the specifics of their datasets, we can still receive a general response regarding this subject. Here's what ChatGPT has to say regarding its training:

Prompt: "What type of data was used to train you?"

Output (Abridged): The training process involved a massive dataset consisting of websites, books, encyclopedias, research papers, and conversational data. [...] It's important to note that my training data is static and was collected up to my last knowledge update in January 2022, so I may not have information on events or developments that occurred after that date.

As we can see from this output, the greatest drawback of ChatGPT 3.5 is the fact that its knowledge base has not received an update since January 2022. This could become an issue if we ever try to use ChatGPT anything that relies on specific data points or statistical data. This problem worsened throughout the project, as ChatGPT's knowledge only became more and more out of date. This is an issue that Bing Chat sought to correct, as we can see in their model's response:

Prompt: "What type of data was used to train you?"

Output (Abridged): “Bing Chat uses live internet data to train its model. [...] Bing Chat uses a technology called Prometheus that combines the Bing index, ranking, and answers search results with OpenAI’s GPT models.

From this output we can see that Bing Chat uses a similar model to ChatGPT, but combines it with the Prometheus model to allow Bing Chat to train itself on live internet data. This gives it access to up to date information and statistics, making it much more reliable for projects that require accurate statistics. This increased accuracy does come at another cost, however, that being that Bing Chat was created as an extension to Microsoft’s search engine. Being part of a search engine means that Bing Chat is designed more so for information retrieval and answering queries, rather than conversational tasks. It is also specifically integrated into Microsoft’s browser, making it hard to integrate into any different platforms. Overall, both platforms have things that they particularly excel at, making the decision between them come down to what is needed in the moment.

A drawback that is inherent to LLMs is that they will only ever be as good as the data they are trained on. Being programs, LLMs cannot yet truly learn and apply knowledge the way humans do. Even if they have access to a wellspring of information, their responses will always be limited to the information that was trained into them while they were being created. This is one of ChatGPT’s most notable flaws, as the LLM was only trained on data as recent as 2021. This means that, as time goes on, ChatGPT’s information slowly becomes more and more out of date, and it lacks the ability to retrain itself on new, current information. We must be aware of this flaw whenever we use ChatGPT for anything that involves sourced data, as it is likely that more up to date data exists.

Another limitation of LLM platforms is that they often output factually incorrect or nonsensical information that is irrelevant or contradictory to the data on which they are trained. This phenomenon is referred to by the term “hallucination” [123]. There are two main contributors to hallucinations in LLMs: source-reference divergence and innate divergence. Source-reference divergence refers to when the LLM incorrectly pairs two pieces of information as one being the source for the other. This could occur when data is presented in ways meant to be easily readable to humans, such as a table summarizing important information in an article. The LLM could mistakenly determine that the table is the source of the information, and then try to find statements supported by the table in the text. Another cause for this type of divergence would be duplicate data being presented to the model. Since these models are trained on enormous amounts of data, it becomes humanly unfeasible to manually filter out any possible duplicate data point. The LLM then incorrectly considers these data points completely different, and ends up biasing itself towards the repeated data. The second form of divergence, innate divergence, is found due to the nature of the LLM itself. Different models are developed for different purposes, and as such, come with innate biases towards their design. For example, models aimed to hold more casual style conversations might mention related facts to the conversation, even if the fact is not present in the input history. This too causes the model

to diverge from the truth, making it slowly build up these hallucinations of data points that just reference and source themselves.

It must also be mentioned that, being man-made, the model's biases could largely come from their developers. The people who develop these models choose the weights of the model's neurons, what data it is allowed to perceive, and what classifies a good or bad answer. Models today are trained on such large data sets that such biases are unlikely, but we must still scrutinize the responses for ourselves.

Considering their capabilities and limitations, choosing to utilize LLMs throughout the completion of our Senior Design project has had the potential to both significantly improve and hinder our team's overall learning experience and the success of the project.

Despite our ultimate decision to accept a sponsored project idea that offered numerous potential directions for development, LLMs were still a helpful resource at the start of Senior Design because they facilitated the generation of creative project ideas which we could further explore. For instance, given that one team member has a strong interest in music, an abridged example of the use of ChatGPT 3.5 to generate some music-related project ideas is below:

Prompt: "Provide ideas for new light driven musical instruments."

Output (Abridged): "Creating new light-driven musical instruments can be a fascinating and innovative endeavor. Here are some ideas for such instruments..."

Optical Theremin: Develop a theremin-like instrument that uses hand movements to control the proximity of hands to light sensors. Adjusting the distance would produce different tones and modulate sound effects.

Optical Synthesizer: Design an optical synthesizer that uses light signals to manipulate sound parameters like frequency, amplitude, and filters, creating a unique and dynamic sound palette...

Laser-Driven Music Box: Reinvent the traditional music box by using lasers to trigger the delicate mechanism that plays music, with different laser patterns generating unique tunes..." [124]

While not all of the ideas generated by this prompt were feasible for a senior design project, the possibility of an optical theremin, for instance, was further researched and eventually evolved into an idea for a cello that utilizes laser diodes rather than traditional strings. In light of experiences like these, it is evident that ideas generated by ChatGPT encouraged us to think creatively and explore a wide breadth of ideas as we decided on the idea for our ultimate senior design project.

Considering LLM-generated ideas not only yielded possible directions our project could take, but also helped us to clarify to each other our strengths, weaknesses, and areas

where we aspire to improve as emerging engineers in a way that may not have happened without the discussion of these ideas that included aspects outside of our scope or expertise. For instance, one idea suggested by the LLM was an animatronic scare actor [125]. Through discussion of this idea, we learned that one of our team members has an interest and background knowledge in robotics, which could be helpful in the execution of many projects revolving around robots or autonomous systems. On the other hand, we were able to clarify that, as a team, we do not have enough knowledge of mechanical engineering to build a mobile robot with many moving parts, such as an animatronic character. This acknowledgement of our limitations, prompted by the LLM's idea, helped to narrow the scope of project ideas that we would devote serious consideration to. Using LLMs has also benefited our learning experience in senior design by providing us with a means to quickly receive grammatical and stylistic suggestions when we are having difficulty phrasing particular ideas or passages within this documentation. This capability has helped us tremendously in completing our documentation efficiently while ensuring that our technical information is conveyed clearly to the reader. An example of such a revision is below:

Prompt: "Revise: Ergo, incandescent lights will become even less common in homes and optimizing the system to work in the presence of incandescent light bulbs as opposed to other types of ambient light sources, which emit light within a common wavelength range, should be of minimal concern. Thus, the wavelength chosen should be outside those ranging from 450 nm to 750 nm."

Output: "Therefore, incandescent lights will become increasingly rare in homes, and prioritizing system optimization to accommodate incandescent light bulbs, as opposed to other ambient light sources emitting light within a typical wavelength range, should be of minimal concern. Consequently, the chosen wavelength should fall outside the range of 450 nm to 750 nm." [126]

While the content of both passages is the same, the output is phrased much more clearly than the input. Specifically, the run-on sentence in the input passage was made more concise while still preserving its overall meaning, and some wording was changed (eg. "even less common" was changed to "increasingly rare") to more precisely communicate the intended ideas.

Despite the fact that passages revised by an LLM are often better stylistically than the input passage, even if they require a few subsequent tweaks, our team has experienced some instances where the LLM was unable to generate a passage that our team members deemed superior to the input text. In particular, with ChatGPT, this was often the case because the output was overly verbose or repetitive in its language, which is a known issue in text generated by ChatGPT, per OpenAI [127]. Still, even this poor output was often helpful, because it could help us identify a better means of articulating a given idea by examining the commonalities between the input text and the unsatisfactory output.

On the other hand, there are instances in which use of LLM platforms could harm our learning experience in senior design, should their output be utilized without awareness of their limitations. For instance, while it is tempting to consult an LLM for information

relevant to our project, utilizing information given by an LLM to make design decisions without verifying that it is factually correct could cause the resulting decisions, and, thus, the project, to be unsuccessful. An example of such factually incorrect information produced by an LLM is given in the following prompt and output generated by ChatGPT 3.5 during the course of this project:

Prompt: “What are the advantages of using a laser diode over an LED?”

Output: “1. Coherent and Directional Light: Laser diodes emit coherent light, which means that all the photons are in phase and have the same wavelength. This results in a highly directional beam of light with low divergence. In contrast, LEDs emit incoherent light in multiple directions, making laser diodes ideal for applications that require focused and precise illumination...” [128]

While it is true that laser light is coherent, meaning that the light emitted by lasers is monochromatic and in phase, it does not follow that the beam exhibits low divergence. In fact, laser diodes exhibit a beam divergence angle of up to 40°, and this is why a collimating lens is often included in systems that utilize a laser diode to correct this divergence, and, thus, cause the light to propagate in a straight line [129].

Large language model platforms can also aid in the design process by providing a starting place for researching various components needed to bring the project to completion. For example when a LLM like ChatGPT is provided with the prompt “Provide me some examples of temperature and humidity sensors that could be utilized in an embedded system”, it proceeds to output a list of common sensors and a brief description about each sensor. Some of the information it provides includes the communication protocols that sensor utilizes and whether that sensor is known to be used in projects that require a low power consumption or high accuracy. This information can greatly help reduce the amount of time that is needed to find desired components since the LLM can automatically sort out components that do not meet the needs of the project. However, since the LLM does not know the complete specifications of the project it may fail to list a potentially more optimal solution or may output a sensor that would be unusable in the design. Due to this, LLM should only be utilized to provide an idea of some components that may be available and further research should be conducted to ensure the most optimal component is selected for a design.

Keeping in mind their limitations, LLM tools such as ChatGPT could help facilitate the success of Senior Design as a learning experience at UCF, and has the potential to catalyze technological advancement at large.

6: Hardware Design

It is important to plan the design before building it. This section details the hardware design of our project, SAFEPADS. It includes the overall block diagram for the hardware, the schematics and board designs for every board involved, and optical schematics. It also goes into detail about the research and thought process behind every decision.

The figure below provides hardware block diagrams that generally represent the overall structure of the smart pet collar and illustrate the main person in charge of each portion of the project. The arrows on the block diagram illustrate the flow of data between each block with arrows going into the PCB illustrating data being delivered for analysis by the microcontroller unit and arrows exiting the PCB illustrating the microcontroller using that data to execute a desired task. The person in charge of each task was selected based on the major they are pursuing. Jesus Pagan Vela is the main person in charge of app design since he is pursuing a computer engineering degree. He was also placed in charge of the camera programming due to the desired image processing to be implemented within the project. Sara Wijas is the main person in charge of the vibrational component due to her experience working with solenoids and the fact that she is pursuing a degree in electrical engineering. She was also placed in charge of the main PCB design due to her desire to learn the PCB manufacturing process. Austin Fugate was placed in charge of GPS and the temperature/humidity sensor due to his knowledge of circuit design and embedded programming. He was also placed in charge of the power supply due to him pursuing an electrical engineering degree and also helped in PCB design. Nadia Khan was placed in charge of the wide field of view camera and strobe light for predator detection and deterrent due to her study in photonics at the University of Central Florida. Rana Scherer was similarly placed in charge of the Indoor Location and Fencing System, due to her study in photonics at the University of Central Florida.

The vibrating component, power supply, camera, GPS chip, and optical components were acquired during the course of this project after a thorough investigation and comparison of possible feasible components.

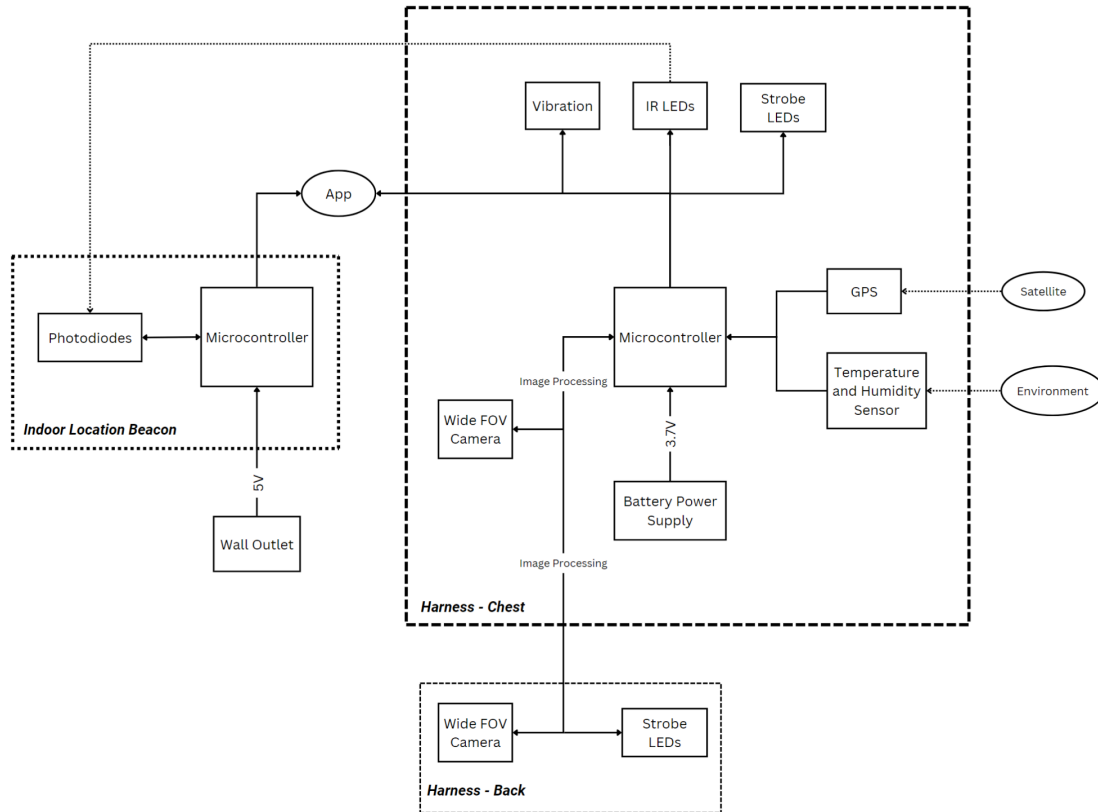


Figure 9: Hardware Block Diagram

6.1: Overall Schematics

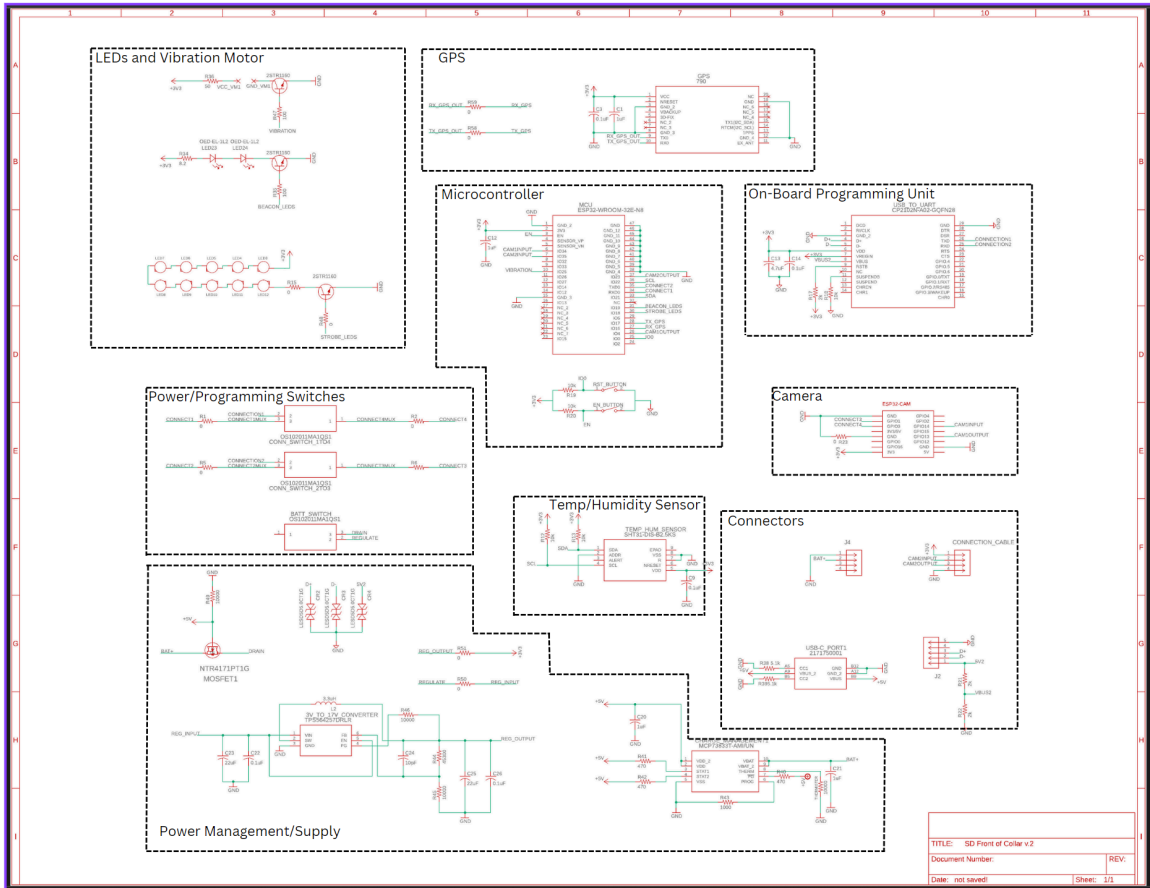
6.1.1: Schematic Overview

Our project, SAFEPADS, required three separate PCBs: one on the front of the harness, one on the back of the harness, and one in the beacon receiver that plugs into the wall.

The board in the front of the harness was designed to be the primary board; this was the PCB that controlled most of the interfacing with the app and all of the peripherals. This is the piece of the harness that sat in the front of the animal and monitored GPS location, temperature and humidity, and interfaced with the wide FOV camera. It also controlled the infrared LEDs for the beacon receiver to detect, the strobe LEDs for defense, and the vibration motor for corrections.

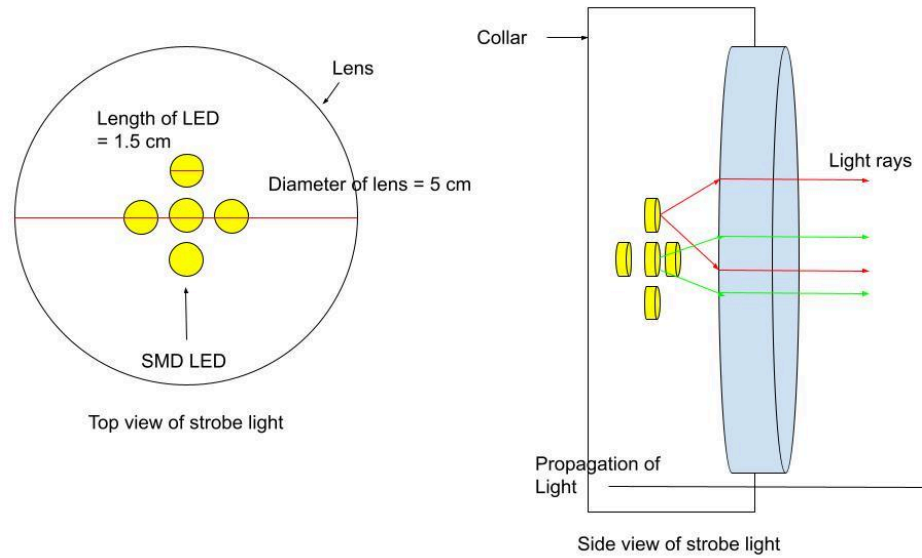
The schematic for this board is shown below in Figure 10. It was made using EAGLE 9.6.0 Free.

Figure 10: Schematic 1 - Chest of Harness Schematic



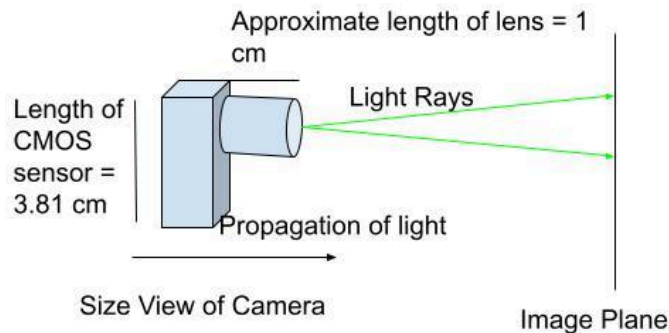
After building the schematic, we went ahead and created the board design. This was done by creating the corresponding board and placing the components where they would need to be in the final physical product, while taking into consideration the constraints of the components being placed by each other. The strobe LEDs are placed in a five component circle pattern on the top two corners so as to maximize the spread of light and make it easy to add a collimating lens over each group of them. Below is the schematic for the strobe light design on the front and back of the collar. The collimating lens schematic gives an in-depth view on how the light rays propagate through the lens. This is important to demonstrate for the design portion because it highlights how the lens helps to produce a more focused beam. This maximizes the output irradiance to yield a brighter strobe light. The final optical schematic is depicted below. The optical schematic depicts only one of the groups, but each group has the exact same design. See Section 6.2.5 for a more in-depth explanation of this design.

Figure 11: Strobe Light Schematic



The camera breakout board was placed in the direct center to have an image that is centered on the neck of the animal. An optical schematic of the two camera systems can be viewed below. Note there is only one camera system pictured, but two similar or identical camera systems will be implemented into the collar. A more detailed discussion of this schematic can be found in Section 6.2.6.

Figure 12: Camera System and Lens Schematic



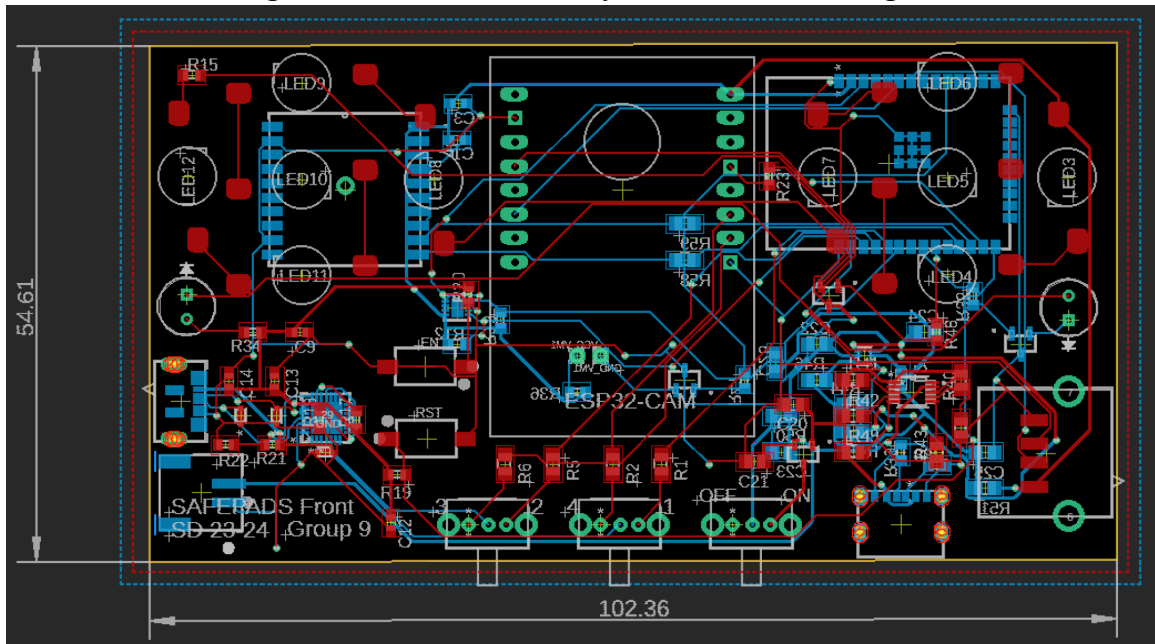
There is a USB-A 2.0 connector port on the right hand side for connection to the board in the back of the harness, as well as a USB-C charging port on the bottom right. Both of the USB ports were placed at the edge of the board so as to make it easy to plug in the cables without maneuvering around other components and potentially breaking the board.

After placing all of the components where they need to be on the board, we went ahead and used the Autorouter tool to gather a few designs that ensured everything was connected properly with the most efficient routing. Then we made an informed decision from the given options. We added text onto the silkscreen in order to personalize the PCB

and more easily differentiate between the multiple boards that we have, as well as include identifying information such as our group number and years.

The screenshot below includes measurements in inches on the side and bottom that read 54.61 mm x 102.36 mm, which was an improvement over the first iteration of our board, which was 107.95 mm x 143.51 mm. We made the board double sided to cut back on size; the red is the front, and the blue is the mirror of the back.

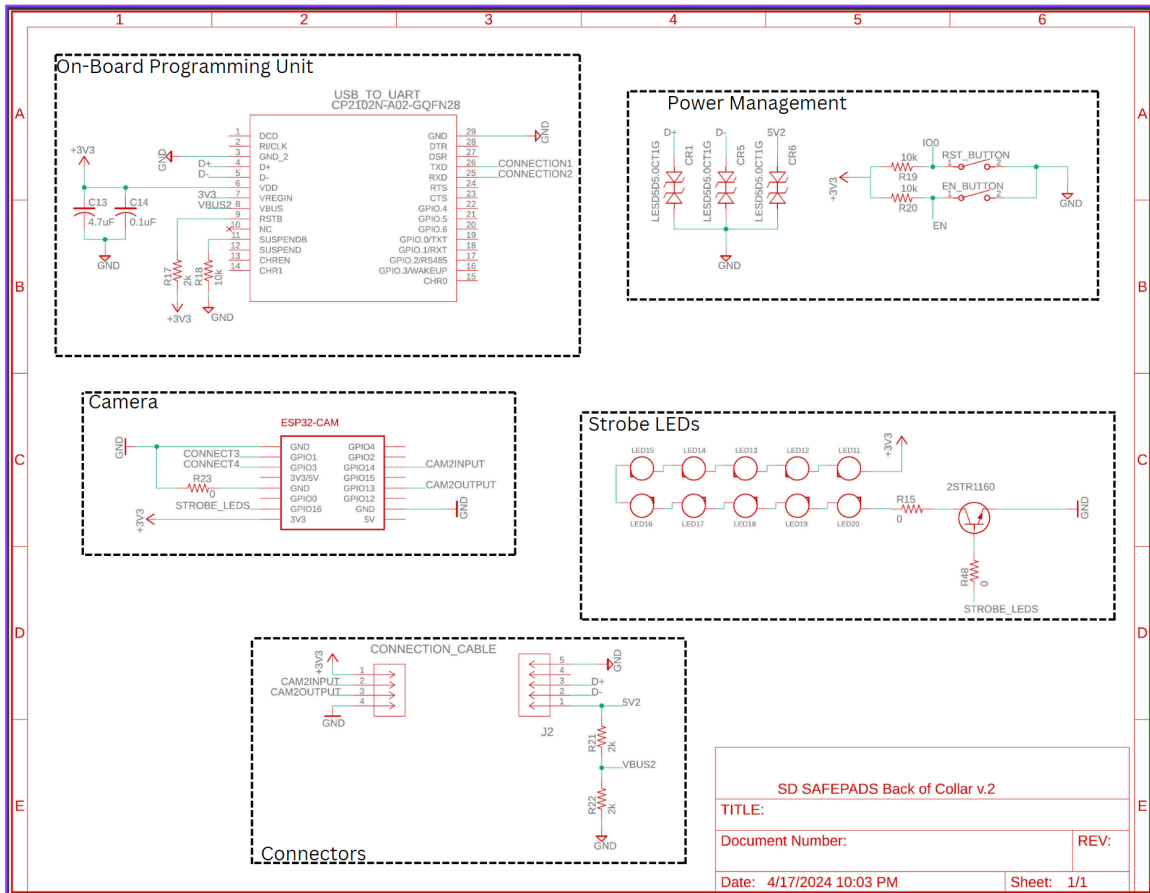
Figure 13: Board 1 - Front of Harness Board Design



The PCB on the back of the harness is much more simple; it includes a wide FOV camera, a second set of ten strobe lights, and the other end of the connection cable. The connection cable connects an ESP32-WROOM-32E board from the front of the harness to power and control the components on the back of the harness.

The schematic below shows the back of the harness. As is easily seen, it is much simpler than the chest of the harness schematic.

Figure 14: Schematic 2 - Back of Collar Schematic



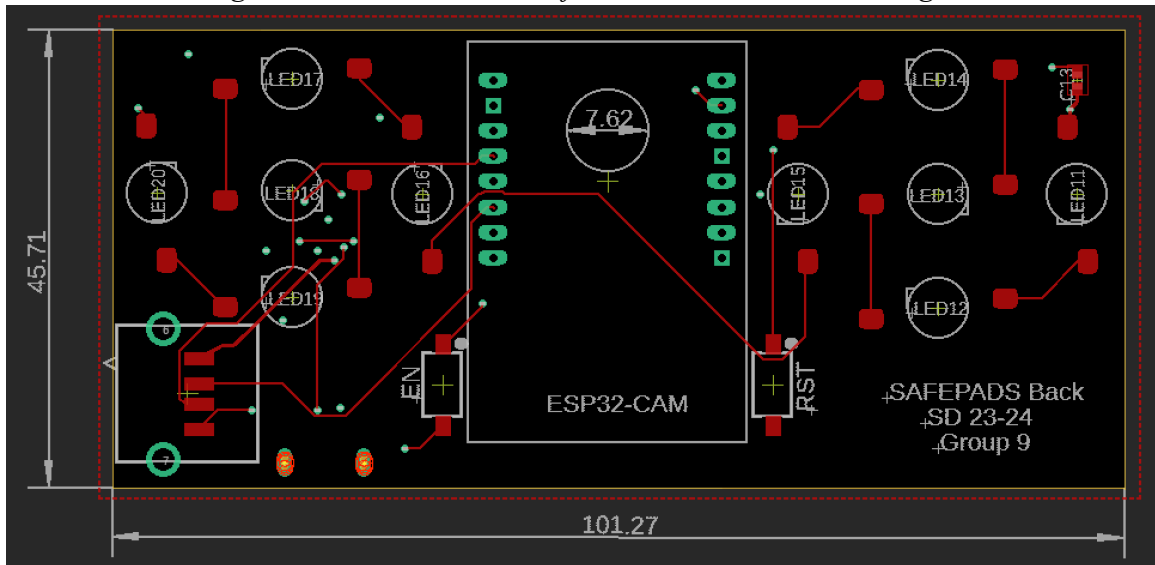
After building the schematic, we made the corresponding board design. We laid all of the components where they need to be on the physical board and then used the Autorouter tool to connect everything again.

The connection cable USB-A port on the back of the collar board is on the left side of the board; this is intentional, so that the two boards on the collar can be connected along the same side of the neck. The strobe LEDs are in the same orientation as the front of the collar board, so as to optimize the light and to make it easier to layer a lens on top.

Once again, this board has the measurements on the side and top of the screenshot. They read 45.71 mm and 101.27 mm, which is an improvement over the original board size of 76.2 mm x 101.6 mm.

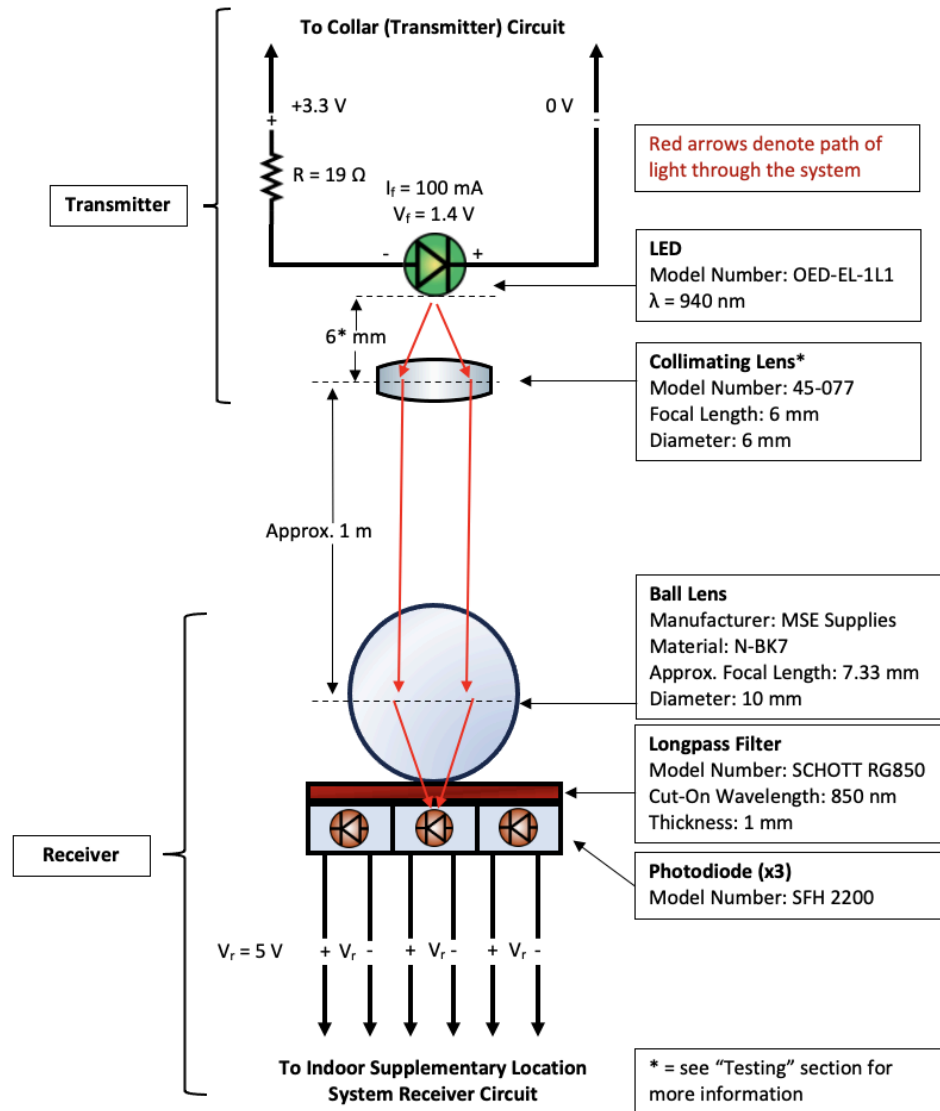
The final iteration of this board is shown below in Figure 13.

Figure 15: Board 2 - Back of Harness Final Board Design



The optical component of the Indoor Location and Fencing System is outlined in the schematic below. The diagram depicts the passage of the light from the infrared LED on the collar (top of the diagram) to the receiver photodiodes on the wall mount (bottom of the diagram). The red arrows that originate at the light emitting diode on the collar denote the path of the light through the system.

Figure 16: Initial Indoor Location and Fencing System Overall Schematic



The schematic below is the electronic component of the Indoor Location and Fencing System. It utilizes a micro USB port in order to power the device and contains the LM828 voltage inverter in order to generate the -5V needed for the proper operation of certain components. The 5V input power provided by the micro USB charging cable is connected to a linear voltage regulator to properly provide the 3.3V needed to power the ESP32 microprocessing unit. The rest of the circuit is connected to photodiodes that will output a signal when it detects the appropriate light output by the collar and operational amplifiers to amplify that signal into a readable value. The output signal is connected to the analog to digital converter pins of the ESP32 which will then notify the user when the corresponding digital output exceeds a certain threshold.

The corresponding board is designed and included below the schematic, in Figure 17.

Figure 17: Schematic 3 - Indoor Location Beacon Schematic

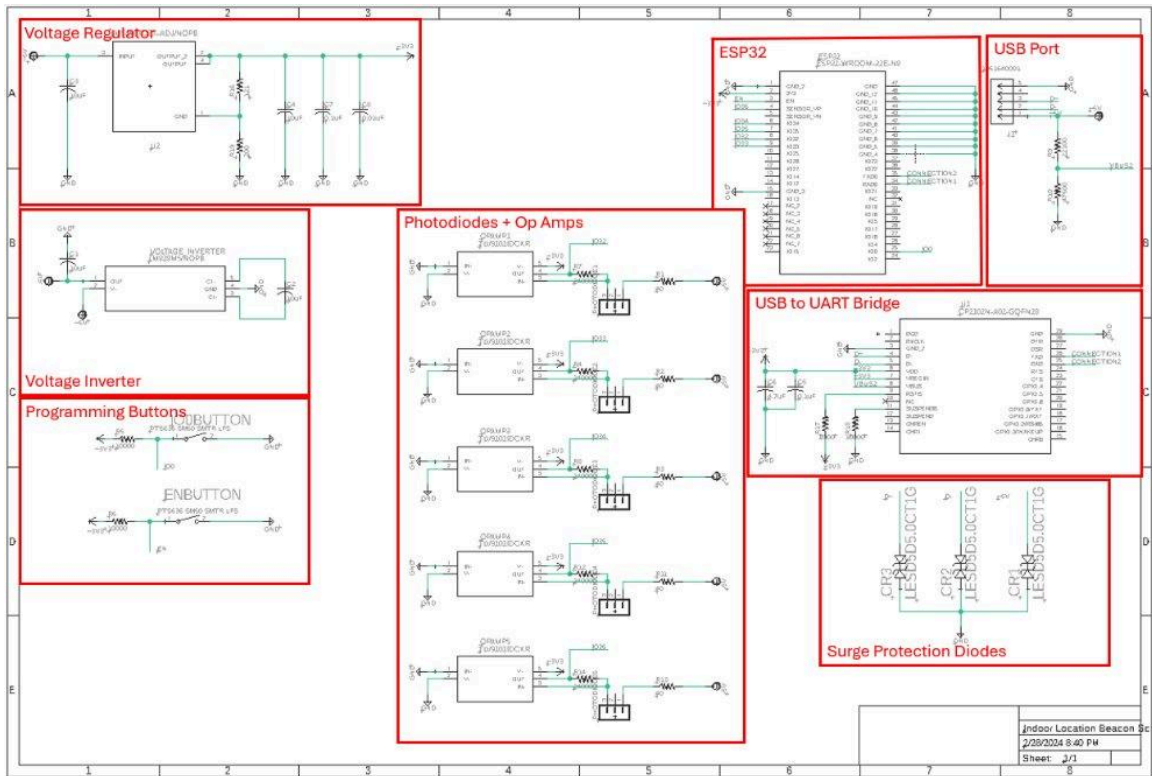
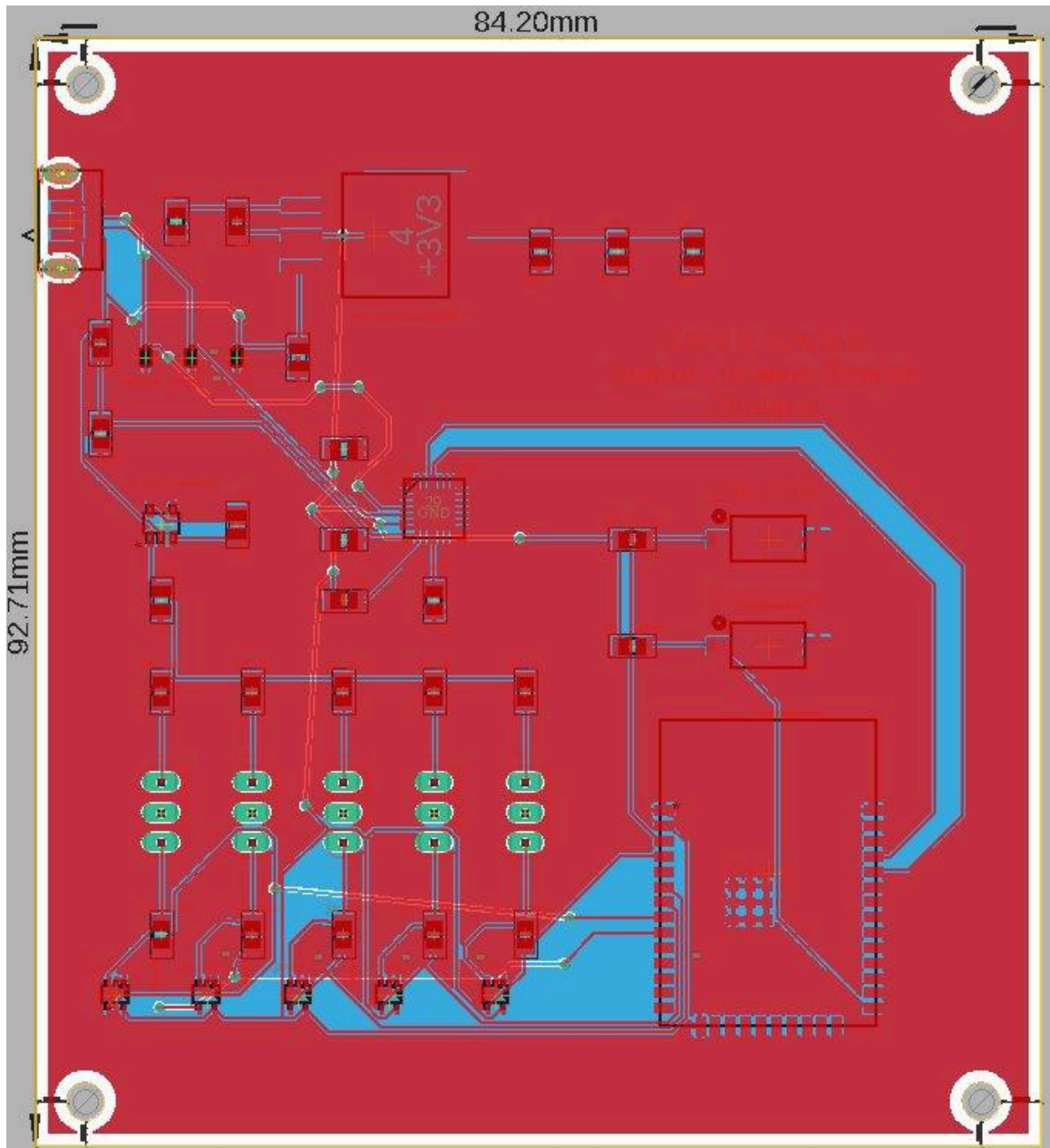


Figure 18: Board 3 - Indoor Location Beacon Board



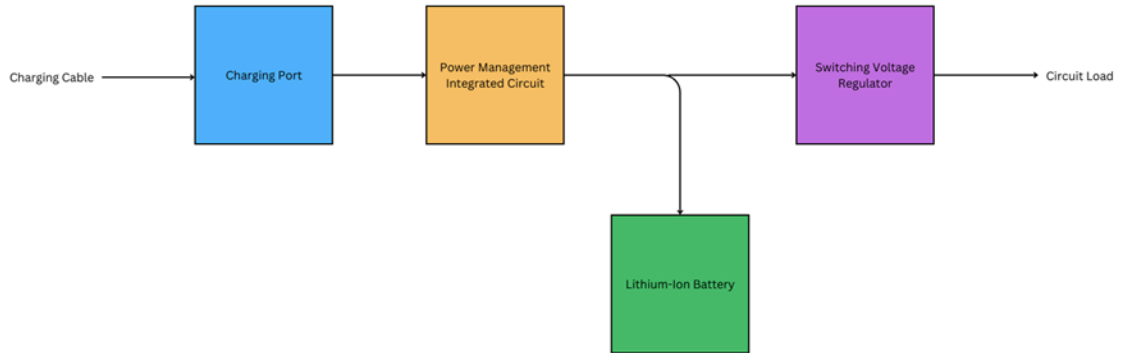
6.2: Schematic Justification and Research

6.2.1: Power Supply Subsystem

The main goals of the power supply subsystem are to allow charging of the device and to supply an appropriate amount of power to the microprocessor unit and the rest of the device's components. In order to achieve a complete working power supply system, multiple components need to work together. First, a lithium-ion battery will be utilized in order to allow the system to be recharged and to distribute energy to the system. Next, a power management integrated circuit will be utilized to ensure the safe charging of the

lithium-ion battery. Additionally, a charging port will be included to allow the user to charge the device. Finally, a switching voltage regulator will be included to ensure that a constant voltage is outputted and to ensure that the appropriate amount of voltage is being distributed to all components. The following block diagram illustrates the desired design of the power supply subsystem.

Figure 19: Power Supply Subsystem Block Diagram



The charging port used will be a simplified USB-C port containing only 6 pins. Since no data transfer through the USB-C port is required for this project, a 6 pin USB port should be sufficient for charging the device. A USB-C charging port was selected due to its wide availability and use. The power management integrated circuit used will be the MCP73833 chip by Microchip Technology. This integrated circuit is included to ensure that the lithium ion battery in the device is not overcharged and to ensure that a proper charging current is supplied to the battery. It is recommended to supply a charging current that is equal to or less than that of the battery's capacity. Since a 2000 mAh battery will be used, a 1A charging current will be selected in order to charge the battery to full capacity over the course of a couple of hours. In order to have a predictable charging current, the load of the device must be disconnected while charging. This will be accomplished by inserting a MOSFET transistor before the switching voltage regulator that acts as switch. While the device is charging, no current will flow to the load of the circuit and once the device is disconnected, the device will once again begin operation. This occurs by specifically using a p-type MOSFET transistor. When the charger is inserted a significantly large gate voltage will be applied to the p-type MOSFET transistor. This causes current to stop flowing to the load of the circuit. When the charger is removed the gate of the p-type MOSFET transistor will be connected to the ground of the circuit allowing current to resume flowing through the load of the circuit. Figure 21 shows the subsystem when the charging port, power management integrated circuit, and lithium-ion battery are connected.

The output of that designed circuit will then be connected to the switching voltage regulator design obtained using Texas Instruments WEBENCH power designer. The selected voltage regulator integrated circuit was the TPS564257 which can accept input voltages from 3V to 17V and should output a voltage of 3.3V to the load of the circuit [131]. Before the design is utilized in the circuit, it is necessary to check that the output voltage of the design is equivalent to the desired value. This can be done by utilizing the

equation $V_{out} = 0.6 \cdot \left(1 + \frac{R_4}{R_5}\right)$ given by the TPS546257 datasheet by Texas Instruments Incorporated [128]. In the generated design $R_4 = 45.3 \text{ k}\Omega$ and $R_5 = 10 \text{ k}\Omega$ giving a V_{out} of 3.318 V which is approximately equal to the desired output of 3.3V. The schematic of the switching voltage regulator generated by Texas Instruments WEBENCH Power Designer can be seen in Figure 20.

Figure 20: Switching Voltage Regulator Schematic

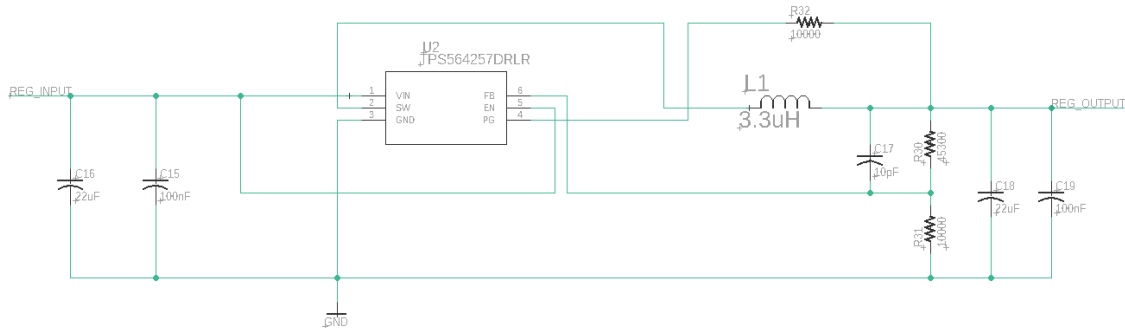
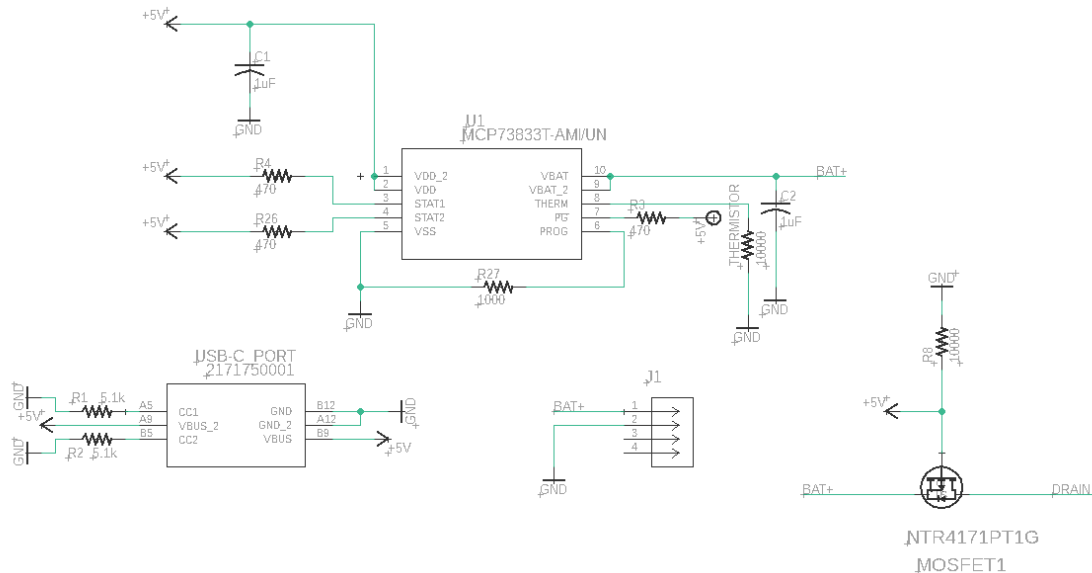


Figure 21: Power Supply Subsystem without Voltage Regulation



6.2.2: Indoor Location and Fencing System Design

The Indoor Location and Fencing System consists of a transmitter and receiver pair which serve to detect when the animal wearing the collar has passed a particular point-of-installation, such as a room or closet entrance, and transmit that data to the product’s companion app. In addition to providing a means to track the indoor location of a pet that overcomes the limitations of current technology, this system is also integrated with the vibration feedback functionality of the collar to provide users with the ability to create an indoor invisible fence that can be selectively applied to one of multiple pets.

This system is to work at distances of a minimum of up to 1 meter between the transmitter and receiver, as reaching this benchmark enables the point-of-installation to reside within a typical doorway.

While design concepts were explored with the transmitter location both at the point of installation and on the collar (with the receiver occupying the other location), it was ultimately decided that the receiver be placed at the point-of-installation in order to afford more flexibility to add optical elements required to facilitate a wide field of view without adding to the size of the collar.

An LED with a peak emission wavelength of 940 nm was chosen as the transmitter light source with the constraints discussed in the Transmitter Light Source Wavelength section as well as this project's Health and Safety Constraints in mind. The LED will only operate within a geofenced area corresponding to the approximate perimeter of the user's home or other indoor space in order to conserve battery life when the animal is outside.

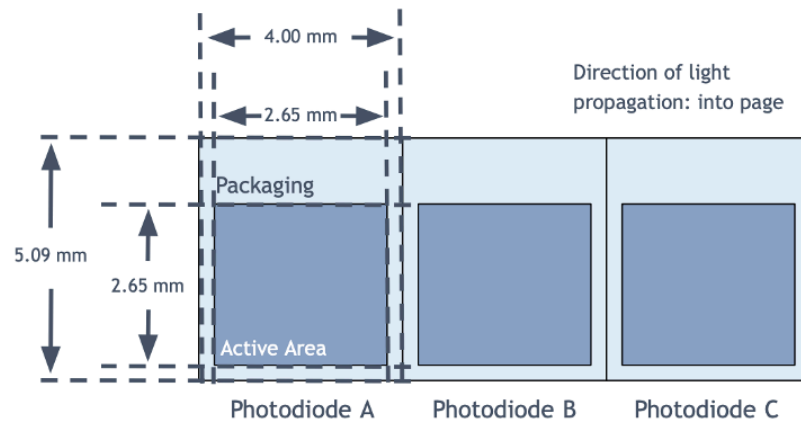
The system transmits and detect a pulsed signal in the 10 kHz to 20 kHz range— assigning a unique frequency to each pet is used as a means to distinguish between multiple animals wearing a SAFEPADS collar, and the use of a pulsed signal safeguards against false positive readings in the presence of other objects that emit infrared light. Utilizing this frequency range ensures that the system does not interpret signals from remote controls, such as those used for televisions, as input, as this frequency range is outside of the 32 kHz to 40 kHz range commonly used by remote control devices [131], [132].

The system should be able to differentiate between an animal entering or exiting a closed room by the number of times a signal receipt is logged within a limited time period (such as a period of 20 seconds. That is, the first signal received will be logged as an entrance, and the second signal received will be logged as an exit. For functionality in open areas or other atypical home configurations, the system could be configured in the app to simply log a passage of the point of installation without an associated direction of motion. A quiescent period of a few seconds occurs between logging each signal to allow time for the pet to move away from the beacon after a signal is received and, if chosen, vibration feedback is administered. The exact length of this time period will be determined after the integration of the system with vibration feedback is tested, and the time necessary to provide the vibration feedback after signal receipt is determined.

If many instances of signal receipt (such as a number greater than 6) occur in succession, the user may be alerted, as this could indicate that the animal wearing SAFEPADS is in distress or may not be responsive to vibration feedback due to improper placement of the collar, malfunctioning of the feedback mechanism, or temperament that is incompatible with this method of feedback. If it is established during testing that the LED shines preferentially on each photodiode throughout the course of the animal's motion past the receiver, this input may be used to determine the animal's speed while passing by the point of installation, satisfying the stretch goal of using the Indoor Location and Fencing System as a means of activity tracking.

A collimating lens was added to the initial design to decrease the divergence angle of the light from the LED. This decrease in divergence angle would result in a smaller spot of higher irradiance incident on the receiver at a given distance than without the collimating lens. However, given the challenges in implementing this lens, which are discussed in the Testing section, the necessity of this element was reconsidered after discussion amongst the team and with advisors and the collimating lens was removed from the final design. The receiver consists of a ball lens, filter, and photodiode panels along two orthogonal axes.

Figure 22: Photodiode Panel Design Along One Axis



The housing for this receiver can easily be mounted on a doorway or wall at the height of the pet collar and receive power from a standard 120 V AC outlet. The system has a wide (90°) field of view along the center of each axis with respect to the others, which is achieved by the inclusion of an appropriate ball lens as described in the part selection section 3.12 and further specified in the Receiver Lens System Design and Simulation section. After propagating through this lens, light will pass through a longpass filter which serves to block most noise typical from indoor light sources (described in the Transmitter Light Source Wavelength section). Because light from common indoor ambient light sources is concentrated near the visible range rather than extending into the infrared range above the transmitter light source wavelength, employing a longpass filter is much more cost-effective than employing a bandpass filter while yielding most of the benefit.

The photodiodes in this system serve to convert the received optical signal into a usable electrical signal. As is discussed in the part selection section 3.12, in order for the system to have a given angular field-of-view, the focal length of the lens system used is related to the size of the sensor used by the equation:

$$AFOV = 2 \times \arctan\left(\frac{H}{2f}\right),$$

where AFOV is the desired angular field of view, H is the sensor size, and f is the focal length. If one of the chosen photodiodes (which has an active area side length of 2.65

mm) were to be used, the necessary focal length for a 90° field of view is 1.33 mm or shorter, which cannot be achieved due to the thickness of the photodiode packaging and filter.

Thus, it was decided most pragmatic to use a panel of photodiodes placed next to each other in order to increase the sensor size and the corresponding maximum focal length to achieve the desired field of view. While there will be a few blind spots in the field of view using this arrangement, this configuration is feasible given the large active area of the photodiodes relative to the space taken by the packaging (0.66 active to total side length ratio on the photodiode's narrow side). Additionally, as was stated earlier in the document, it is not practically possible for the animal wearing the collar to pass the receiver in a manner where the only incident is a blind spot without passing through the receiver's field of view. An odd number of photodiodes should be used so that light propagating in a direction normal and near-normal to the system, which is the ideal use-case, lands near the center of a photodiode's active area. In order to minimize the size of the system while benefiting from the panel configuration, a panel of three photodiodes in either direction is used. This yields two panels placed orthogonal to each other within the photodiode plane with practical active-area dimensions of 10.65 mm (measured from the edge of one active area to the other, including spacing from packaging) by 2.65 mm. The signal received by the photodiodes will be amplified into a usable voltage by a transimpedance amplifier associated with each photodiode. This voltage will then be read by a microcontroller integrated into the receiver, which will store the result as a boolean variable on the microcontroller's ram. The user will then be able to ping the beacons from the companion application, which will show them if any of the beacons can currently see the pet, and if not, which receiver beacon last saw them. The information will be transmitted through the user's home wifi network, and will only need to read the boolean values stored on the beacons themselves. All the processing of the information in terms of displaying it legibly to the user will then happen within the GUI app, not on the beacons (see Chapter 7 for further details). This setup allows us to cut back on the energy cost of transmitting live updates from the beacons in favor of only receiving information when necessary.

6.2.3: Transmitter Light Source Wavelength

In order for the system to function, the operating wavelength chosen must be such that the system would not be susceptible to environmental noise while also remaining cost-effective to implement. To reduce the presence of environmental noise, the system wavelength should overlap as little as possible with wavelengths emitted by common indoor light sources while still working with cost-effective optical components.

Per the US Energy Information Administration, most households as of 2022 utilize LED light bulbs (47%), have no predominant lightbulb type (26%), incandescent light bulbs (15%) or compact fluorescent lightbulbs (12%) [133]. Typical white LED light bulbs emit light strictly within wavelengths ranging from 400 nm to 750 nm, and compact fluorescent lightbulbs also emit light within this range of wavelengths, though some may exhibit minor peaks in their spectra at longer wavelengths. On the other hand, incandescent light bulbs emit heavily in the infrared range [134]. It is worth noting that

the sale of incandescent light bulbs for most indoor lighting applications has ceased in the United States as of August 1, 2023 due to their failure to meet federal energy efficiency requirements [135]. Therefore, incandescent lights will most likely become increasingly rare in homes, and prioritizing the accommodation of incandescent light bulbs, as opposed to other ambient light sources emitting light within a typical wavelength range, should be of minimal concern. Consequently, the chosen wavelength should fall outside the range of 450 nm to 750 nm.

On the other hand, the wavelength of light chosen should also be in a range compatible with cost-effective optical components, such as components made out of NBK-7 glass. The transmittance range of NBK-7 components is from around 350 nm to 2000 nm.

Furthermore, to prioritize the health of pets and pet owners who utilize the collar, as discussed in detail in the “Health and Safety Constraints” section, the light source should be of a wavelength that does not upset the circadian rhythm of pets or people. This limits the wavelengths utilized further, as cats may have some visual sensitivity in the near-infrared wavelength range [119]. Thus, the light source chosen for the transmitter should have a wavelength greater than 900 nm and less than 2000 nm.

6.2.4: Receiver Lens System Design and Simulation

To quickly determine the optimum placement and size of the ball or half-ball lens used in the receiver lens system given the layers of different refractive indices introduced by the filter and photodiode packaging, as well as the possible benefit yielded by including other lenses in the system, Zemax OpticStudio was used. The optimum lens produced by the simulation was then compared to commercially available lenses. Now distributed by Ansys, Zemax OpticStudio is an optical design software that models the paths taken by propagating light rays through an optical system.

The first step taken in simulating the system was inputting the specifications of the surfaces present, including the type of material behind each specified surface and thickness of this material. Given that N-BK7 is the one of the most common and cost-effective materials used for lens fabrication, this material was chosen for the ball lens and is a pre-set material in OpticStudio’s glass catalog. Furthermore, the ball lens’s front radius of curvature was set to be 6 mm as a starting point, as the focal lengths of ball lenses are on the order of the lens radius. To construct the ball lens, the lens’ semidiameter was also set to be equivalent to the radius of curvature using Zemax’s pickup solve function (scale factor of 1), the lens’ back radius of curvature was set to be the equivalent to and in the opposite orientation of the front radius (scale factor of -1), and the lens thickness after the front surface was set to be twice the radius (scale factor of -2) to yield a sphere shape. The front radius and thickness of air behind the back lens surface were specified within OpticStudio to be variable so that they were regarded as degrees of freedom by OpticStudio’s optimization algorithm. The lens size and placement were then optimized by OpticStudio using the steps to follow.

RG850, the glass that the filter was constructed from, was not a preset material within the OpticStudio glass catalog, so the material was manually added to OpticStudio based on

the parameters specified in a datasheet for a filter made from this glass before choosing it as the filter material [136]. Similarly, the type of silicone used for the photodiode packaging was not specified by the manufacturer, so typical parameters for the refractive index and transmittance of optical silicone were manually inputted into OpticStudio after investigation before specifying this silicone as the photodiode packaging material [137], [138].

In OpticStudio's field editor, three fields of rays with a wavelength 940 nm and incident angles of 0° , 22.5° , and 45° in the y-direction were made to simulate the propagation of rays at various angles within the desired field of view (45° on each side, for a total of 90°). Using angles only in the y-direction was sufficient, since the lens to be used is rotationally symmetric.

To achieve optimization within acceptable parameters for the system, a Merit Function was constructed within OpticStudio's Optimization Wizard. Per Zemax's documentation, "The Merit Function is a numerical representation of how closely an optical system meets a specified set of goals. From within the MFE, OpticStudio uses a list of operands which individually represent different constraints or goals for the system. Once the Merit Function is complete, the optimization algorithm in OpticStudio will attempt to make the value of the Merit Function as small as possible," [139].

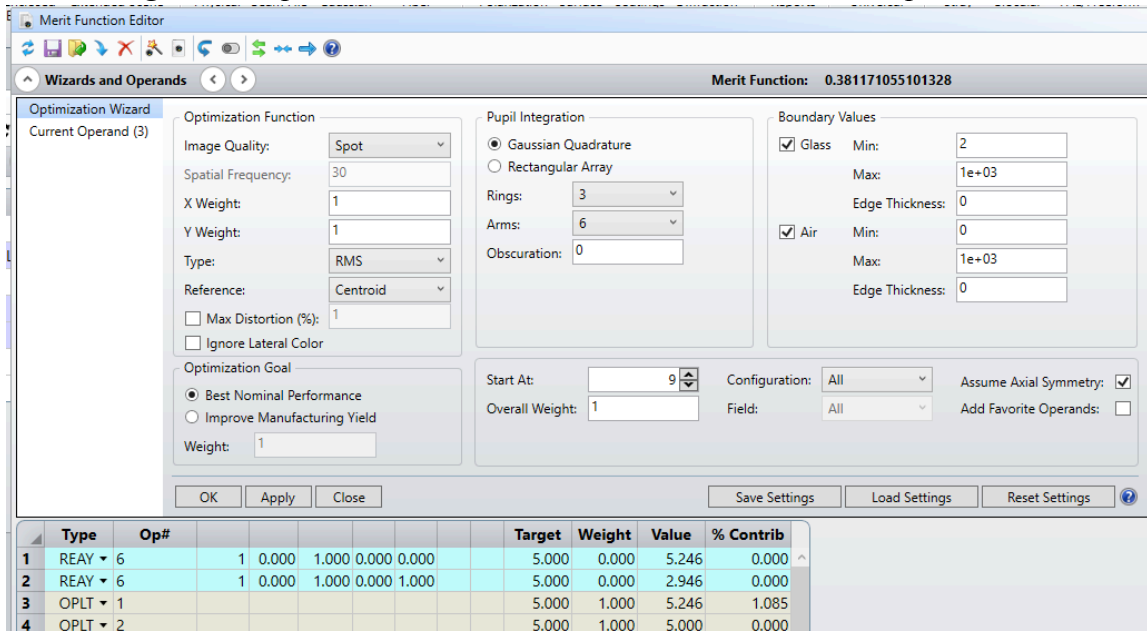
Within the Optimization Wizard, the minimum glass thickness for variable parameters was set to 2 mm, as ball lenses with a smaller diameter than this would be extremely difficult to handle and mount while also having a smaller focal length than the required minimum. The minimum air thickness for variable parameters was also set to 0 mm, so that OpticStudio would not generate solutions where the lens resides within the glass filter.

The Local Real Ray Y-Coordinate (REAY) and Operand Less Than (OLPT) operands were used within the Merit Function to constrain the maximum displacement of light propagating through the system incident at 45° , which, having the largest angle of incidence, is the field with a focal point furthest from the image center. The REAY operand allows one to specify a target y-coordinate for a given ray within the Merit Function. The OLPT operand allows one to make the value of a previously specified operand less than the target value. In combination, use of these operands enabled the selection of the chief ray, a ray from an off axis object point passing through the center of the aperture stop (the aperture that most limits the amount of light that can propagate through the system), and the marginal ray, a ray from an on-axis object point that passes through the edge of the aperture stop, and constrain the positions where they are incident on the image plane to be within the boundaries of the photodetector to 5 mm. This ray selection was performed with the REAY operand by setting the H(y) coordinate, which is the normalized field coordinate, to 1 in order to select the field most displaced from the center of the image plane and setting the P(y) coordinate, which is the normalized placement of each ray with respect to the pupil of the aperture stop, to 0 and 1 for two different rays. Then, the OLPT operand was applied to each REAY operand to stipulate that the value of the ray coordinate should be less than 5 mm to allow for a margin of

error from the photodetector panel side length of 5.325 mm in each direction, as was discussed previously in Section 3.12.

Then the optimization function was set to minimize the RMS spot size, that is, to focus the incident light as tightly as possible across the entire field of view, and the optimization was performed by OpticStudio over an automatically determined number of iterations. Below is an image of the Optimization Wizard and Merit Function parameters inputted.

Figure 23: Optimization and Merit Function Parameters in OpticStudio

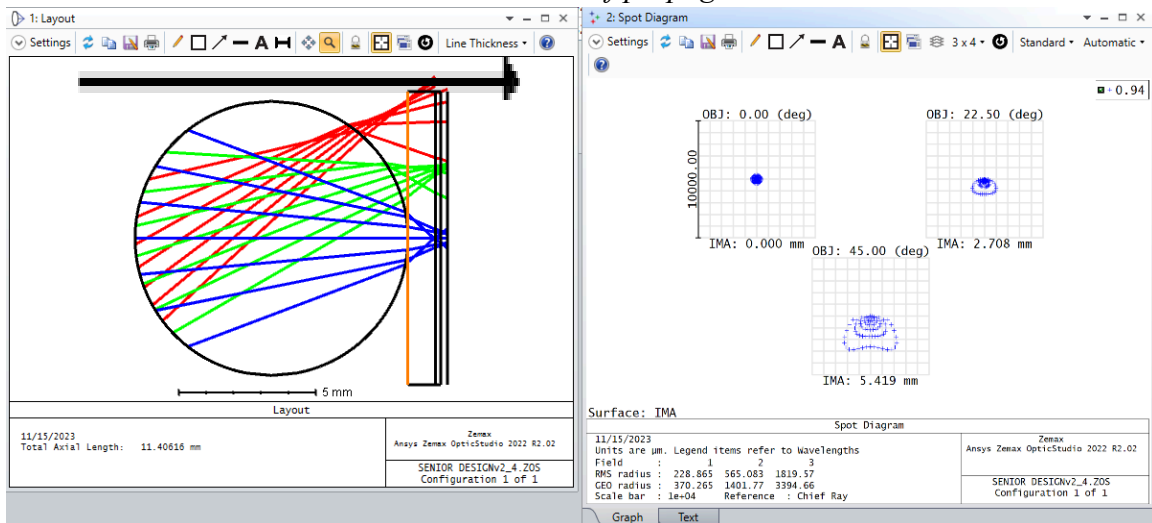


Despite stipulating that the minimum air thickness should be 0 mm, and the inclusion of the OLPT operands, OpticStudio produced a result that placed the resultant lens inside of the filter glass and placed some rays above 5 mm on the image plane, but still with much light incident within the photodetector boundaries. However, this is explicable in that OpticStudio's Merit Function works by minimizing a weighted sum of the differences from the target value for all included operands rather than by checking the fulfillment of each individual criteria. The lens data were edited to place the lens 0 mm from the filter surface to remedy the issue of negative distance between the lens and the filter, and the results achieved were similar and are shown below.

Figure 24: Lens Data of Optimized Lens System

Surface	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard	Infinity	Infinity			Infinity	0.000	Infinity	0.000	0.000
1	STOP	Standard	LENS FRONT 4.978 V	9.956 P	N-BK7		4.978 P	0.000	4.978	0.000	-
2		Standard	LENS BACK -4.978 P	0.000 V			4.978 P	0.000	4.978	0.000	0.000
3	(aper)	Standard	FILTER Infinity	1.000	RG850.ZTG		5.325 U	0.000	5.325	0.000	0.000
4	(aper)	Standard	SILICONE Infinity	0.200	SILICONE.ZTG		5.325 U	0.000	5.325	0.000	0.000
5	(aper)	Standard	AIR Infinity	0.250			5.325 U	0.000	5.325	0.000	0.000
6	IMAGE	Standard	Infinity	-			5.325 U	0.000	5.325	0.000	0.000

Figure 25: Optimized Receiver Lens System Spot Diagram and Cross Section. Arrow denotes direction of propagation.



As can be seen from the spot diagram and system cross-section, this system is somewhat defocused and there is a visible amount of field curvature—that is, a curved plane of focus. Furthermore, the spots exhibit some spherical aberration and coma. However, given that this is not an imaging system, a slightly defocused system is acceptable, especially in light of the fact that light from the entire field-of-view can be captured. Thus, an N-BK7 ball lens with a diameter of 10 mm, which is approximately equivalent to the optimized ball lens specification, was ordered from MSE supplies— the most cost-effective reputable supplier of a lens with these specifications.

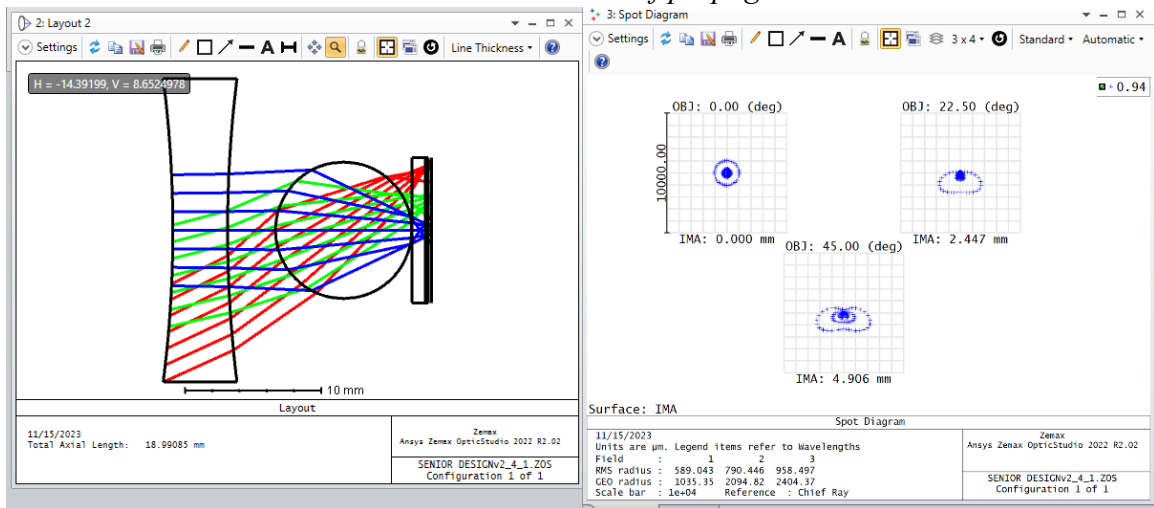
Still, in the event that the field of view shown in the simulation is difficult to replicate experimentally, a means considered to more tightly focus the light across the entire field of view was the introduction of another lens, in spite of the additional expense it would incur and bulk it would add to the system. Thus, two surfaces were inserted with a material of N-BK7, and the surfaces were given clear semidiameter of 12 mm, radii of curvature of infinity, a thickness of 3 mm, and an air thickness of 5 mm between the back surface and the ball lens front placed, each set as variable parameters that OpticsStudio could successively use to yield an optimized lens.

The optimization was run once again with the ball lens parameters fixed. Given that the first optimized lens output was excessively thick (17 mm), the Merit Function was edited to allow a maximum glass thickness of 4 mm in the optimized lens (the maximum thickness available from most reputable manufacturers investigated). The results of this subsequent optimization are displayed below.

Figure 26: Lens Data of Secondary Optimized Lens System

Surface	Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	
0	OBJECT	Standard	Infinity	Infinity			Infinity	0.000	Infinity	0.000	0.000	
1	Standard		-87.480 V	4.020 V	N-BK7		11.116	0.000	11.116	0.000	-	
2	(aper) Standard		89.937 V	3.521 V			11.116 P	0.000	11.116	0.000	0.000	
3	STOP	Standard	LENS FRONT	5.000	10.000 P	N-BK7		5.000 P	0.000	5.000	0.000	-
4	Standard	Standard	LENS BACK	-5.000 P	0.000		5.000 P	0.000	5.000	0.000	0.000	
5	(aper) Standard	Standard	FILTER	Infinity	1.000	RG850.ZTG		5.325 U	0.000	5.325	0.000	0.000
6	(aper) Standard	Standard	SILICONE	Infinity	0.200	SILICONE.ZTG		5.325 U	0.000	5.325	0.000	0.000
7	(aper) Standard	Standard	AIR	Infinity	0.250			5.325 U	0.000	5.325	0.000	0.000
8	IMAGE	Standard		Infinity	-			5.325 U	0.000	5.325	0.000	0.000

Figure 27: Secondary Optimized Receiver Lens System Spot Diagram and Cross Section. Arrow denotes direction of propagation.

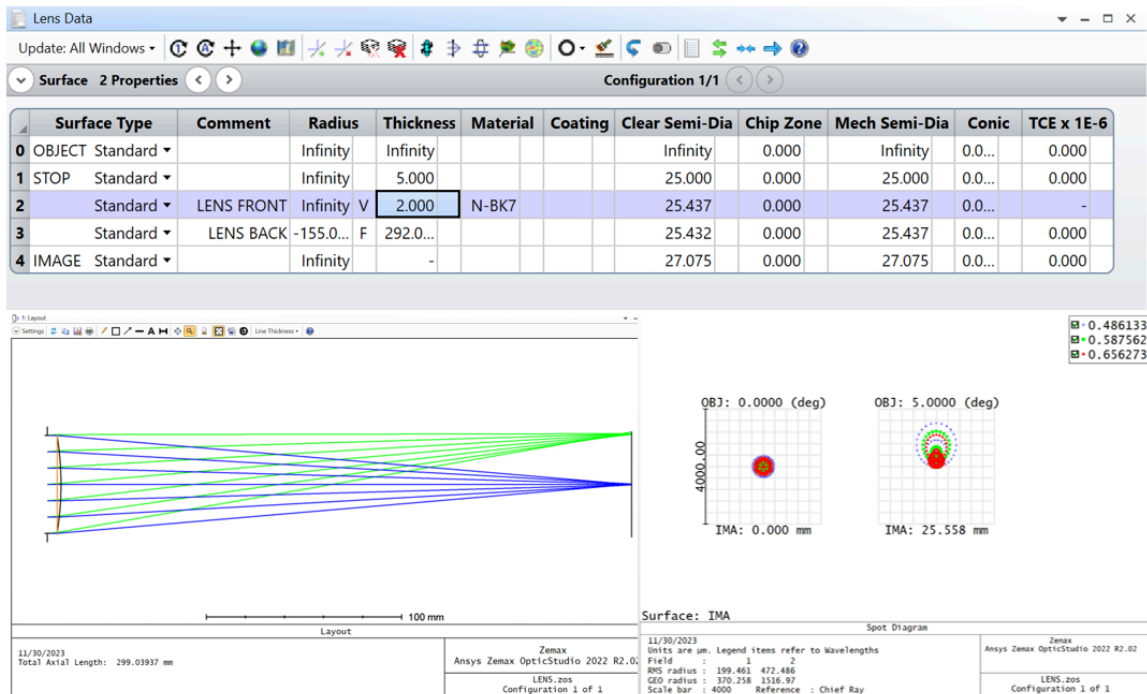


As shown above, the addition of the optimized biconcave lens resulted in a decrease of the spot size of light incident at 45° field and placement of this spot squarely on the photodetector, though the spot size of light at a lesser angle of incidence increased. While a lens of this exact thickness and radius of curvature isn't commercially available, this simulation shows that utilizing the most similar commercially available lens could yield an improvement, if necessary, given the additional cost, or that an improved system could potentially be attained by modifying the ball lens with the insertion of a second biconvex lens or other lens with negative power in mind.

6.2.5: Strobe Light Design

The strobe light design consists of two different groups of five SMD LEDs arranged in a cross pattern and a collimating lens. The LEDs are connected in series and parallel, creating the rows. The strobe light must output a certain amount of power to be effective in the design. The collar poses a size constraint, so the number of LEDs used must be minimized while still producing an effective power output. Using ten total LEDs in the final design would produce about 21.52 milliwatts of power for the whole system with the collimating lens based on testing done with the LED and collimating lens. Based on the available data for the SMD LED chosen one SMD LED would produce 110 lumens. This means ten LEDs would produce 1100 lumens for the whole system which is very bright and would prove to be sufficient for scaring off predators. This would be fitting for the size of the collar as well. It would be difficult to fit a lot of LEDs on the collar in a way that is conducive for fitting a collimating onto the collar as well. A larger collimating lens serves to collimate light from the LEDs. This lens is different from the one previously discussed in the research portion of the document. Two groups of LEDs needed to be done to and conserve space on the collar. Having all the LEDs placed in one group would be too large to fit on the collar. This means a larger collimating lens than the one chosen needs to be purchased. The following specifications for the lens design are based on a larger collimating lens that has been researched and fit into the design. Therefore, the collimating lens is placed at about 5 centimeters from the LEDs, as this focal length is typical of larger lenses. This distance is feasible for the collar and does not stick out excessively once placed on the collar. The collimating lens design was simulated on Zemax. The lens design depicted had to incorporate the values from a large collimating lens. This means the thickness and radius of curvature could not be optimized. This lens design was used to maximize power output through collimation, so less emphasis was placed on getting a precise spot size.

Figure 28: Collimating lens set up, layout, and spot size.



6.2.6: Wide FOV Lens Design

To make a lens system that is economical the best approach that was found was getting a premade lens system and modifying it to fit the needs of our system. Each lens will be individually tested and the specifications for each lens will then be documented. The whole lens system will also be documented and then compared to the lens design being designed. This will be done to show the overall improvement made to the system through the lens design made. The camera system will comprise two different camera and lens sets. Two systems will therefore undergo testing. An important note for the following lens design is the lenses exact radius of curvature and refractive index were not able to be precisely input because the specifications of these values were not able to be obtained after multiple attempts of contacting the producers of these lenses. Estimates of these values were made but may differ from the actual performance. The thickness and radius of curvature were not made variable in the simulations because the lenses could not be changed from what was originally in the lens kit. This inhibited some optimization for the lens design.

The lens system that will first be analyzed and modified is the M25156H14 lens from the lens kit. To increase the field of view the focal length of the lens system needed to be increased. The angular FOV or the AFOV is the angle that can be seen through a lens or an optical device. This value does not change with the sensor size and therefore can be used when determining the focal length that needs to be used to achieve a sufficient field of view. The AFOV and FOV are directly proportional, which means they can increase with each other. Typically, a shorter focal length increases the AFOV and FOV. The following equation was used to determine the width of the sensor given in the lens specifications:

$$AFOV = 2 \times \tan^{-1}\left(\frac{H}{2f}\right)$$

The H value is equal to the width of the sensor. The lens specifications were tested on a sensor size of 1/4. To find the H value the given AFOV and focal length were plugged into the equation and the H value was solved for. The H value found was 8.81 mm. This information can then be used to find the focal length for an AFOV of 180. The inverse tangent for values at or above 180 degrees are unable to be found based on the nature of the tangent function. A value of 179 was plugged in for the AFOV of the above equation. The focal length was solved for and found to be 0.0384 millimeters. This value was used in the merit function of Zemax to adjust the lens system for this focal length. The EEFL that was calculated by Zemax when the lens system was originally put in was 24.6798 mm. This differed from what was given in the lens specifications. The lenses used in the lens system were unable to accommodate a focal length this small. In order to reduce the focal length, trial and error was used to reach an FOV that was sufficient for this design. A lens was input into the system and the focal length decreased from around 24 to 20. Since the FOV is directly proportional to the focal length a ratio was used to determine the new FOV with this lens input. This ratio can be viewed in the equation below:

$$\frac{f_1}{f_2} = \frac{FOV_1}{FOV_2}$$

$$\frac{24.6798}{20.2102} = \frac{FOV_2}{140}$$

$$FOV_2 = 170.962^\circ$$

This shows an increase of about 30 degrees, which will suffice in the final system, since the goal for the final FOV of the system is 300 degrees this field of view will help to accomplish this. The following images show Zemax schematics for this. The lens system will show some distortions, which is evident in the spot size diagram. This is because of the nature of wide field of view lenses having some distortion.

Figure 29: Modified M25156H14 lens set up and layout.

Surface	Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard	Infinity	Infinity			Infinity	0.000	Infinity	0.0...	0.000
1	STOP	Standard	Infinity	0.000			1.250	0.000	1.250	0.0...	0.000
2	Standard	Lens 1	150.000	1.000	N-BK7		1.250	0.000	1.305	0.0...	-
3	Standard		Infinity	0.000 V			1.305	0.000	1.305	0.0...	0.000
4	Standard	Lens 2	50.000	2.000	N-BK7		1.306	0.000	1.397	0.0...	-
5	Standard		Infinity	0.000			1.397	0.000	1.397	0.0...	0.000
6	Standard	Lens Holder	Infinity	3.657 V			1.397	0.000	1.397	0.0...	0.000
7	Standard	Lens 3	150.000	1.500	N-BK7		1.652	0.000	1.715	0.0...	-
8	Standard		Infinity	0.000			1.715	0.000	1.715	0.0...	0.000
9	Standard	Lens Holder	Infinity	2.200 V			1.715	0.000	1.715	0.0...	0.000
10	Standard	Lens 4	25.000	1.000	N-BK7		1.860	0.000	1.875	0.0...	-
11	Standard		Infinity	0.000			1.875	0.000	1.875	0.0...	0.000
12	Standard	Lens Holder	Infinity	0.183 V			1.875	0.000	1.875	0.0...	0.000
13	Standard	Lens 5	75.000	0.500	N-BK7		1.881	0.000	1.884	0.0...	-
14	Standard		Infinity	0.000			1.884	0.000	1.884	0.0...	0.000
15	Standard	Lens 6	50.000	5.000	N-BK7		1.885	0.000	1.885	0.0...	-
16	Standard		Infinity	0.000			1.861	0.000	1.885	0.0...	0.000
17	Standard	AIR	Infinity	19.596			1.861	0.000	1.861	0.0...	0.000
18	IMAGE	Standard	Infinity	-			2.495	0.000	2.495	0.0...	0.000

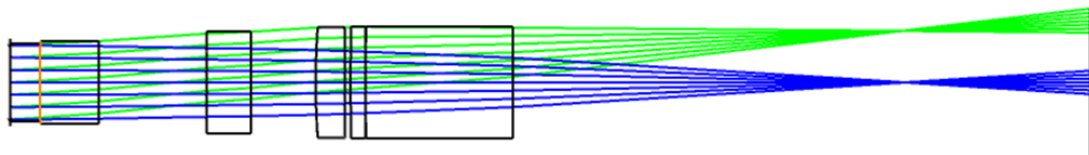


Figure 30: Modified M25156H14 lens spot size and merit function.

OBJ: 0.0000 (deg) OBJ: 5.0000 (deg)

IMA: 0.000 mm IMA: 2.094 mm

Wizards and Operands Merit Function: 0.015660239281251

Optimization Wizard

Optimization Function: Wavefront

Image Quality: 30

Spatial Frequency: 1

X Weight: 1

Y Weight: 1

Type: RMS

Reference: Centroid

Max Distortion (%): 1

Ignore Lateral Color:

Optimization Goal: Best Nominal Performance

Improve Manufacturing Yield

Weight: 1

Start At: 10

Configuration: All

Assume Axial Symmetry:

Overall Weight: 1

Field: All

Add Favorite Operands:

OK Apply Close Save Settings Load Settings Reset Settings

Surface: IMA

Type	Wave	Target	Weight	Value
1	EFFL	1	20.000	3.000

12/31/2023 Zemax Ansys Zemax OpticStudio 2022 R2.02

Units are um. Legend items refer to Wavelengths

Field : 1 2

RMS radius : 298.555 305.230

GEO radius : 393.018 406.961

Scale bar : 3000 Reference : Chief Ray

M25156H14 lens 1st system.zos Configuration 1 of 1

The second lens system to be analyzed and modified is the M30171H16 lens from the lens kit. This lens system will undergo a design like the first one. The width of the lens used for testing was found from the same equation as the one used above. The H value found using the field of view and focal length from this lens was 19.3958 mm. To find an increased FOV for this system the working distance will be used to determine this. The working distance is the distance from the front of the object to the image plane. This value was found by simulating the original lens design in Zemax and taking the distance from the last lens to the image plane. This distance was found to be 39 millimeters. The

following equation was used to find the focal length needed for an AFOV of 180. The following equation was used to find the new focal length value:

$$AFOV = 2 \times \tan^{-1}\left(\frac{WD}{2f}\right)$$

$$179 = 2 \times \tan^{-1}\left(\frac{39}{2f}\right)$$

The f value was solved for and found to be 0.17 millimeters. This focal length was not feasible to accomplish when the lens system was put into Zemax. The focal length given in Zemax was 48.3969 millimeters. The focal length was able to be reduced to 31.2331 millimeters by inserting an additional lens into the system. This greatly reduced the focal length, and the distances between lenses were reduced to also decrease the focal length. Additional lenses were added to reduce the focal length even more but the spot size was greatly distorted, which would result in a blurry or unrenderable image. The system was optimized to a focal length of 30 millimeters. The same ratio as the one used for lens system 1 was used to find the new FOV of this lens system. The new system FOV was 247.926. This FOV will be more than sufficient in the final design and still maintains a spot size focused enough to render an image. The final Zemax design can be viewed in the images below.

Figure 31: Modified M30171H16 lens set up and layout

Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT Standard	Infinity	Infinity			Infinity	0.000	Infinity	0.0...	0.000
1	STOP Standard	Infinity	0.000			1.500	0.000	1.500	0.0...	0.000
2	Standard Lens 1	50.000	2.000	N-BK7		1.502	0.000	1.596	0.0...	-
3	Standard	Infinity	0.000			1.596	0.000	1.596	0.0...	0.000
4	Standard Lens Holder	Infinity	0.000	V		1.596	0.000	1.596	0.0...	0.000
5	Standard Lens 2	100.000	0.500	N-BK7		1.597	0.000	1.617	0.0...	-
6	Standard	Infinity	0.000			1.617	0.000	1.617	0.0...	0.000
7	Standard Lens 3	50.000	2.000	N-BK7		1.619	0.000	1.680	0.0...	-
8	Standard	Infinity	0.000			1.680	0.000	1.680	0.0...	0.000
9	Standard Lens Holder	Infinity	0.500	V		1.680	0.000	1.680	0.0...	0.000
10	Standard Lens 4	75.000	2.000	N-BK7		1.704	0.000	1.750	0.0...	-
11	Standard	Infinity	0.000			1.750	0.000	1.750	0.0...	0.000
12	Standard	Infinity	39.024	V		1.750	0.000	1.750	0.0...	0.000
13	IMAGE Standard	Infinity	-			4.250	0.000	4.250	0.0...	0.000

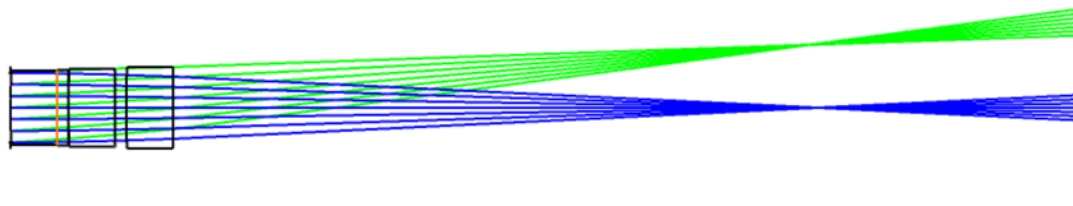
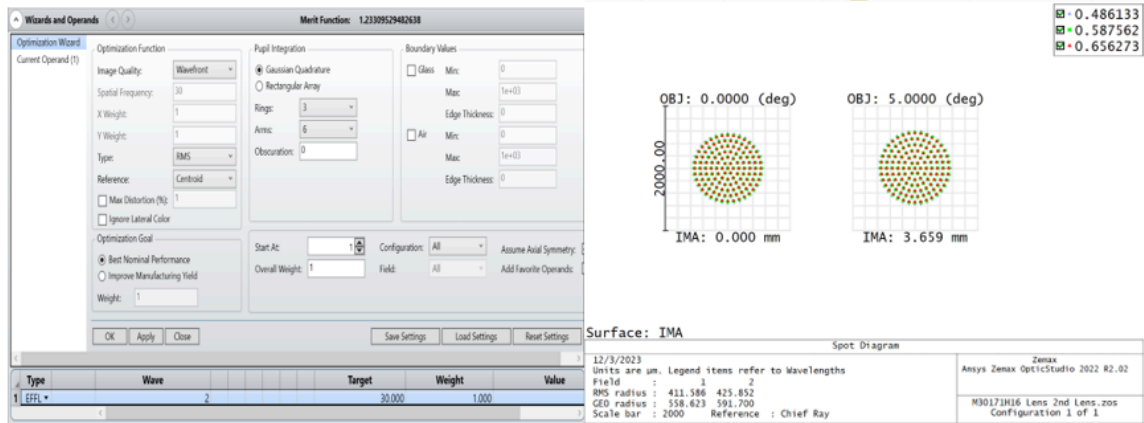


Figure 32: Modified M30171H16 lens spot size and merit function.

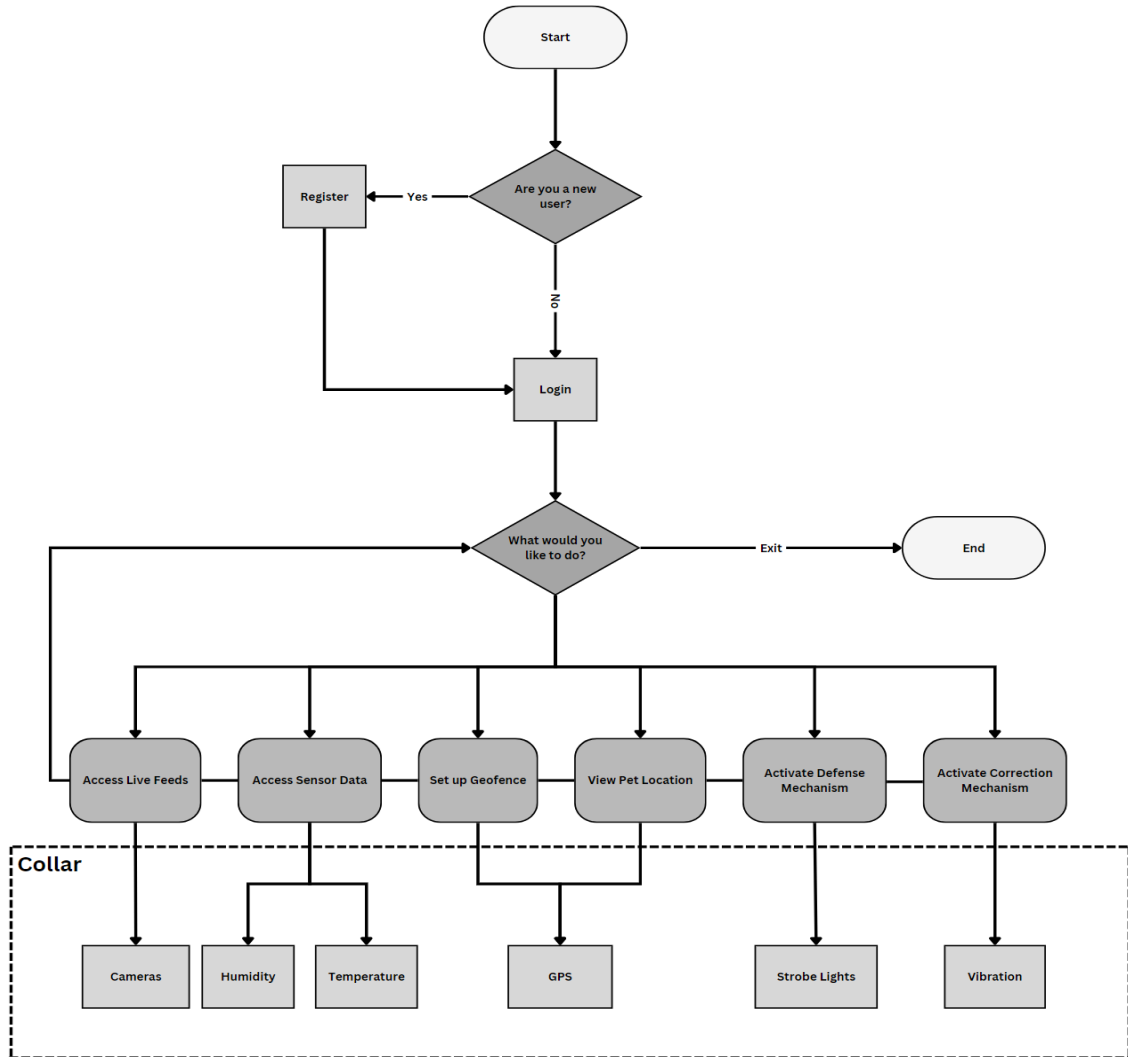


7: Software Design

In order to tie all of our hardware components together, our project is going to depend on a few applications. We are going to need software physically on the MCU, software that controls the auxiliary beacons, and a GUI application that allows the user to interface with the previous two systems. The MCU's software is our most important task, as it is what will handle predator detection and data collection. After that, the GUI application will need to be sleek and professional, as well as act as a hub for all of the information. Lastly, the simplest software will be the beacons, as they only need to keep track of the collar if it is indoors.

The flow diagram above demonstrates the way that the application will work with the inputs and outputs of the hardware. At the launch, the system will prompt the user to either register for an account or to log in. Then, it will ask the user what task they would like to do: access live camera feeds, access live temperature and humidity data, set up or adjust the geofence, check on the pets' location in the world, activate the defensive strobe LEDs, or manually activate the vibrational correction response. After the user exits a task, the program will go back to the previous page to ask what the user would like to do, from which the user can continue to pursue different options. When the user decides they are done with the application, they can simply exit, and the application will close.

Figure 33: Software Flow Diagram



7.1: MCU Onboard Software

The software that will be running on the collar’s onboard MCU must have the following features: the abilities to detect predators, GPS tracking, and sensor storage. Although there are other features on the collar, the features just listed are the ones that need to be functioning autonomously at all times. The software’s most important feature is the active predator detection, which will be responsible for keeping the pet safe and is one of our main selling points. Next in priority is the GPS functionality, which is a standard inclusion for most smart collars and is important for our geofencing and training features. Finally, we must make sure that the data gathered by the sensors is being stored on the collar itself whenever the pet is on its own. The collar must also be able to notify the user if the sensors believe the conditions around the pet are potentially dangerous.

7.1.1: Predator Detection

As mentioned previously, predator detection is the main selling point for our collar. The ability for a collar to automatically detect danger around your pet and react accordingly is one that is not found in similar products currently on the market. As such, it is particularly important for this feature to work as intended.

For this feature we are using Python's OpenCV library. OpenCV comes with its own deep neural network which we can borrow for our computer vision software. Using OpenCV's model comes with its own pros and cons, particularly relating to the fact that it is a third part model which we are accessing. The upside to doing it this way is that the model comes pre-trained with useful weights, meaning that it is easy to set up and use. This also helps us on the power side, as the highly optimized model would do well on our collar's MCU. The downsides to this approach come from the model's accessibility. Since we do not have this model on our physical devices, we can not go in and tweak the weights in order to fine-tune the results. Thus, if we find that we are unhappy with the model's performance, we must create a new model from the ground up, without the use of OpenCV's inbuilt DNN.

Figure 34: Model identifies a hawk as "bird" at high confidence

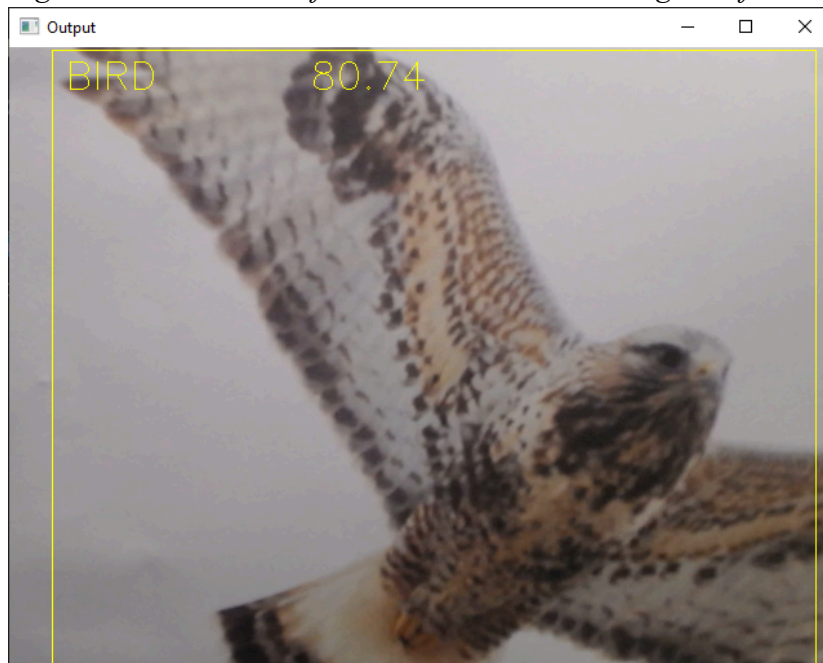
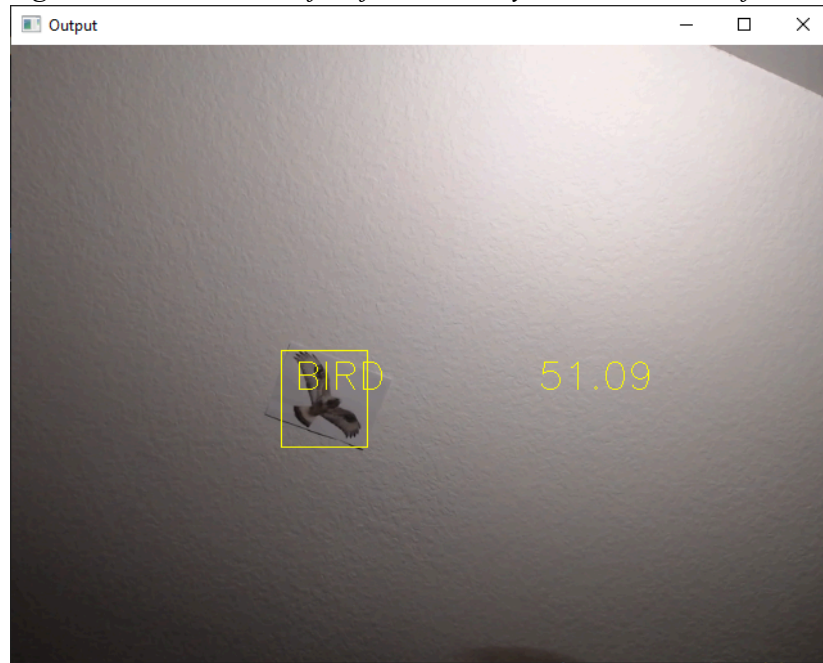


Figure 35: Model identifies further away hawk at low confidence



In our testing, the performance of the model was satisfactory for the time being. We used it in combination with COCO's image library to create a prototype detection software. Although the model is functional, it still has a long way to go before it can be used to protect a pet. As seen by the figures ? and ?, the model is currently not accurate enough to classify a hawk as anything more specific than "bird". This presents a problem, as there are many things that the model could potentially classify as "bird", many of which are not dangerous to a typical pet. This is due to the fact that the COCO image library, which the model is currently using, does not go into detail when it comes to what type of bird it is classifying. Were we to continue using this library, the model would be unable to differentiate a harmless bird from a bird of prey, which would lead to improper use of the predator deterrent system. As we move onto the second semester of this project, we must ensure to properly research a dataset that will allow us to differentiate between not just birds, but many other specific animals that must be detected.

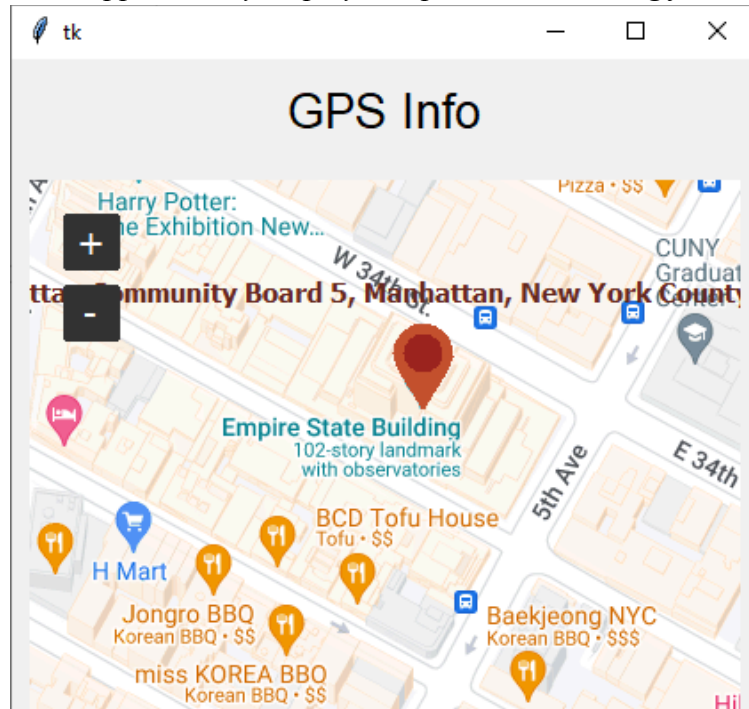
7.1.2: GPS Tracking

The collar will utilize the PA1616S GPS module to obtain its position in the form of coordinates. Once the module reads its coordinates, this information will be stored on the MCU's memory and updated every 5 seconds. This time interval was chosen as a good middle point between accuracy and power consumption, affording us a more efficient solution while still delivering on our promised goals. Once these coordinates are being stored on a known location on the MCU, the user will be able to use the app to retrieve the collars' location.

In order to display the location of the collar in a simple, intuitive fashion, we needed to find a library that supports displaying maps on our GUI application (more information in

section 7.3). Thus, we are utilizing a Python library developed by GitHub user Tom Schimansky named TkinterMapView. This allows us to use coordinates to display a map with a corresponding marker, effectively tracking the collar.

Figure 36: GPS app correctly displays Empire State Building from coordinates



Another feature that the PA1616S GPS module will be responsible for is the geofencing. The goal of a geofencing feature is to restrict the pet from entering or leaving an area that has been previously denoted by the user. In order to accomplish this, the app will allow the user to drop “nodes” directly on their own location by utilizing their device’s in-built location services. Once the user places at least three of these nodes, the app will allow you to finalize the area. The user must then specify if the area is a “keep in” or a “keep out” geofence, so that the app knows on which side of the geofence the collar must stay in. Once the geofence is in place, we can use the Python library Shapely to create a polygon that uses the coordinates of the geofence as its vertices. Shapely allows us to easily create this polygon and, using its within() function, find out if a point is currently inside the polygon or not. By combining these features, along with a clock to make sure that the collar is pinged frequently, we will be able to successfully implement a geofence feature.

7.1.3: Sensor storage

The collar will use sensors to read the temperature and humidity around the pet every 5 seconds. The on-board software will then check these values against preset critical values before storing them. If the values exceed critical levels, the user will be immediately notified. If not, they will be stored for data tracking purposes. By collecting these values over time, we will be able to construct a report for the user. This way, the user can make informed decisions about the environment their pet is in, and whether or not it is safe to

leave them outside in the current conditions. As a stretch goal, we also plan to include information within the app itself that the user can use to judge if the temperatures are dangerous.

To accomplish this, we have two main approaches. We could either convert the data to a csv file and display it using matplotlib, or keep a few values within a queue. The csv approach would offer more detailed data, however, the collar has limited memory space. Additionally, most users wouldn't need such detailed information to begin with, making this approach unnecessary. Instead, we will use a small queue, which operates in a first-in-first-out fashion. This way, we can keep around a day's worth of values in the queue, where the oldest value is forgotten in order to make space for new values. This approach allows us to declare a fixed amount of space for this data that will not change in size as the collar is used.

7.2: Auxiliary Beacon Software

The goal of the beacon system is to locate the pets within the user's house. This system is primarily geared towards users who either have large homes or are unable to move easily. Using this system, the user will be able to easily find their pet no matter where they are in their home, as long as there is a beacon in the room.

The hardware design for this system has already been discussed in section 6, so this section is focused on the software. In order for the system to work, the beacons need to be able to communicate to the device with the main application on it. This is simply done using the ESP32's wifi connectivity, allowing us to connect all the devices using the user's home network. Once connected, the beacons will not constantly stream information to the device, instead, they will internally store data and transmit it only on request from the main device. In order to keep track of the pet, each beacon will run using the UNIX timestamp, which it can keep updated thanks to their wifi connectivity. Each beacon will have a boolean variable stored in their memory that it will update every second. This variable denotes whether or not a certain beacon can currently see the collar, and will update to "true" if this is the case, or "false" if not. Once a beacon detects the collar and its value is set to true, it will also store the UNIX timestamp for that reading, doing so every second that the collar remains in view, until it eventually moves away from the beacon and the value is updated to false.

When the user wishes to check up on their pet, they will send a ping through their home network to each beacon they have registered. The response will follow a simple logic in order to display the most relevant information to the user:

```
On ping:
```

```
retrieve all beacon boolean values and timestamps

if (there is a "true" among the responses)
    return (beacon which currently sees the collar)
else
```

```
return (beacon with the most recent timestamp)
```

Once all the beacon responses are gathered, if there is a “true” among them, that’s all that needs to be returned. This “true” value means that the beacon can currently see the pet, meaning the pet has been successfully located. Alongside this response, the application will also display the difference between the timestamp when the value first switched to “true” and when it was pinged, letting the user know how long the pet has spent in that room. If none of the beacons respond true, then instead the application will return the beacon with the most recent timestamp, serving as a way for the user to know the last room their pet was in before they went out of view. Due to the nature of the beacons, it is possible that they miss the light coming off of the collar even if the pet is in the same room. The pet could be behind an obstacle or oriented in a certain way that blocks the LEDs, so this “last seen” function will be very useful in these scenarios.

7.3: GUI Application

The presentation and development of the GUI application is very important for the finished product. In the market that our team is trying to break into, it is standard for smart collars to be controlled by an application on the user’s personal device. Although we will be developing the application for PCs first, the design of the application can be translated into iOS or Android devices as a stretch goal.

7.3.1: Preliminary Design

In order to design the GUI in an efficient manner, a plan must first be created. By nature, our product comes with many features, all of which must be accessed by and controlled through our GUI app. For this reason, we must ensure that everything here is delivered upon.

Video Feed/Defense Activation: One of the main selling points of our collar is the live video feed and defense mechanism. Through the application, the user must be able to see this feed and manually activate the strobe lights if necessary. Additionally, the application will include a debug feature to see snapshots of when the defense mechanism was automatically activated.

GPS location and Geofencing: A standard feature for smart collars, the GPS location will also be accessed through the application. The application will display a live map with the pet’s location displayed on it. Through this feature the user will also be able to set up geofences by walking to certain locations and pressing a button on the app, which will drop a geofence node on their current location.

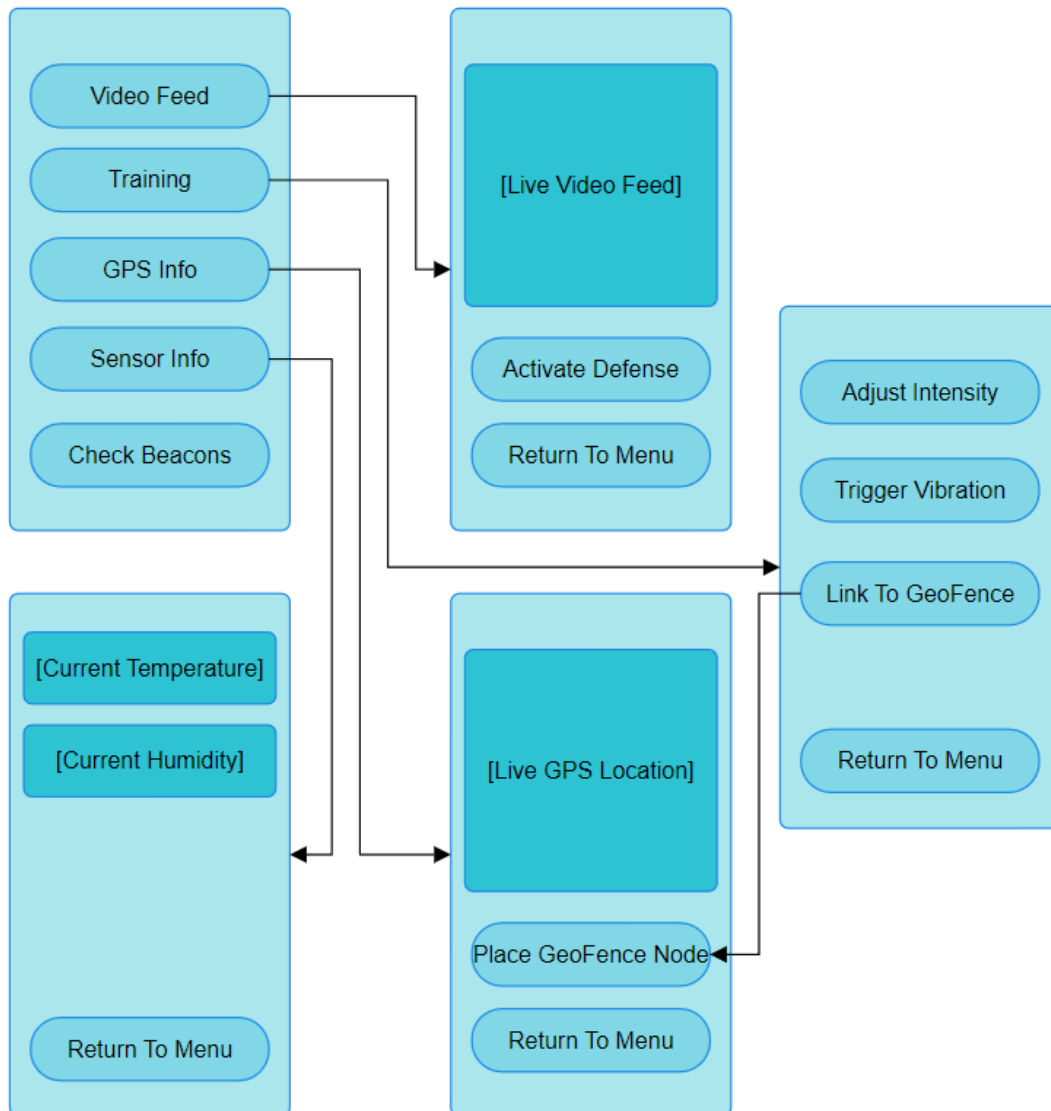
Sensor Information: The app is also how the user will view any extra information gathered by the collar, such as humidity and temperature. The app will display the pet’s current humidity and temperature, as well as a graph of the sensor’s readings throughout the day. This is also how the user will receive notifications relating to these readings, informing them that their pet might be at risk of heat stroke.

Training Functions: The collar comes with vibrating motors that are meant to assist with training. The user will be able to use the app to change the intensity of the vibration, as well as manually trigger them to assist with pet training. They will also be able to link this training function to geofenced areas, automatically triggering the vibrations if the pet wanders into a restricted area.

Beacon Connectivity: If the pet is currently indoors, the app will allow the user to check if a beacon can currently see the pet. This will be done by pressing a button that will ping the beacons, which will then return which beacon, if any, can see the pet.

With all these features in mind, a GUI must be designed in a way that displays all the information to the user in the simplest and most logical way. Below is the first prototype mock design for our GUI application.

Figure 37: Mock GUI Design

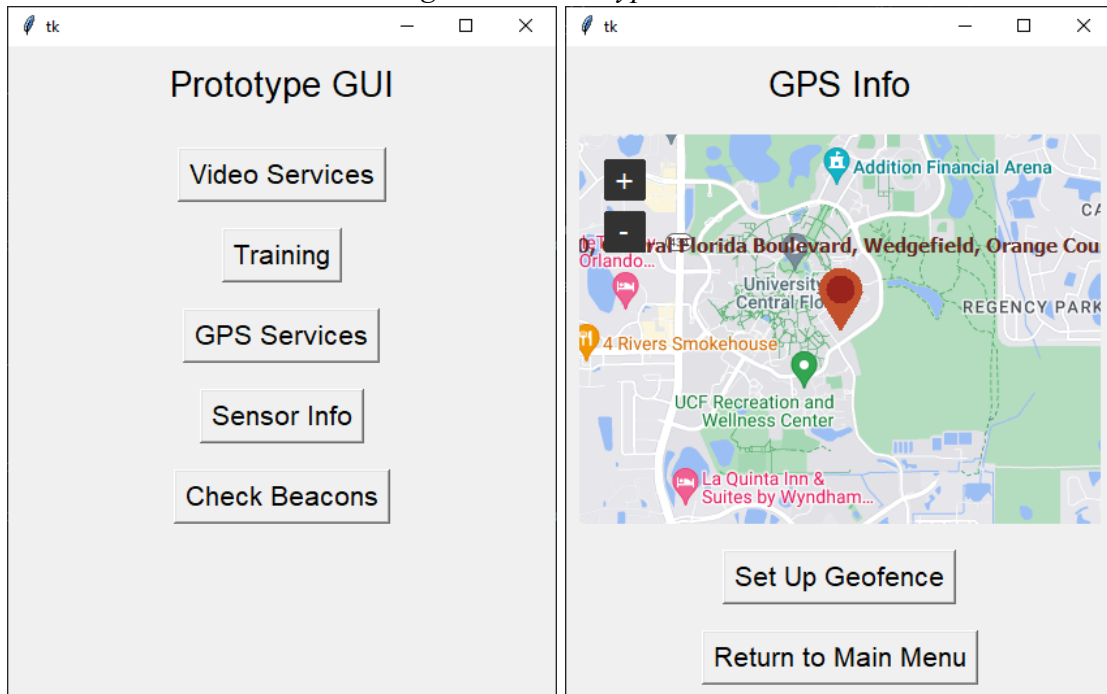


7.3.2: Design Process and Testing

Since our project is being developed in Python, the library we have decided to utilize for GUI design is going to be tkinter. The team's reasoning behind this choice was its position as Python's standard library for interface design. Being as popular as it is, tkinter is extremely well documented online, with substantial resources and tutorials freely available for learning. While coming to a decision, we ruled out other options for libraries such as dearpygui, pyqt6, and easygui. As niche, smaller, and less well known libraries, we found them to be either too restrictive or too difficult to navigate with the few available online resources.

This isn't to say that using tkinter was our optimal choice. Due to our team's decision to develop in Python for its image detection libraries, we needed to find a way to create a GUI in it as well. For the reasons mentioned before, we decided to go with tkinter. Though widely documented, there was still a learning curve when it came to designing the GUI. We are using VSCode as an IDE for our Python development, which has plenty of tools on its own. However, when it comes to tkinter, the GUI for our program does not come with an IDE interface to make the design easier, meaning every element of it must be written out by hand.

Figure 38: Prototype GUI



Pictured in Figure 37 is the mock GUI put into practice. So far, it is extremely simple and serves only as a proof of concept. In the figure, you're able to see the bare bones of the main menu and the GPS feature, although the GPS is not currently connected to any actual device, and essentially works as a map viewer. The point of crafting this prototype

GUI is to have everything set in place for once the collar itself is done. Once the development and manufacturing for the collar is complete, we will be able to connect the collar's data into this GUI application, and control its many features through it.

8: Product Fabrication

8.1: PCB Design Software

An important component in this project is designing a printed circuit board that is able to contain all of the necessary components. In order to create a printed circuit board, the appropriate PCB design software needs to be considered. The PCB design software considered should be easy to use, allow for inspection of the designed PCB, and should additionally be affordable. Additionally, the PCB design software must have a library that contains the components that will be utilized in the completion of this project or must have the ability to import those components' footprints into the design. This will ensure that all components will be able to fit on the finished printed circuit board.

8.1.1: KiCad

KiCad is an open source PCB designing software that allows the development of circuit schematics and printed circuit boards. Since the software is open source, it is free to use for the development of any PCB and project which makes it ideal in order to save money. Additionally, the KiCad PCB development software allows the import of various components, schematics, and footprints from Ultra Librarian which is a library that contains all of the components needed for this project's design. KiCad's website lists some additional capabilities of their PCB designing software [140]. One such feature is a footprint editor that allows the creation of custom footprints if any component does not have an available footprint online. A final benefit of the KiCad PCB development software is its 3D viewer. The 3D viewer allows the user to view the final PCB design in 3-dimensions allowing for a detailed inspection. This could be useful for visualizing the size of the design and ensuring that the PCB works for our project.

8.1.2: Altium CircuitMaker

Altium Designer is an extremely popular PCB Design software and CircuitMaker is a free version from the same company with less features. Many features of Altium CircuitMaker can be found listed on their website [141]. CircuitMaker features a large component library in which users can share parts or they can make their own custom parts. CircuitMaker allows the design of boards up to 16 layers and can also generate a 3D schematic of the PCB when the design is complete. This allows for complex boards and easy analysis of the end result of the design.

Additionally, CircuitMaker includes an auto router which allows components attached in a schematic to be quickly connected on the PCB. One downside of CircuitMaker is that it does not appear to be compatible with Ultra librarian which could limit the components that could be used or add unnecessary time designing individual footprints for each component.

8.1.3: Autodesk Eagle

Autodesk Eagle is a paid PCB design software that costs about \$70 per month to utilize. Fortunately, Eagle is free to use non-commercially for students and teachers allowing it to be utilized for this project. One benefit of Autodesk Eagle is that UCF students already have experience using it due to its use in the Junior Design coursework. This allowed us to skip some of the learning curve with learning how to import components and their footprints and design the PCB. Being able to skip this learning curve was extremely important for this project due to the limited time constraints given in Senior Design. Autodesk eagle also works with Ultra Librarian allowing all the footprints for every component to be imported into Eagle and utilized to efficiently design the project.

Another feature Autodesk Eagle offers is the autorouting tool. Once a schematic has been built, PCB components can be placed as desired and automatically connected together by the software allowing for less time to be wasted completing that task. Furthermore, Autodesk eagle contains a large library with many common components utilized in the design process. Autodesk Eagle also allows a 2D view of the board which can aid in seeing where components will be located in the final design. A final feature of Autodesk eagle is its inclusion of the electronic rule checker to display whether pins are disconnected which allows for easy verification that all connections have been made before ordering a printed circuit board.

One downside of Autodesk Eagle is that the software will no longer be available in 2026 meaning that all experience gained using it may be obsolete in a few years if it is selected to be used for this project.

8.1.4: PCB Design Software Selection

The chosen PCB design software for this project was Autodesk Eagle. Due to the time constraints of this project it was deemed important to utilize a software that was familiar with members in the project. Our group's current knowledge of how to use Autodesk Eagle will greatly speed up the PCB design process by allowing us to skip learning how to utilize the software. Additionally, with the amount of components being utilized in this project, access to the ability to import component footprints from Ultra Librarian was deemed a necessity.

It is also important to note that Autodesk Eagle's electronic rule checker will allow the easy verification that all components are properly connected. This will hopefully allow our group to avoid mistakes during the PCB design process since any mistake could've been detrimental to the successful completion of the project.

8.2: PCB Vendors

Building the schematic is only half of the process. Not any company can be trusted to bring the PCB, or Printed Circuit Board, to fruition, so it's important to make the decision as to where to print the circuit board carefully. When deciding on the vendor, it's important to consider a few different aspects of each. The most important feature to keep in mind is the lead time; if the lead time is too long, we wouldn't have gotten our PCBs

with enough time to assemble it and test the project before it's due. This is especially true since we won't necessarily be able to test right away sometimes, or will run into different problems that we haven't accounted for or anticipated, and we will need as much time as we can get to be able to test as thoroughly as we need to.

Another important aspect is the quality and reliability of the vendor. We want the highest possible quality for our boards, because if they aren't made well they might break easily or have bridges between buses which would mean it wouldn't work properly. We also need to be reasonably sure that if the PCB doesn't work, it's due to our own circuitry and not the PCB itself being broken.

We must also bear in mind the relative cost of each vendor. If one of them is substantially more expensive than the others, it might be worth it to have a potential guarantee of quality. Alternatively, it may be unethically overpriced if the quality is bad, which we would want to avoid.

We also wanted a vendor that provided consistent and clear communication throughout the process. It's going to be important that we are kept up to date with any updates regarding our PCB in the manufacturing process.

Below is the comparison between some of the biggest PCB vendors that we could've ordered from [143].

8.2.1: Camptech

Camptech is a circuit board manufacturer based out of Ontario, Canada. They offer both prototype boards and production boards, with the lead time of the prototype boards being 2 to 10 days and the lead time for final production boards ranging from 5 days to 4 weeks.

Camptech also offers an educational sponsorship for engineering students, which would greatly benefit our team if we were eligible since we have multiple PCBs involved in our project. [144]

Although they offer a quote request on their website, they require the inclusion of a completed schematic before they can give an estimation of the price. Since we are not at a point where our schematics are ready to be built, we were unable to use their quote feature, and therefore are unable to gauge the price of a 2" by 3" board.

8.2.2: Advanced Circuits

Advanced Circuits is a PCB vendor based in Colorado and is the third largest PCB manufacturer in the United States [145]. They boast a same-day turnaround time if the order is placed before 8:15 a.m. MST, or are able to schedule an order to be delivered Monday morning if the order is placed the previous Friday.

Advanced Circuits also offers many student discounts and programs for engineering students wanting to order a PCB. One of the discounts is a prototype board with no

minimum requirements for only \$33 each, which would be beneficial to us as we would want a prototype board before committing to a PCB design. They also claim to sponsor engineering students' projects, which would help us to save costs on PCBs since our design includes multiple boards [146].

Using the quote tool on their website, the cost for 5 boards with no special customizations that are 3" by 2" for same-day shipping is \$95. The cost for the same input but 5 day shipping is \$36.35. The below table is from their quote and details the prices for different shipping times and quantity of boards.

Table 19: PCB Quantity vs. Shipping Time vs. Price, Advanced Circuits

Qty	Same Day	1-day	2-day	3-day	4-day	5-day	E Test(Lot)
5	\$95.00	\$76.41	\$50.91	\$39.26	\$37.80	\$36.35	\$110.00
10	\$49.91	\$40.06	\$26.54	\$20.37	\$19.60	\$18.83	\$135.00
50	\$13.83	\$10.97	\$7.05	\$5.26	\$5.03	\$4.81	\$169.20
150	\$9.65	\$7.53	\$4.63	\$3.30	\$3.14	\$2.97	\$169.20
Tooling NRE = \$0							

8.2.3: OSH Park

OSH Park is located in Oregon and claims to have professional quality service at hobbyist prices. They offer both prototype boards and fully realized PCBs. The prototypes cost \$5 per square inch and are in multiples of 3. The prototypes will ship within 9 to 12 calendar days [147].

OSH Park also offers Medium Run Service, which is a board that is between a prototype and final PCB. They run at \$1 per square inch with a 100 in² minimum. These boards ship within 12 - 21 calendar days. This option is not beneficial to us because our boards will be very small and won't meet the minimum size requirement.

They also have a 2-Layer Super Swift Service with a turnaround time of 4-5 business days. The pricing for these boards are \$10/in² and can be ordered in multiples of 3. This would mean that a board that is 3" by 2" would be approximately \$60 for 3, 6, or 9 boards.

8.2.4: Digikey Red

Digikey Red is a relatively new PCB vendor associated with Digikey, the electronic components distributor. They are based in Minnesota which would mean that shipping from them would not cost as much as overseas shipping.

They don't appear to offer prototype boards, however their PCBs are reasonably priced. For example, a plain 3" by 2" board with no customizations is \$9/board with a minimum of 4 boards, bringing the total to \$36 [148]. Their boards are built in 5 to 10 business days and have free shipping to addresses in the United States.

8.2.5: PCBWay

PCBWay is based in China. They offer both prototypes and fully realized PCBs. Since they are based in China, the cost of their shipping is significantly higher than the other options on this list – a whopping \$20.

The quote for a 2x3” PCB on their website with no additional customizations is \$5 for 5 boards, with shipping costs of \$20 bringing the total up to \$25.86. The amount of time it would take to have it delivered is approximately 2 to 4 business days. The breakdown of prices versus quantity given on the website is included below.

Table 20: Price Comparison Matrix, PCBWay

Price Comparison Matrix				
Quantity	Build Time	Total	Build Time	Total
5	24hours	\$5.00	Express 12hours	\$94.56
10	24hours	\$5.00	Express 12hours	\$99.53
15	24hours	\$23.64	Express 12hours	\$109.74
50	24hours	\$41.55	Express 12hours	\$126.90
75	3-4 days	\$58.99		
100	3-4 days	\$69.41		

PCBWay also offers special sponsorships and scholarships for students and hobbyists. They have a page on their website that details the innumerable projects they have sponsored. If our team was able to get a sponsorship from PCBWay, that would save costs for the multiple boards included in our project.

8.2.6: Final PCB Vendor Comparison

While each of the vendors have their own benefits and drawbacks, the one vendor that stood out would have to be PCBWay. Their prices and turnaround were second to none, and since our project isn’t going to be professionally distributed and manufactured at this time, we have to consider the cheapest option even if that means that the quality may not be as good as pricier options listed. Although they aren’t based in the USA, meaning we will have to cover shipping costs, the overall price including shipping was still less than all of the USA based companies.

The below table summarizes each of the vendors that were discussed. Considered in selecting a vendor were prices, turnaround time, and location.

Table 21: Vendor Comparison

Vendor	Offers Prototypes	Turnaround Time (days)	USA Based	Quote for five 2”x3” PCBs
CampTech	Yes	5 to 20	No	Unknown

Advanced Circuits	Yes	Up to 5	Yes	\$36.35
OSH Park	Yes	12 to 21	Yes	\$60
Digikey Red	Unknown	5 to 10	Yes	\$36
PCBWay	Yes	2 to 4	No	\$25.86

8.3: Component Types

When it comes to electrical components, the most common types are surface mounted devices (SMD), dual in-line packages (DIP or DIL), and through-hole technology (THT).

Dual in-line packages, or DIP, are integrated circuits that are encased in a protective plastic shell and have two parallel rows of metal pins. They are simple to use and make, and generally have a very low price compared to other types of components. Due to the nature of the component being so large and spindly, DIP components have great heat dissipation. They are also very easy to replace without impacting the rest of the surrounding circuitry.

That being said, DIPs aren't without flaws. They're substantially larger than other types of components which can take up valuable space on our collar. This isn't desirable because our collar requires as small of a footprint as possible in order to fit comfortably on the animals' necks, and the use of large components will greatly increase our footprint. DIP components are also not as immune to temperature fluctuations as other types, which is important because the animals could be in any sort of environment and will also be moving between the indoors and outdoors, guaranteeing a change in hot and cold, humid and dry, etc. [149].

Surface mounted devices (SMDs) are components with small leads that mount directly to the surface of the PCB [150]. They are typically very flat components that don't take up any more space than they need to. SMDs are advantageous due to many factors, including the idea that now the PCB can be double sided. This would be good for our purposes because the collar must be a small size and having access to both sides of the PCB would enable us to optimize as much space as possible. These components also boast a higher tolerance to physical disturbances like environment and vibrations. Since they have such a small stature, they are less susceptible to shrinking and expanding in changing temperatures like the pins on DIPs, and don't move and bend like the leads on THTs.

SMDs have a few disadvantages, however. Since these components are so small, it's nearly impossible to solder them by hand. This means that when it comes to assembly time, the process will have to be outsourced to a company that can do it for us. These components also have problems with the solder being where it's supposed to – since the pins are all so close together, it's easy for the solder to leak or “bridge” between multiple pins, damaging and potentially ruining the entire circuit. These mistakes are also very difficult to find, since it's so hard to see such small mistakes. Visual inspections and

probing tests are rendered essentially useless for PCBs made with entirely SMD components [151]. These components would also be impossible to remove and replace in the event of one getting damaged, even if the rest of the board is operational.

Through hole technology (THT) is the oldest form of components and is most commonly used during testing and breadboard designing. They consist of components with metal leads that extrude out from the component either axially or radially. THT components have to be threaded through holes in the board and once they're soldered, the excess leads must be trimmed off to prevent the metal from touching anything. While simple to use, they're the clunkiest of the component types and are least size efficient. They take up a lot of real estate on the PCB, which isn't desirable due to the small stature of the collar and a bigger PCB would mean a greater cost. The through-board nature of the holes also means we wouldn't be able to use both sides of the PCB. The leads on these components also can allow for the components to move and bend, and if they bend too much it can break the leads and the component will be lost.

On the other hand, these components are really good for heat dissipation since they're large and have distance between them and the board in most spots [150]. The through-hole solder boasts the strongest bond out of any of the component types meaning that so long as the leads aren't moving, THT is the most secure type. These components are also best with encountering environmental stress such as impacts and shocks, which is good for a device that will be worn by an animal that potentially will be running around and jumping a lot. Overall, THT devices have its benefits for specific applications, but may not be very useful in our instance.

Based on the previous analysis, surface mounted components will be the best for our purposes as they're the smallest and we require the most compact PCB possible for our collar. They also mean we can use both sides of the PCB instead of having to order two or more boards for each part of the collar.

8.4: Optical Prototype Mount Design

In order to test optical components, it is necessary to mount them such that they can be aligned on a surface such as an optical breadboard. Custom mounts for some Indoor Supplementary Location System components including the ball lens, the LED, and the photodiodes, were designed in the CAD software SolidWorks and fabricated using a 3D printer. For use in testing, these mounts were then fixed to posts for use on an optical breadboard. Below are some images of the design of these mounts within Solidworks (including drawings that showcase some key dimensions of these mounts) as well as the actual mounts that were fabricated. It should be noted that the photodiodes were attached to their mount by use of hot glue after wires were soldered to each photodiode's cathode and anode.

Figure 39: Prototype Ball Lens Mount Design in SolidWorks. Dimensions are in mm.

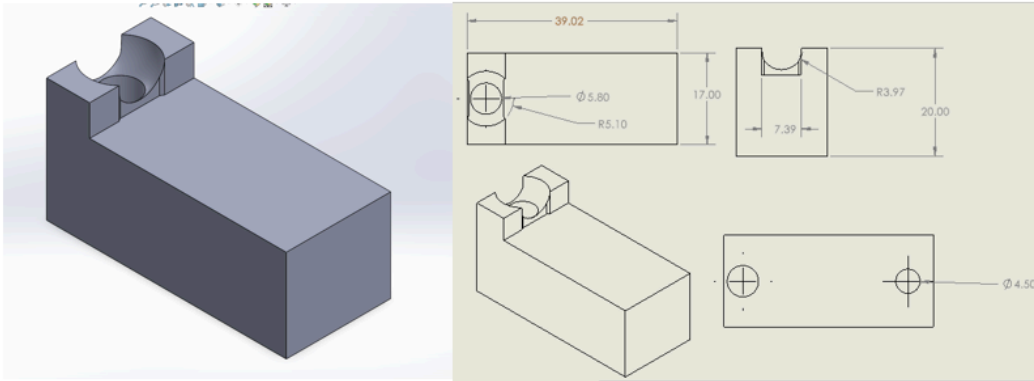


Figure 40: Prototype LED Mount Design in SolidWorks. Dimensions are in mm.

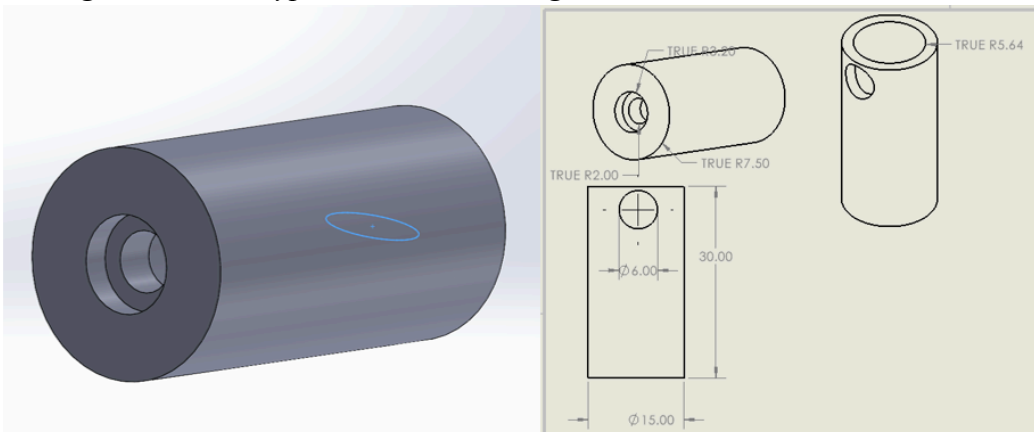


Figure 41: Prototype Photodiode Mount Design in SolidWorks. Dimensions are in mm.

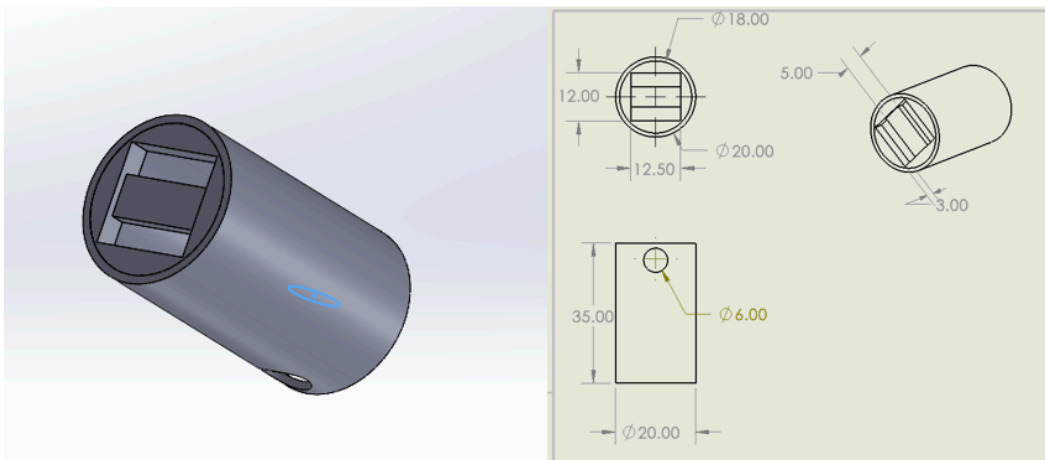
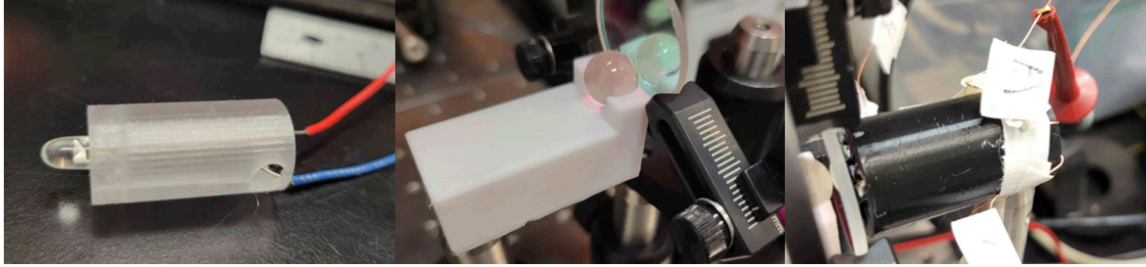


Figure 42: Fabricated Mounts In Use With Components. From left to right: LED mount, ball lens mount, photodiode mount.



During initial testing of the Indoor Location and Fencing System's field-of-view, it was speculated that the prototype mount was unsatisfactory in that it did not keep the photodiodes sufficiently flat and properly aligned with respect to one another. Thus, a more sophisticated mount was designed for this purpose. This mount also included a means to hold the lens and filter in place in order to facilitate proper alignment of all receiver components, as shown in Figure 42. The two pieces pictured are attached to each other using screws after the photodiodes (with wire leads) and filter are inserted into the lower piece and the ball lens is inserted into the upper piece to make the fixture shown in Figure 43. This mount was later adapted into a mount combined with a container for the PCB.

Figure 43: Prototype Combined Photodiode and Lens Mount Design In SolidWorks, Lower Piece. Dimensions are in mm.

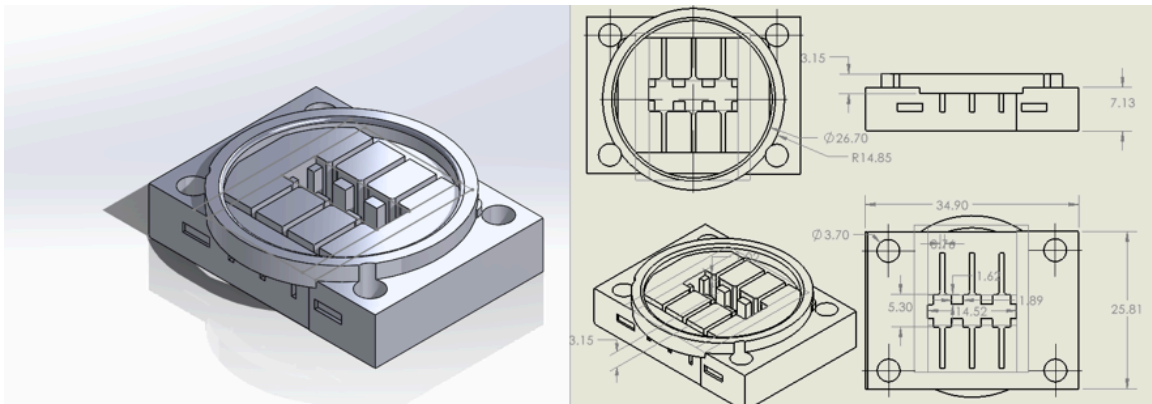


Figure 44: Prototype Combined Photodiode and Lens Mount Design In SolidWorks, Upper Piece. Dimensions are in mm.

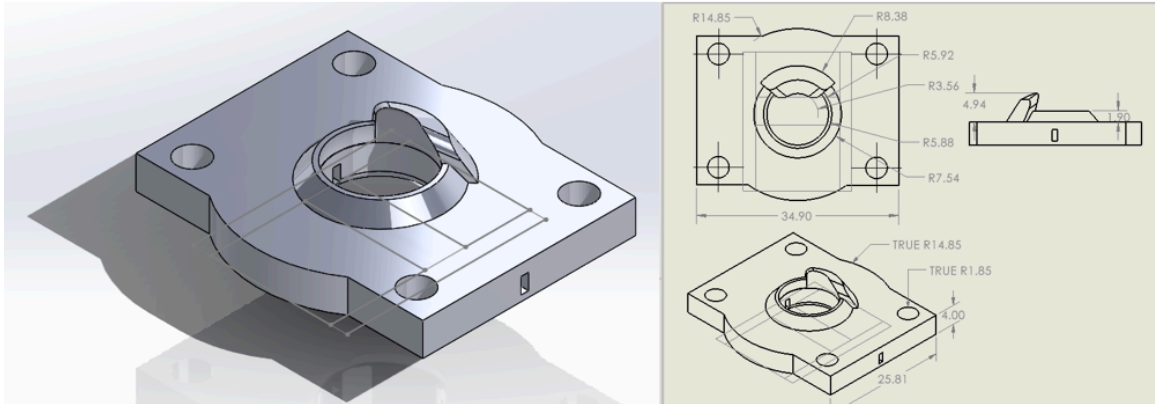
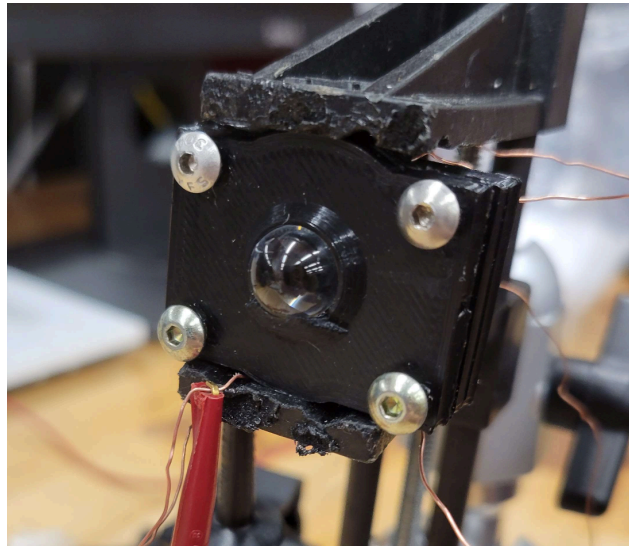


Figure 45: Prototype Combined Photodiode and Lens Mount In Use.



9: Project Testing Plan

Testing the individual components before adding them onto the final circuit board is a crucial step when building a project. The components might not be functional for some reason, and by testing them before soldering them onto the PCB, it can be discovered and a new one can be ordered instead of accidentally committing to a broken or faulty part. If every component is immediately soldered onto the final board without being tested first, it could jeopardize the quality of the project; a component might be broken and it would keep the PCB from working as expected, and we would not know why. It also helps to know if the chosen component is compatible with the circuit before the PCB is finalized and mistakes become time-sensitive and harder to undo.

A few of the components that were purchased for production use are SMD components, which required special adjustments to test. Unlike through-hole components, surface mounted devices can't be simply plugged into a breadboard to test them. Due to the

nature of the design, they don't have leads that stick out to connect to alligator clips, solder wires onto, or simply plug into a breadboard circuit. Thus, we had to come up with a creative solution to test our SMD components.

After some research, we discovered the use of SMD adapter boards. These are premade PCB boards that SMD components can be soldered onto that essentially expands the component and gives it header pins to stick into a breadboard. They come in a variety of sizes for a variety of pin numbers. Since the surface mounted components we need to test are the photodiodes (SFH2200) which are 2 pins and the transimpedance amplifiers (OPA2380) which both have 8 pins, we decided to go with PCBs that have SOIC-8 to DIP-8 on both sides but one side has smaller metal pads to solder to for smaller components [153]. Some of the other components needed for testing have less than 8 pins, however they can still be tested using the SOIC-8 boards by leaving the unused pins unconnected.

9.1: Power Supply Subsystem Testing Plan

The power supply subsystem is one of the most important parts of the project due to the necessity of supplying the appropriate amount of power to the entirety of the circuit. The testing procedure for the power supply subsystem must be divided into multiple parts due to the number of components needed for the subsystem to completely function. The first component that needs to be tested in the power supply subsystem is the charging port. The next thing that needs to be tested is the power management integrated circuit. Then the p-type MOSFET and lithium-ion battery need to be tested to ensure that they are functioning as expected. Finally, the circuit's switching voltage regulator needs to be tested to ensure it is outputting approximately 3.3 V.

Testing the charging port of the power supply subsystem should be a relatively easy process. USB-C chargers output 5V so to ensure that the charging port is functioning, the output measured from the voltage bus to the ground should be equal to 5V when a charger is connected. Additionally, USB-C charging ports work no matter the direction the charger is inserted so the charger must also be removed, flipped, and then reinserted to ensure that the charging port outputs 5V no matter which way the charger is inserted.

The power management integrated circuit will be tested by analyzing its output as it charges a lithium-ion battery. While charging, the MCP73812T-420I/OT should be outputting a current into the lithium-ion battery of 250 mA. This value will be confirmed through the use of an ammeter to ensure that the proper charging current is supplied to the lithium-ion battery. Once the lithium-ion battery reaches its full capacity and has a voltage of 4.2 V, the circuit will be checked to ensure that minimal current is then being supplied to the battery. Additionally, these values will be checked throughout the charging process to view the changes as the battery charges. Additionally, the outputs at different times throughout the charging process will be graphed. This serves two purposes, the first is to ensure that the power management integrated circuit is completely functioning and the second is to obtain the amount of time it takes to charge the circuit to full capacity.

The p-type MOSFET transistor and battery will be checked through the use of an ammeter, voltmeter, and a load resistor. First, the charger will be inserted and thus the p-type MOSFET should act as an open circuit for the load resistor. An ammeter will be used to confirm that when the charger is inserted, a negligible amount of current is going through the load resistor. When the charger is removed, the MOSFET should act as a closed circuit. A voltmeter will then be used to confirm that the potential difference across the lithium-ion battery is approximately equal to the potential difference across the load resistor.

The circuit's switching voltage regulator will be tested through the use of a voltmeter. First, the voltage across the battery will be measured to determine what voltage it is outputting. Then, the voltage across the load of the switching voltage regulator will be measured to ensure that it is outputting approximately 3.3 V. This process will be repeated to ensure that the voltage outputted by the switching voltage regulator remains constant even when the voltage supplied by the lithium-ion battery decreases as it discharges. Using this information it will be determined at what point the battery no longer has enough voltage to ensure the proper output of the switching voltage regulator.

9.1.1: Power Supply Subsystem Initial Testing

Initial testing of the power supply subsystem was done through the use of a breadboard. A breadboard was required in order to simplify the wire connection process. Additionally, due to the size of some of the integrated circuits and the fact they are surface mount devices, surface mount to dual inline package adapters were needed to complete initial circuit testing. These adaptors allow the surface mount device to be soldered to them and then the adaptor can be connected to a breadboard which aids in simplifying the testing of the circuit.

The first thing tested was the charging port of the device to ensure that it was able to output 5V when a charger was inserted. Initial testing of the USB-C port indicated that 5.09V were outputted when the charger was inputted in one direction. When the charger was flipped, the USB-C port once again outputted 5.09V indicating that the charging port is behaving as expected. The output value is slightly higher than expected but the switching voltage regulator is able to handle voltage far exceeding the measured value so the device should still be able to function as intended.

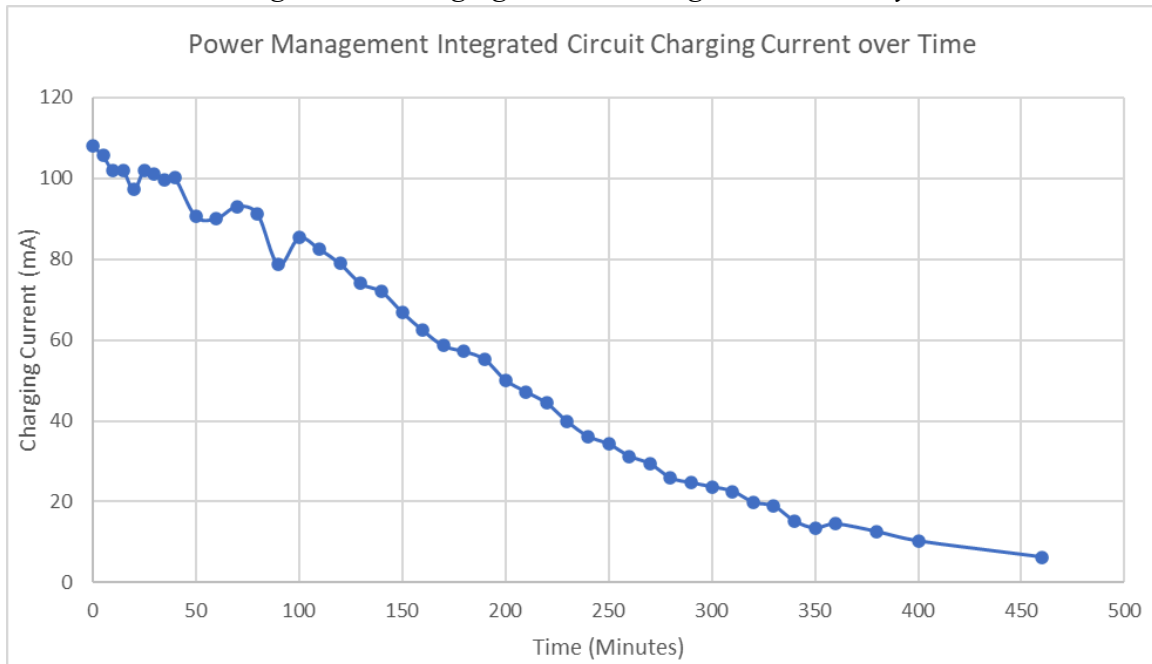
When testing the p-type MOSFET, the charger was initially disconnected from the circuit which should result in an approximately equivalent potential difference across the load of the circuit. For this test, a load resistance of 10000 Ω was utilized in place of the load of the complete system. The potential difference across the lithium-ion battery was measured to be 3.42 V at the time of testing. The potential difference across the load resistor was measured to be 3.40 V indicating that when the charger is disconnected, the p-type MOSFET is behaving as expected. A slight voltage drop of 0.02 V across the transistor was observed but that voltage drop should not significantly impact the system. When the charger is connected to the circuit, the potential difference across the load resistor of the circuit should be approximately equal to zero volts. When measured using a multimeter, the potential difference across the load resistor was found to be exactly

equal to zero volts indicating that the p-type MOSFET is behaving exactly as expected within the system. Additionally, no current was going to the portion of the circuit.

When testing the power management integrated circuit, the current exiting the circuit and going into the lithium-ion battery was measured. The initial measured current going into the battery was found to be 12 μA indicating there was an error with the power management integrated circuit. The expected current going into the lithium-ion battery is supposed to be 250 mA and a current of 12 μA would result in significantly larger charging times.

Upon further analysis of the power management integrated circuit, it was noticed that they rearranged the pins in their example circuit to be in a different layout than the actual pins on the integrated circuit. The result was the circuit initially being incorrectly constructed which explains why no current was going into the lithium-ion battery. The main issue was that the charge enable pin was connected to ground which told the circuit not to charge the battery. Once the circuit was rebuilt, 130 mA of current were found to be going into the battery and the current was found to slowly decrease as the battery charged. This makes sense since the current going into the battery is supposed to decrease as the battery reaches full charge. The current going into the battery was then graphed over a period of time and the results of that graph can be seen in the following image.

Figure 46: Charging Current Going into the Battery

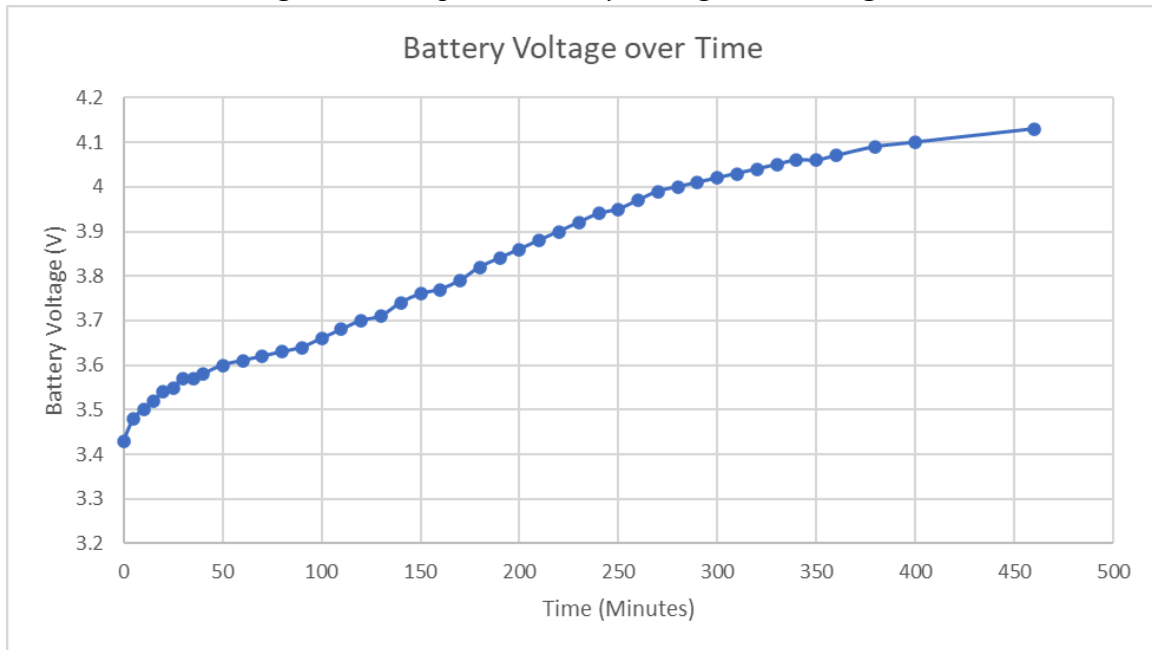


As shown by the results it can be seen that the power management integrated circuit is successfully implementing its purpose to efficiently and safely charge the lithium-ion battery. When the battery was not fully charged it outputted a large amount of current but as the battery got closer to being fully charged, the amount of current being outputted

quickly decreased to near zero. By doing this, the power management integrated circuit is able to prevent the battery from being overcharged.

Additionally, in order to determine how close the battery was to being fully charged, the voltage across the lithium-ion batteries terminals was measured in addition to the charging current going into the battery. The results of this test can be graphically shown in the following image.

Figure 47: Outputted Battery Voltage as it Charges



When comparing these results to the charging current graph it can be seen that the charging current is appropriately decreasing as the output of the battery neats its full charge voltage of 4.2V. Additionally lithium-ion batteries are approximately 80% charged around when they reach 3.75V. It can be seen that this battery achieved this point of charging around 2.5 hours into the charge cycle and then it took a significantly longer amount of time to reach near full charge. The results of this testing indicate that a majority of its capacity could be achieved in a short amount of time but the user of the device should be able to achieve a full device capacity if it is charged overnight.

9.2: Global Positioning System Testing Plan

The global positioning system used will be utilized in order to enable geofencing and allow the owner to view their pets location. In order to test this functionality, the Adafruit Ultimate GPS Breakout Board (PA1616S) will be utilized. Since the global positioning system is a surface mount device, it is necessary to use a breakout board to ensure that the device will function when utilized within our project and to ensure that it has the required functionality desired for this project.

The breakout board will first be connected to a board containing the ESP32 micro-processing unit. Then, four pins on the breakout board need to be connected in order to allow for the proper communication of data between the GPS and the micro-processing unit. The input voltage and ground pins will be connected to a 3.3V voltage source and the ground of the circuit respectively. Then, the UART TX pin will be connected to PIN3 of the ESP32 microprocessor and the UART RX pin will be connected to PIN1 of the ESP32 microprocessor. The GPS can then be tested through the use of the Arduino integrated development environment.

In the Arduino IDE, the Adafruit GPS Library can be installed which will allow for a basic test of the GPS. The Adafruit GPS Library includes an example code titled GPS Hardware Serial Echo Test. Using this code will enable the location to be printed out to the user. To ensure proper communication, the output location will be analyzed and put into google maps to ensure that the GPS is properly communicating information and that it is communicating accurate information. This basic test will be conducted in various locations to determine where the global positioning system can and can not obtain a signal. Additionally, the time it takes for the GPS to obtain a signal in various locations will also be recorded.

After it has been verified that the GPS is able to properly function, the systems geofencing capabilities will be analyzed. In order to do this, a program will be set up and a predesignated geofenced area will be inputted into the program. Then when inside the geofence area, a LED attached to the system will be turned off and when outside the geofenced area, the LED attached to the system will be turned on. This will ensure that geofencing capabilities are able to be achieved in the system. The response time of the system and distance from the designated area will be recorded to ensure the system is able to achieve the desired specifications.

9.2.1: Global Positioning System Initial Testing

When the PA1616S GPS module was initially tested utilizing an ESP32 microprocessing unit and the serial echo test given in the Adafruit GPS library, the following output was obtained.

Figure 48: GPS Initial Test Results

```
16:18:13.487 -> $GPRMC,211810.086,V,,,,,0.00,0.00,241123,,,N*4F
16:18:14.427 -> $GPGGA,211811.086,,,,,0,0,,,M,,M,,*4C
16:18:14.459 -> $GPGSA,A,1,,,,,,,,,,,,,*1E
16:18:14.490 -> $GPGSV,1,1,02,31,,,30,26,,,22*7E
```

As shown, the GPS outputs a magnitude of different pieces of data but some of the outputs are missing with only a comma in their place. It was found through initial testing that if the GPS is unable to determine its location, it will instead not output any information pertaining to its coordinates. Additionally, the breakout board used included an LED that would rapidly flash indicating that the GPS was still trying to figure out its location. Since this initial testing was done indoors, it can be seen that the GPS chosen

may have some difficulty finding its location if a significant amount of material blocks its path from a satellite.

After approximately 30 minutes and without moving the GPS, the output shown by the serial monitor began showing location data of the GPS as seen in the image below.

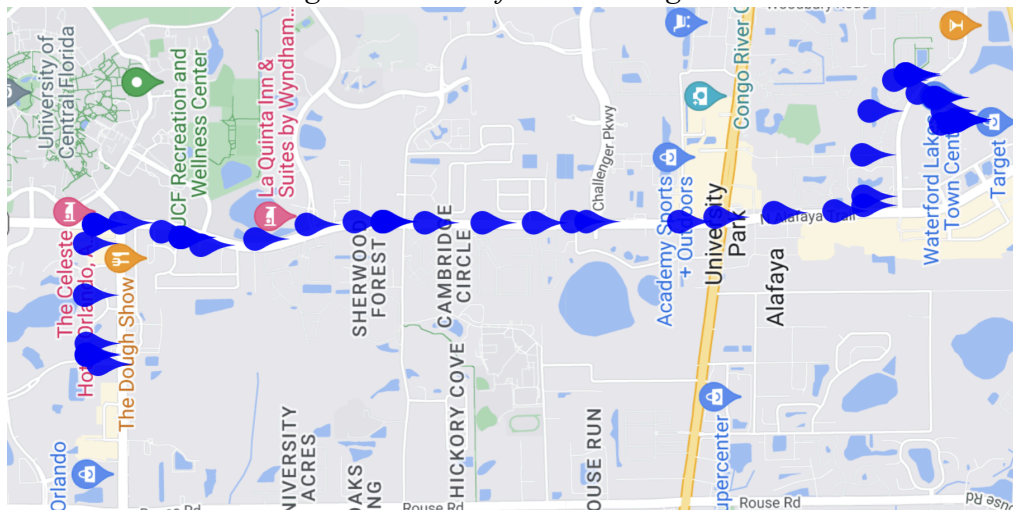
Figure 49: GPS Data When Location Determined

```
16:45:10.368 -> $GPGGA,214507.000,2835.6867,N,08112.6880,W,1,04,3.63,167.4,M,-31.1,M,,*5C
16:45:10.431 -> $GPGSA,A,3,16,26,21,31,,,,,,,,,7.23,3.63,6.25*01
16:45:10.463 -> $GPRMC,214507.000,A,2835.6867,N,08112.6880,W,0.08,72.95,241123,,,A*40
16:46:04.495 -> $GPGSV,3,1,12,04,66,204,,08,64,172,18,27,59,067,24,09,56,287,*74
```

For ease of viewing, the latitude coordinates outputted by the GPS are highlighted in blue and the longitude coordinates outputted by the GPS are highlighted in yellow. In order to view the location given by these coordinates, they can be input into google maps following the format 28 35.6867, -81 12.6880. Upon inputting the data it was confirmed that the location obtained was approximately equal to the position where the device was being tested. When indoors it was seen that it takes a significantly long time for a satellite to determine the global positioning systems location but once the location was determined, the GPS was able to continuously output data. This result indicates that as long as power is supplied to the GPS and a satellite is able to connect to the GPS when the device is turned on, it will be able to determine the GPS's location.

Further testing was done to test the accuracy of the GPS system. The GPS was transported over a long distance within a car in order to verify that the GPS accurately shows the traversed path as well as to determine if the GPS is able to show that I stay on the road for the entirety of the trip. A plot showing the locations I traversed can be seen in the image below.

Figure 50: Plot of Travel Using GPS



As shown the GPS was able to show my location on the road throughout the entirety of my journey as I traveled away from target. Additionally, the GPS was able to accurately

show which side of the road I was on. Due to this, I can be confident that the GPS is working as expected.

9.3: Temperature and Humidity Sensor Testing Plan

The temperature and humidity sensor will be utilized to monitor the pets environment to ensure they are not within a location that can be deemed to be excessively hot for an extended period of time. In order to verify the functionality of the SHT31 temperature and humidity sensor, a breakout board must be utilized. A breakout board is necessary for multiple reasons, one of which is that surface mount devices are excessively hard to test without being soldered onto something first. The other reason is that it is beneficial to have something pre soldered due to the size of the integrated circuit. It is necessary to quickly verify that the selected device will meet the specifications of the project and making a PCB to test one component would not be cost or time effective.

The breakout board will first be connected to the ESP32 micro-processing unit which has been selected to be utilized within our project. Since the SHT31 sensor utilizes inter-integrated circuit communication, it is necessary to connect the sensor to the appropriate pins on the microprocessing unit. The serial data output (SDA) should be connected to PIN21 and the serial clock (SCL) should be connected to PIN22 on the microprocessing unit. Additionally, the ground of the sensor should be connected to the decided 0V reference node and the input voltage should be connected to a 3.3V voltage source.

The Arduino integrated development environment will be used to verify the functionality of the device. In the Arduino IDE, the SHT31 library can be downloaded which will provide pieces of example code that will show whether the SHT31 sensor is operating as expected. To verify the sensor is properly working, the SHT31 demo code will be utilized. Initial functionality will be determined by monitoring if the sensor responds to changes in temperature and humidity. For example, the sensor will begin measuring the temperature of my room and it can be analyzed if the temperature increases when I put my finger on it due to my body's increased temperature compared to my room. Once it has been verified that the sensor can respond to changes in temperature, it can then be tested by comparing its output to the listed weather of an area. This will help test the device since weather apps attempt to provide both the temperature and humidity of an area. The output data from the sensor can then be compared to ensure that its data is approximately accurate with the weather app and to ensure that the device works in an environment similar to what a pet might experience. Finally, since this team already has other temperature and humidity sensors available, the output can be compared to those other sensors. This will ensure that multiple integrated circuits are able to obtain the same reading of an area which will help ensure the accuracy of our chosen sensor.

9.3.1: Temperature and Humidity Sensor Initial Testing

When the SHT31 is connected to the ESP32 microprocessing unit and uploaded with the example code the following output is generated. This output was generated indoors at room temperature.

Figure 51: SHT31 Outputted Data at Room Temperature

```

15:40:53.868 ->      4707    24.6    71.4
15:40:53.978 ->      4707    24.6    71.4
15:40:54.056 ->      4707    24.6    71.5
15:40:54.197 ->      4707    24.5    71.4
15:40:54.309 ->      4707    24.5    71.4
15:40:54.387 ->      4707    24.5    71.3
15:40:54.498 ->      4707    24.5    71.4

```

The left most data indicates the time the data was taken followed by the number of microseconds needed to read data from the sensor which in this instance was 4707 microseconds. As shown by the obtained data, the sensor is able to obtain data multiple times per second. The third column outputs the temperature in degrees celsius. The sensor outputted that room temperature was approximately 24.5 degrees celsius which can be converted to approximately 76 degrees fahrenheit. This value makes sense since the air conditioning of the room was set to 74 degrees fahrenheit and it is likely human body temperature and distance from the air conditioning unit would cause a slight increase when compared to the listed air conditioning temperature. The fourth column of the outputted data indicates the relative humidity the sensor got while measuring. In this case, the measured relative humidity of the room was measured to be approximately 71.4%.

When my finger was placed on the sensor for approximately one minute, the output data indicated a 1.8 degrees celsius increase in the measured temperature and a 17% increase in relative humidity. These changes indicate that the sensor is able to respond to changes in the environment since it was accurately able to increase the output temperature when a warmer object was placed upon it.

Further testing was done to test the accuracy by comparing the data outputted to that of another temperature and humidity sensor, the DHT11. The tables below show the results obtained from that comparison.

Table 22: Temperature Accuracy Comparison

Time	DHT11 Temp (°F)	SHT31 Temp (°F)
8:05pm	77	78.53
8:06pm	77	78.71
8:07pm	77	78.55
8:08pm	77	78.40
8:09pm	77	78.33
8:10pm	77	78.23
8:11pm	77	78.33
8:12pm	77	78.20
8:13pm	77	78.07
8:14pm	77	78.07

Table 23: Relative Humidity Accuracy Comparison

Time	DHT11 Humidity (%)	SHT31 Humidity (%)
8:05pm	60	63.78
8:06pm	60	61.44
8:07pm	59	60.61
8:08pm	59	60.85
8:09pm	59	60.65
8:10pm	59	60.83
8:11pm	60	60.99
8:12pm	59	61.04
8:13pm	59	60.90
8:14pm	60	61.00

Since the data indicates that the SHT31 was always within at least 2 degrees celsius from the DHT11 it can be verified that the SHT31 is likely reading accurate temperatures. Additionally, since both sensors both read approximately the same relative humidity it can be inferred that the SHT31 is able to determine the relative humidity with an accuracy of $\pm 5\%$. This data indicates that the sensor is working at the desired specifications.

9.4: Indoor Location and Fencing System Testing Overview

The Indoor Location and Fencing System serves to create an easily implementable means of tracking pet location and creating geofencing boundaries indoors. As is the case with other subsystems within this project, testing individual components and subsets of components is crucial to find potential points of failure before testing the system overall. Thus, the transmitter LED and collimating lens are to undergo testing as a standalone system first. Then, the photodiodes and filter are to be incorporated in further testing. Subsequently, the overall system is to be tested in both stationary and dynamic conditions. All testing of the system in a stationary configuration is planned to occur in UCF's CREOL Senior Design Lab and UCF's ECE Senior Design Lab as these locations have an abundance of equipment and resources that can be utilized during testing. Furthermore, these locations have lighting and temperature conditions that are typical for the indoor home environment in which the system is intended to be used. Additional testing of the system's functionality during typical use may also be conducted in other indoor environments after its functionality while stationary is established.

Components of the aforementioned tests were repeated after potential points of failure are found and revisions are made to the design to verify that they have been rectified. This was the case when it was decided to switch from using OED-EL-1L1 LEDs to OED-EL-1L2 LEDs. All tests involving the OED-EL-1L1 LEDs up to the point where this component was deemed unsatisfactory were repeated using the OED-EL-1L2 LEDs, and subsequent planned tests that were not completed with the OED-EL-1L1 LEDs were completed using the OED-EL-1L2 LEDs.

In initially testing the OED-EL-1L1 LEDs' functionality, an LED was mounted in the LED prototype mount produced per Chapter 8 which is affixed to a post secured to an optical breadboard, and connected to a DC power supply. The LED was supplied with 1.4 V and 100 mA. An infrared detector card sensitive to light at 940 nm was used to see the light emitted by the LED to observe its performance.

In testing the OED-EL-1L2 LEDs' functionality, an LED was mounted in the LED prototype mount produced per Chapter 8 which is affixed to a post secured to an optical breadboard, and connected to a DC power supply. The LED was supplied with 1.2 V and 200 mA, as these values were decided for use in the final product. An infrared detector card sensitive to light at 940 nm was used to see the light emitted by the LED to observe its performance.

Then, the collimating lens was placed approximately 6 mm away from the LED. Its position was adjusted in attempt to successfully observe collimated light. While parallel rays, considered a construct in geometric optics, aren't observable in reality, collimation can be determined by the absence of an image of the LED emitter on the IR card at any distance. Additionally, minimal spreading of the spot projected on the infrared detector card at different distances indicates successful collimation.

The LED's optical power was measured using an optical power meter configured to measure the presence of 940 nm light. The measurements were taken at 10 cm distance increments away from the LED at distances ranging from ~0 cm (as close as possible to the LED) to 100 cm in the direction of light propagation. These measurements helped gauge the LED's conformity to the datasheet specifications and gauge photodiode functionality later in testing.

Then, the photodiodes were tested. Three photodiodes were tested, as the photodiodes were mounted in a panel configuration during the testing process, as described in the Indoor Location and Fencing System Design Overview section. Wire leads were soldered to the cathode and anode of each photodiode. To perform a preliminary test of each photodiode's functionality before attachment to the prototype mount, they were directly connected to a digital multimeter, and the presence of a photovoltage when exposed to light from the 940 nm LED 5 mm away from each photodiode was verified. The measured voltage was also recorded with the LED off to verify the effect of the light exposure on the voltage reading.

After this preliminary test, the photodiodes were secured to the prototype mount by hot-melt adhesive until a revised custom mounting fixture was constructed. A filter was placed flush against the photodiodes, as specified in Chapter 6 of this paper. However, given the potential to mar the filter surface during repeated repositioning during testing, a different filter was used for testing purposes until a fixture was created to mount the filter to be used in the final product.

The filter used during initial testing (OED-EL-1L1 LEDs), which was available in the CREOL Senior Design Lab, was Newport's 10LWF-700. This filter has a cut-on wavelength of 700 nm, a 2 mm thickness, and a 25.4 mm diameter. While a slightly larger of ambient light may pass through the testing filter than the final selected filter, and the additional filter thickness compared to the chosen filter may somewhat impact the system's performance during testing, the majority of light emitted by common ambient indoor light sources theoretically are still blocked by the 10LWF-700 filter, and this filter

was much more practical to utilize during initial testing until a fixture was created to mount the filter to be used in the final product.

During tests involving the OED-EL-1L2 LEDs, the HOYA IR85N filter was used since a mounting fixture was created to hold it in place with respect to the photodiodes without need for excessive repositioning or alignment.

During testing, each photodiode was reverse-biased at 5V and connected in series to a load resistor with a resistance of 240 k Ω (switched from the initial 500 k Ω value to adjust the op-amp gain). The current through each photodiode was measured by a digital multimeter connected in series with the photodiode circuit. The individual photodiodes are identified with identifiers “A”, “B” and “C”, which are listed in order of placement from left to right on the prototype mount as viewed facing the direction of propagation. As was the case with the LED optical power testing, the measurements were taken at 10 cm distance increments away from the LED at distances ranging from ~0 cm to 100 cm in the direction of light propagation. After placement at each distance in the direction of propagation, the LED was aligned in the directions normal to the propagation direction such that a maximum current reading was shown. The dark current (current without incident light) through each photodiode was also recorded prior to this testing.

The system’s horizontal field of view was then tested. While maintaining the previous configurations of the photodiode and filter, the ball lens was placed in the system, and the mounted LED was placed on a rotation stage. The rotation stage was rotated in increments of 10° in both possible directions (which were arbitrarily be labeled as positive and negative) with respect to the major axis of the photodiode panel, as well as a test at 45° in either direction. This procedure was revised from that proposed in the Senior Design 1 Documentation, as collecting data at 5° increments would consume significantly more time without yielding necessary information as a preliminary test. The rotation stage was then translated such that the optical axis intersects the receiver lens system and is the desired distance away from the receiver. The current through each photodiode was recorded using a digital multimeter. This test was performed with the transmitter light source at distances of 10 cm (since a test at 0 cm cannot be performed practically), 25 cm, 50 cm, 75 cm, and 100 cm from the LED in the direction of light propagation.

The system’s minimum vertical field of view was then tested. The LED and rotation stage were reoriented such that the LED spot would move with respect to the minor axis of the photodiode panel and placed at the correct height. The final vertical field of view will be approximately 90° also near the center of the horizontal angular field of view since a 3 photodiode panel will be utilized both in the horizontal and vertical directions. However, this 90° vertical field of view cannot be extended to the edges of the horizontal field of view by use of more photodiodes, since the device’s microcontroller can only read a limited number (6) of analog input sources. Thus, there was reason to measure the minimum vertical field of view for reference purposes. To perform this test, the rotation stage was rotated in increments of 5° in both possible directions (which were arbitrarily be labeled as positive and negative) until the signal was lost. The current through the

central photodiode (the minor axis of the panel extends only along one photodiode) was recorded using a digital multimeter. This test was performed with the transmitter light source at a distance of 100 cm from the LED in the direction of light propagation.

Testing of the system's accuracy was performed as follows: The receiver system, which was housed within the Prototype Combined Photodiode and Lens Mount, was held in place with a clamp and connected to the Indoor Location and Fencing System PCB. The output of this PCB was transmitted over wifi and read via a group member's computer. This output is used by the software application to determine that the transmitted passed the receiver. A distance of 1 meter from the receiver was marked on the ground to ensure that the accuracy of the receiver was measured at the edge of its required working range.

It was first ensured that environmental noise did not produce false readings in the system. For a period of 15 minutes, the receiver system was activated in an environment with indoor lighting typical to a home environment (the ECE Senior Design Lab). The system was monitored for this 15 minute duration to ensure that no analog-to-digital converter (ADC) voltage output above the threshold value, which would yield a reading of "Pet Entered Room", was registered.

Thereafter, the accuracy of the system was first tested using the IR LED operating with a constant 3.3V source so that it could be ensured that the optical system works well and so that possible failures in the program to distinguish pulse frequency could be better isolated. The LED was held in place by a group member at the approximate receiver height, measured visually — the same process by which users of the product would place the receiver to match the height of their pet. Then, the group member walked past the receiver briskly (speed of approximately 2 miles/hour), making sure to stay behind the 1-meter distance marker. The group member would then wait 1 minute to see that a reading of "Pet Entered Room" was displayed on the computer before walking past the receiver again. This test was repeated for ten trials. In order to quantitatively analyze the data, an accurate reading of "Pet Entered Room" was assigned to a value of 1, while a missed reading or a false positive "Pet Entered Room" reading was assigned to a value of 0.

9.5: IR LED and Collimating Lens Testing

After setting up the OED-EL-1L1 LED as specified in the Indoor Location and Fencing System Testing Plan, the LED spot (which appears as a green spot on the card surface) was successfully viewed on the infrared detector card, as shown in the figure below.

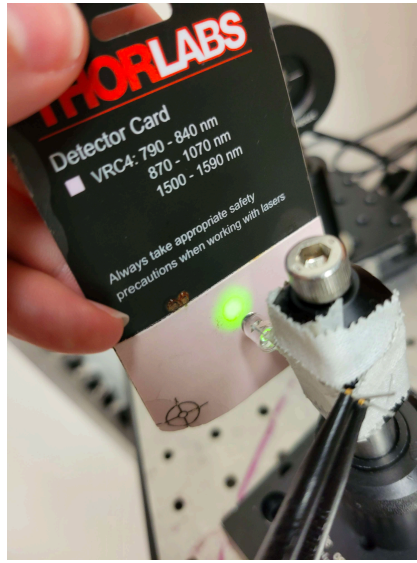
Figure 52: LED Output on Infrared Detector Card



However, when the collimating lens was added, a focal point with a clear image of the LED emitter was always present at some distance from the LED despite repeated attempts to adjust the lens position. Thereafter, the 6 mm lens was switched for a larger lens with a focal length of 3 cm and a diameter of 2.54 cm to determine whether the scale of the lens was responsible for the lack of collimation seen. The new lens was placed at its focal length of 3 cm and, as was the procedure before, its position was adjusted in an attempt to find a position where an image of the LED emitter could not be found at any distance from the lens, and the spot size changed minimally. As was the case before, no collimation was seen. Through consultation with others [154], it was postulated that the cause of this failure might be the presence of additional focusing optics within the LED housing, which were not described on the LED datasheet. It was also determined that there is no real necessity to include this collimating lens, as a larger spot incident on the receiver, provided that it has adequate power, may make the system more robust to deviations from ideal alignment. Furthermore, without the inclusion of a collimating lens, power loss due to ray divergence in propagation may be easily compensated for by the addition of more LEDs, which are low-cost and relatively compact. Thus, the collimating lens was removed from the design, and this decision was further supported by the improved testing results obtained when OED-EL-1L2 LEDs, which have a larger divergence angle than OED-EL-1L1 LEDs, were used.

After setting up the OED-EL-1L2 LED as specified in the Indoor Location and Fencing System Testing Plan, the LED spot (which appears as a green spot on the card surface) was also successfully viewed on the infrared detector card, as shown in the figure below.

Figure 53: LED Output on Infrared Detector Card



9.6: IR LED Optical Power Testing

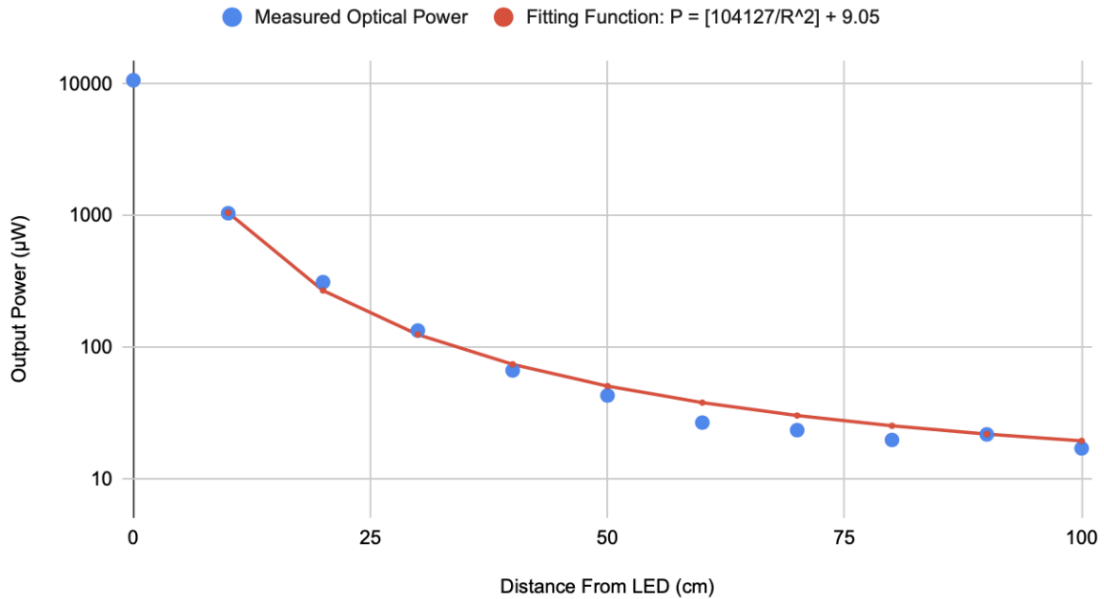
Below are the tabulated and plotted results of the initial infrared LED (OED-EL-1L1) optical power testing as performed according to the testing plan. Since the collimating lens did not work, the procedure was only conducted without the collimating lens in place.

Table 23: Infrared LED Optical Power Testing Data

Distance From LED (cm)	Measured Optical Power
0	10.63 mW
10	1.04 mW
20	0.312 mW
30	133.8 μ W
40	66.6 μ W
50	43 μ W
60	26.78 μ W
70	23.46 μ W
80	19.77 μ W
90	21.78 μ W
100	17.07 μ W
Noise Power	87 nW

The graph below is a visual representation of the data from Table 22.

Figure 54: Infrared LED Optical Power Testing Data
 Measured Optical Output Power of 940 nm Infrared LED



As can be seen in the plot above, these results were fit to the function $P_{\text{optical}} = [104127/R^2] + 9.05$ (where R is the distance in cm from the LED and P_{optical} is the measured optical output power). Given the Pearson correlation coefficient of 0.997 between the fitted data points and the measured data, it is clear that the data fits the typical $1/R^2$ dependence of optical power with distance from a point source. Note that the point at 0 cm from the LED was excluded from this fitting, as this distance is too close for a point-source approximation of the LED to apply. Note also that the measured power output is only that near 940 nm (the wavelength the power meter was set to measure). Some of the output power is within the LED bandwidth but may not be near enough to 940 nm to be registered by the power meter at the 940 nm setting.

Because the LED was switched from the OED-EL-1L1 to the OED-EL-1L2 following the unsatisfactory results of the field-of-view testing, the IR LED optical power testing was repeated with the same procedure as the initial test to ensure that the new LED (OED-EL-1L2) provided adequate optical power. Below are the tabulated and plotted results of this next iteration of testing.

Table 24: Infrared LED Optical Power Testing Data

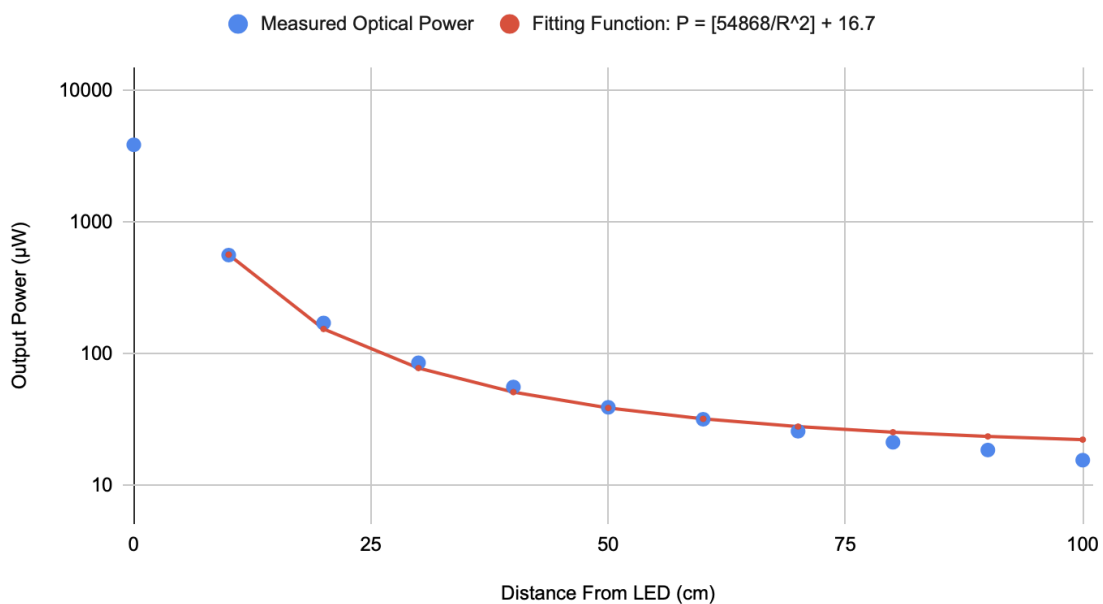
Distance From LED (cm)	Measured Optical Power
0	3.87 mW
10	0.561 mW
20	0.171 mW
30	85.2 µW
40	55.8 µW
50	39.1 µW

60	31.7 μW
70	25.7 μW
80	21.2 μW
90	18.5 μW
100	15.5 μW
Noise Power	6.42 μW

The graph below is a visual representation of the data from Table 22.

Figure 55: Infrared LED Optical Power Testing Data

Measured Optical Output Power of 940 nm Infrared LED



As can be seen in the plot above, these results were fit to the function $P_{\text{optical}} = [54868/R^2] + 16.7$. Given the Pearson correlation coefficient of 0.998 between the fitted data points and the measured data, it is clear that this data also fits the typical $1/R^2$ dependence of optical power with distance from a point source. In this case, the power readings obtained were less than those obtained in the initial testing. Lesser readings may have been obtained if a lesser proportion of optical power is emitted near the 940 nm peak emission wavelength.

When implementing the IR LEDs into the chest board, we noticed that the combined power draw of the many I/O systems was nearing the maximum current draw of the battery. In an effort to minimize this draw, we decided to add a transistor between the microcontroller and each circuit to act as a digital switch that could be turned on independently by setting the associated GPIO pin to “HIGH”. The circuit depicted in Figure 56 was utilized to enable the chosen NPN transistor to be used as a digital switch. [\[source\]](#)

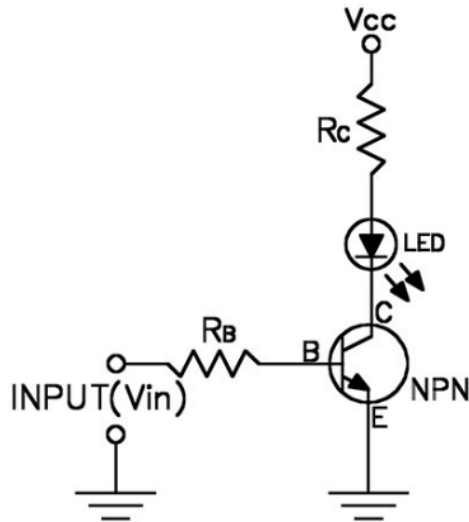


Figure 56: Switching Transistor Circuit

The values for R_C and R_B were calculated using the formulas below.

$$R_C = \frac{V_{CC} - V(LED) - V_{ce(SAT)}}{I_C(MAX)}$$

$$I_B = \frac{I_C(MAX)}{\beta_{min}} \times \text{Overdrive Factor}$$

$$R_B = \frac{V_{in} - V_{be(SAT)}}{I_B}$$

9.7: Photodiode Testing

Below are the results of the preliminary photodiode testing

Table 25: Photodiode Testing

Photodiode Identifier	Voltage (V), LED On	Voltage (V), LED Off
A	0.541	0.182
B	0.567	0.204
C	0.552	0.206

As can be seen, each photodiode produces a similar photovoltage in the presence of the infrared light source, indicating their functionality. While there is some voltage with the LED off, it should be noted that there is some ambient light in the room, the filter is not yet in front of the photodiodes, and the voltage is much greater when the LED is on.

Below are the results of the initial testing the relationship between the photodiode output current and LED distance:

Table 26: LED Distance vs. Photodiode Output Current

Distance From LED (cm)	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
0	22.9	22.9	22.8
10	22.6	22.5	22.5
20	18.0	20.8	19.2
30	9.2	7.8	9.7
40	5.8	4.1	6.2
50	3.8	2.6	3.8
60	3.0	3.1	2.9
70	2.4	2.1	2.3
80	1.8	1.3	2.0
90	1.6	1.1	1.5
100	1.3	1.0	1.4
Dark Current	0.5	0.5	0.5

Some of the differences between the measured output current between photodiodes can be attributed to variations in the components themselves, but other factors also most likely contribute to these observed differences. Securing the photodiodes onto the prototype mount manually with hot-melt adhesive resulted in them not sitting flush against the mount surface. Thus they were misaligned from the desired placement normal to the optical axis. This issue was fixed with the mount fabricated for the final product. Additionally, the testing setup was inherently misaligned since an optical breadboard of sufficient size to contain the entire setup and/or optical rails to move the LED along was unavailable.

This test was repeated with the OED-EL-1L2 LEDs and HOYA IR85N filter in place. Below are the results of this testing

Table 27: LED Distance vs. Photodiode Output Current

Distance From LED (cm)	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
0	22.8	22.9	22.8
10	22.3	22.3	22.2
20	8.8	8.6	8.8
30	4.3	4.2	4.2
40	2.7	2.7	2.7

50	2.0	2.0	2.0
60	1.1	1.1	1.1
70	0.9	0.9	0.9
80	0.7	0.7	0.7
90	0.5	0.5	0.5
100	0.5	0.5	0.5
Dark Current	0.0	0.1	0.0

As can be seen above there was less current output overall from the photodiodes in this test than the initial test. This most likely is due to the candidate filter more effectively blocking environmental noise from visible light sources than the interim test filter. In the final setup, the lens serves to focus an adequate amount of light onto each photodiode to produce a clear signal. More consistent readings at a given distance between photodiodes were most likely obtained due to better alignment of the photodiodes with respect to each other in the next mount iteration.

Table 28: LED Angle vs. Photodiode Output Current at a Distance of 10 cm, Initial Test

Angle of LED (°)	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	22.4	8.3	22.6
-40	22.2	5.5	22.7
-30	21.9	5.0	22.8
-20	19.3	21.9	22.5
-10	22.4	22.3	22.8
0	22.5	22.9	22.5
10	17.3	22.3	8.4
20	22.5	17.5	11.9
30	22.5	6.1	13.7
40	22.7	10.0	10.5
45	22.4	8.6	11.6
Dark Current	0.5	0.5	0.5

Table 29: LED Angle vs. Photodiode Output Current at a Distance of 25 cm, Initial Test

Angle of LED	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	1.5	0.4	22.5
-40	1.4	0.6	22.4
-30	4.3	1.5	22.7
-20	7.0	5.3	22.3

-10	1.1	22.5	8.0
0	4.0	22.6	2.5
10	2.2	22.6	1.1
20	22.1	22.2	1.7
30	22.1	7.2	3.3
40	22.4	1.5	2.5
45	22.4	0.7	1.6
Dark Current	0.1	0.1	0.1

After attempting testing for the 50 cm distance case, testing was discontinued due to inconsistent and unsatisfactory results—when the system worked with the transmitter on one side of the ball lens, it would not work upon moving the transmitter to the other. Furthermore, minor tweaks in the position of the transmitter light source would cause the measured current to fluctuate beyond acceptable levels. Determined possible causes included misalignment of the photodiodes with respect to each other and the ball lens as well as the LED spot size being too small. To remedy misalignment of the photodiodes and receiver optics, design of a new prototype receiver mount that better held the photodiodes flat in the panel configuration and included fixed slots for all optical components. This design is shown in more detail in the Optical Prototype Mount Design section. Furthermore, an LED that has a larger emission angle, and, thus, yields a larger spot size, was selected, as detailed in the Part Selection section.

Still some interesting results were found from this initial testing. In the 10 cm distance case, the fact that the minimum current is in the center of system’s overall field-of-view as opposed to the angle opposite the expected extreme in photodiodes A and C can most likely be attributed to the fact that the lens does not cover the entire filter or photodiode surface. Because of this lack of coverage, some light most likely bypassed the lens and landed directly on the photodiodes in the extreme-angle cases. However, the results still indicate that a satisfactory portion of light goes through the lens system to achieve the desired field-of-view at the extreme angles, and the more expected results (increasing current with increasing angle in photodiode A and increasing current with decreasing angle in photodiode C) at 25 cm corroborate this statement.

The testing was then repeated with the new OED-EL-1L2 LED and the new mount, yielding the results to follow.

Table 30: LED Angle vs. Photodiode Output Current at a Distance of 10 cm, Second Test

Angle of LED	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	22.7	2.3	22.4
-40	22.7	2.5	22.5
-30	22.5	14.8	22.5

-20	22.4	22.4	22.5
-10	22.2	22.6	22.3
0	3.3	22.7	6.5
10	1.1	22.6	1.3
20	0.4	22.2	1.3
30	0.4	15.9	0.3
40	0.4	2.6	0.1
45	0.4	1.7	0.1
Dark Current	0.1	0.1	0.1

Table 31: LED Angle vs. Photodiode Output Current at a Distance of 25 cm, Second Test

Angle of LED	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	21.3	0.4	17.4
-40	22.1	1.7	20.3
-30	22.3	6.0	20.5
-20	21.7	16.2	20.6
-10	19.4	22.3	15.0
0	10.3	22.3	10.1
10	1.0	22.3	2.4
20	0.5	18.1	0.5
30	0.3	12.2	0.1
40	0.2	3.6	0.1
45	0.2	1.2	0.1
Dark Current	0.1	0.1	0.1

Table 32: LED Angle vs. Photodiode Output Current at a Distance of 50 cm, Second Test

Angle of LED	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	0.1	3.9	8.2
-40	0.1	4.1	9.5
-30	0.1	9.5	10.0
-20	0.1	13.1	9.0
-10	0.1	15.3	6.6
0	0.3	16.0	0.4
10	1.6	15.8	0.2
20	6.8	10.0	0.1

30	11.5	5.6	0.1
40	11.2	0.9	0.1
45	11.4	0.8	0.1
Dark Current	0.1	0.1	0.1

Table 33: LED Angle vs. Photodiode Output Current at a Distance of 75 cm, Second Test

Angle of LED	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	0.1	0.1	3.2
-40	0.1	0.2	3.3
-30	0.1	2.0	3.7
-20	0.1	3.9	3.3
-10	0.2	5.3	1.7
0	0.5	5.6	0.7
10	1.3	5.7	0.3
20	3.2	4.8	0.1
30	3.7	2.2	0.1
40	3.7	1.1	0.1
45	3.7	0.4	0.1
Dark Current	0.1	0.1	0.1

Table 34: LED Angle vs. Photodiode Output Current at a Distance of 100 cm, Second Test

Angle of LED	Current, Photodiode A (μA)	Current, Photodiode B (μA)	Current, Photodiode C (μA)
-45	0.1	0.1	1.9
-40	0.1	0.1	1.8
-30	0.1	1.2	1.8
-20	0.1	1.9	1.3
-10	0.1	3.1	0.5
0	0.1	3.3	0.1
10	0.5	3.1	0.1
20	1.2	1.8	0.1
30	2.0	1.0	0.1
40	2.1	0.1	0.1
45	2.0	0.1	0.1
Dark Current	0.1	0.1	0.1

From the data at all distances, it is clear that the system has an acceptable and symmetrical field of view (90° total). The optical signal was successfully amplified by the transimpedance amplifier and read by the microcontroller when the photodiode output current was measured to be 1.4 μA during preliminary testing. Therefore, these results indicate the optical portion of the indoor location and fencing system functions successfully at distances of 1m and below across the entire field of view. It is also apparent that the individual photodiodes are somewhat more sensitive on one side of the active area than the other, which cannot be rectified since it is an issue intrinsic to the component.

Below are the results of the photodiode vertical field of view testing. The half-maximum value of the current output is 1.35 μA . Therefore the FWHM minimum vertical field of view, or the FWHM field of view using the active area of only one photodiode, is approximately 34°. This finding corroborates the need to utilize a panel of 3 photodiodes to achieve a 90° field of view with the chosen lens system.

Table 35: LED Vertical Angle vs. Photodiode Output Current at a Distance of 100 cm

Angle of LED	Current, Photodiode B (μA)
-30	0.1
-25	0.3
-20	1.1
-15	1.6
-10	1.8
-5	2.5
0	2.7
5	2.7
10	1.5
15	1.1
20	0.2
25	0.1
Dark Current	0.1

9.8: Indoor Location and Fencing System Accuracy Testing

After the 15 minute idle period described in the Indoor Location and Fencing System Testing Overview, no false positive readings were produced by the Indoor Location and Fencing System. This lack of false positives indicates that the system is sufficiently robust against typical indoor environmental noise.

Below are the tabulated results of testing the system at a distance of 1 m using a constant LED signal.

Table 36: Indoor Location and Fencing System Accuracy at a Distance of 1 m

Trial Number	“Pet Entered Room” Reading Present	Assigned Value
1	Yes	1
2	Yes	1
3	Yes	1
4	Yes	1
5	Yes	1
6	Yes	1
7	Yes	1
8	Yes	1
9	Yes	1
10	Yes	1
		1
Mean		1
Variance		0

As shown above, the system accurately detected the passage of the collar at a distance of 1 meter for all 10 trials, and no false positives were given (such as doubled positive readings or readings when the LED was not directed toward the receiver’s field of view) by the system.

9.8: SMD LED and Collimating Lens Strobe light Testing

The SMD LEDs being used for the strobe light have a power output of 2.502 milliwatts. The resistance was found by taking the input voltage and subtracting the voltage used by the LED, or forward voltage. This value was estimated to be 3.25, as it was assumed the LED would use close to the total amount of voltage supplied. Using a datasheet for a SMD LED like the ones being the forward current was 30 milliamps. The datasheet for the LEDs ordered was not provided, therefore a datasheet for a similar LED had to be used to find these values. To find the required resistance, the following equation was used:

The resistance was rounded up to two ohms, since a resistance of 1.667 ohms is not a resistor value that is readily available. The LED was connected to a power source and the voltage was set to 3.3 V, which is the voltage sent to the LEDs in the collar. This was then shined into a power meter as close to the LED as the detector could go. This distance was defined as 0. The power was then tested at 10 different distances increasing in increments of ten centimeters. The power of one LED was then tested when being shined through the collimating lens, to note the improvement from the collimating lens. The LED was kept the same distance from the power meter and the collimating lens was placed at the focal length of the collimating lens, which was 3 centimeters from the LED. The collimating lens for testing differed from the one being used for the final design. This is because the collimating lens for testing was already mounted, and the equipment needed for mounting

the lens was not available due to the size of the lens ordered. The purpose of using the collimating lens was to demonstrate the difference collimating the LEDs made. The difference in power output between the collimating lens used and the one ordered would most likely be the same since the light was still being collimated. The detector was placed as close to the collimating lens as possible, and this distance was denoted as 0. The power output measured by the power meter was then 2.152 milliwatts. The reflector was also tested but showed no difference in the power output of the LED. The reflector was unable to reflect much light back from the LED based on the nature of how the LED was oriented in relation to the reflector. This testing shows the importance of each element in the strobe light set up and how it can maximize the power output. The power output is an important measurement because a higher power output would result in higher brightness. Based on the information from a single LED the total amount of LEDs can be estimated. The collimating lens showed a vast improvement of power values at larger distances away from the source. This is important to note since the brightness of the LED needs to be effective at longer distances to deter predators. Tables summarizing the values found from the LED are shown below.

Testing with one LED:

Table 37: Optical Power Measurement of Broadband LED Alone at Sample Wavelength

Distance (cm)	Power (mW)
0	2.502
10	0.4
20	0.110
30	0.0533
40	0.02643
50	0.01731
60	0.01304
70	0.01117
80	0.00875
90	0.00737
100	0.00614

Testing with one LED and a collimating lens:

Table 38: Optical Power Measurement of Broadband LED with Collimating Lens at Sample Wavelength

Distance (cm)	Power (mW)
0	2.152
10	1.411
20	0.606
30	0.334
40	0.2635
50	0.1607
60	0.0811
70	0.0436
80	0.0484
90	0.0456
100	0.0302

9.9: Wide FOV Lens Testing

The lens system was deconstructed by soaking it in isopropyl alcohol. This was noninvasive to the system as a whole and the best and safest method for loosening the glue holding the system together. After soaking the lens for ten to twenty minutes the top portion was able to be removed and then the lens system could be taken out of the holder and analyzed further. The lenses were laid out in the order they were in the holder. Several measurements were needed for the lens system design of the wide FOV camera. The thickness of each lens and the focal length of each lens was measured. The lens thickness was measured using a ruler or tape measure. The focal length was measured by shining a point source through the lens and then measuring where the minimum spot size occurred, this was the focal length for the lens. The refractive index and radius of curvature of each lens in the system was not provided in the specifications for each lens system. To find the refractive index the radius of curvature is needed and vice versa, therefore some assumptions for each lens had to be made to get approximate values. Silica is the most common glass used in commercial lens systems so the refractive index of each lens being looked at was estimated to be 1.5. The lenses used in this system could be found on Thorlabs and Edmund optics. The lenses were closely matched to these lenses. The reason this was done was because the radius of curvature and glass type were listed on these websites. This would further validate our assumptions. This was then used to find an approximate radius of curvature using the lens maker's equation:

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Some of the lenses in the lens system have a radius of curvature of zero or infinity, this means that when calculating the radius of curvature using the lens maker's equation this value would be negligible in calculation of the other radius of curvature.

To get a preliminary idea of how each lens system was made the 10 degree FOV lens was deconstructed. This was able to give an idea of how the lens system was made and how it was bound together. This also gave some leeway for any mistakes before testing the lenses being used. This offered an opportunity to test multiple different ways to deconstruct the lens system. Two methods were explored using isopropyl alcohol and using a heat gun to loosen up the glue. The heat gun was aimed towards the outside of the lens holder and aimed around the top where the first visible lens was located. This method took very long and was not super effective in loosening the glue. There was also more risk of damage to the lens holder and potentially damaging elements inside the holder. These include apertures, lens holders, and lenses made from a plastic material inside the lens. The level of heat these items could handle was not specified and there was a risk of damaging them if exposed to high heat for an extended period. When testing with the heat gun the lens did loosen with a short exposure to heat and was not effective in loosening multiple elements. When the lens system was exposed to alcohol and most of the system was exposed to the alcohol and was effective in loosening the glue. There was a minimal risk of damaging the system as most glass can be exposed to isopropyl alcohol without damages occurring to the lens. These methods were tested on the ten FOV and the one hundred FOV lens system. Each was able to be deconstructed and examined. This was useful in understanding the general idea of how the lens systems were constructed and would be able to give somewhat of an understanding of what to expect for the lens system being looked at in the final design.

The lens systems used in the final design of the wide FOV cameras were the 140 and the 160 FOV systems. These systems were deconstructed, and the original system was implemented into Zemax after the testing specified above was performed. This information was documented in the table for each lens system. The lenses are numbered based on their position in the lens holder. The first lens visible is lens one in the table and the rest are labeled accordingly. The first lens has typically been the largest lens and is the one that is first screwed into the holder.

The first lens tested was the M25156H14 lens from the lens kit. This lens had an optical format of 1/2.5". The optical format refers to the angle of view the lens system has when used on a sensor of a certain size. This is useful when trying to put a lens onto a camera as it specifies what size circular output image of the lens is large enough for the rectangular mount of an image sensor. The initial lens system has an effective focal length of 1.56 millimeters. The field of view is broken down into three different values when evaluated at an optical format of 1/2.5". The FOV diagonally is 185 degrees, the FOV horizontally is 185 degrees, and the FOV vertically is 140 degrees. The horizontal FOV measured on a 1/4 RPI camera, which is the intended camera of use for this system, is 141 degrees. The total lens holder height is 13 millimeters. The total lens holder height is relevant information because this impacts if the same lens holder can be used based on the modifications made in the final design of the lenses. The main goal of this lens design

is to increase the field of view to at or above 180 degrees. The effective focal length may be subject to change based on the final design.

The lens system is laid out in the following chart. The lens holders were added into the testing to display the layout of the lens system. These created spacing between each lens while also ensuring the lenses did not move once inside the entire lens system. The thickness of each lens holder was taken to display the length of the lens system. Recording this spacing would also be necessary when inserting this lens system into Zemax for the design portion of the lens system.

Table 39: Lens Testing 1

Lens #	Thickness (mm)	Focal Length (cm)	Estimated Refractive Index	Lens Type	R₁	R₂
Lens 1	1	2.5	1.5	Plano concave	150	0
Lens 2	2	1	1.5	Plano concave	50	0
Lens holder	4	-	-	-	-	-
Lens 3	1.5	3	1.5	Doublet, Plano convex	150	0
Lens holder	2.5	-	-	-	-	-
Lens 4	1	0.5	1.5	Plano convex	25	0
Lens holder	0.4	-	-	-	-	-
Lens 5	0.5	1.5	1.5	Plano Convex	75	0

The second lens tested was the M30171H16 lens from the lens kit. This lens had an optical format of 1/3". The initial effective focal length of this lens was 1.71 millimeters. The field of view is broken down into three different values when evaluated at an optical format of 1/3. The FOV diagonally is 184 degrees, the FOV horizontally is 184 degrees, and the FOV vertically is 104 degrees. The horizontal FOV measured on a 1/4" RPI camera, which is the intended camera of use for this system, is 180 degrees. The total lens holder height is 13 millimeters. The main goal of this lens design is to increase the FOV to at or above 180 degrees. Since this is specified to be at 180 the lens design will be implemented into Zemax to ensure this. The lens design will therefore be increased

beyond 180 if this is possible with the lenses in the system. The vertical field of view is relatively low, so this will be increased in the final design. The total system will be evaluated to improve any chromatic aberrations and overall image clarity.

The lens system is laid out in the following chart. The apertures and lens holders were added into the chart for testing to display the layout of the lens system. The thickness of each aperture or lens holder was taken to display the length of the lens system.

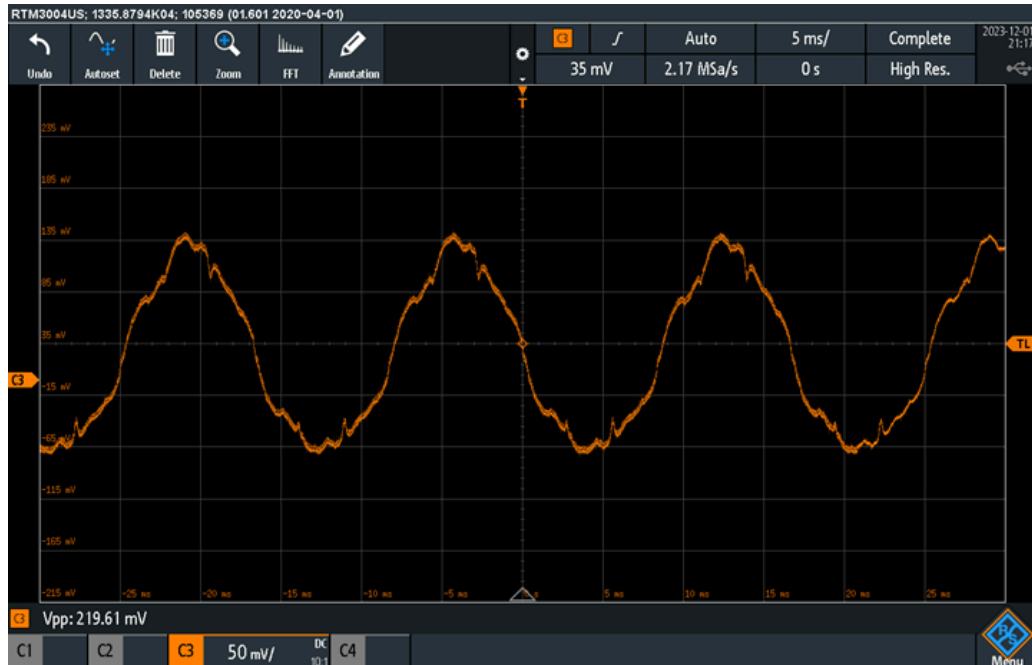
Table 40: Lens Testing 2

Lens #	Thickness (mm)	Focal Length (cm)	Estimated Refractive Index	Lens Type	R ₁ (mm)	R ₂ (mm)
Lens 1	2	1	1.5	Plano concave	50	0
Lens holder	9	-	-	-	-	-
Lens 2	0.5	2	1.5	Plano convex	100	0
Lens holder	4	-	-	-	-	-
Lens 3	2	1.5	1.5	Doublet, plano convex	75	0

9.10: CMOS Camera Testing

The CMOS sensor will be tested first. An image output cannot be seen with the CMOS sensor being used because this CMOS camera is unable to be connected to a computer with image processing software. This sensor will need to be fully embedded into the system to render an image. The sensor will not be fully embedded until the assembly part of this course and therefore only the sensor functionality is being tested to ensure the sensor works. The lens is responsible for the quality of the image so testing to see if there is a signal output will ensure that the CMOS sensor is working. The sensor will be given a power supply and connected to an oscilloscope to view the signal output. A voltage of 3.3 was applied according to the voltage requirements of the sensor, this is also compatible with the battery going into the collar. After the voltage is applied to the sensor a signal can be output from it. The CMOS sensor was connected to an oscilloscope and the signal output can be viewed below. This signal output solidifies that the CMOS sensor is working.

Figure 57: CMOS Oscilloscope Output



The CMOS camera needed to be tested to see if the lens system could be fit onto the camera and if the camera would then render an image. The CMOS camera ordered had a camera already attached to it. This camera would need to be taken off and the lens from the lens kit ordered was then attached to the camera. The lens initially attached to the camera was glued onto the camera chip. The camera will be removed using the same method as the lens disassembly. The camera will be soaked in 91% isopropyl alcohol to not damage the CMOS sensor in any way. The lens would need to be soaked for about twenty to thirty minutes. Once this camera is removed the lens from the lens kit will be fit onto the sensor. Adjustments can be made by 3D printing a lens mount in the case that the lens mounts do not fit, based on the optical format. The camera has a charge coupled device (CCD) size of $1/4$ " which is compatible with the lenses from the lens kit. The lens systems from the kit were able to fit onto the sensor after the original lens was removed. The lenses from the lens kit will need to be glued onto the sensor once the lens design is made and finalized.

9.11: Vibrating Motor Testing

The Adafruit 1201 Vibration ERM Motor came with one red wire and one black wire sticking out of it. Per the datasheet, the component should simply connect directly to power and can be adjusted in intensity by increasing or decreasing the applied voltage. The higher the applied voltage, the stronger the vibration. To reduce the current draw or the strength, a resistor of value 100-1k Ω can be placed in series with the motor. Or, for full control, a transistor can be placed to control the motor [155].

The datasheet was very sparse and did not include a specific way to test the vibration motor. We started by connecting it in series with a 1k Ω resistor and applying 3.3V, since

that is going to be the general output from the microcontroller. With those inputs, the motor was unable to vibrate at all.

Since $1\text{k}\Omega$ resistance was too high, we decided to try directly connecting the motor to the 3.3V and turning it on to make sure it worked. Once we tried that, it proved it was able to vibrate very powerfully. However, with the wires clamped onto the power supply, we ran into a problem; the vibrations were so powerful that the motion of the wire being moved back and forth so quickly in the alligator clamps was enough to sever the blue wire. We striped more of the sheath off and tried connecting in series with a 100Ω resistor to see if that helped any.

With the 100Ω resistor in series with the motor, the motor vibrated relatively gently. When any amount of pressure was applied to the body of the motor, it would stop moving. Since the 100Ω resistor was too gentle and likely wouldn't be felt through the collar, we tried it again without any resistor. The motor was very loud when it was powered and would make a lot of noise when it hit anything. This might not be ideal if it makes that much noise inside of the collar. For the final design, we went with a 50Ω resistor in series with the motor, which was just enough to control the vibration.

9.12: Software Testing

In order for all previous features to communicate, the main GUI application must be capable of receiving, editing, and sending data in live time. (add)

The collar has 10 separate triggers, which are Geofence_Enabled, Within_Fence, Training_Mode, Temp_Hazard, Camera_Enable, Indoor_Beacon_Enabled, Indoor_Beacon_Triggered, Vibration_On, Vibration_Level, and Predator_Detected. In order to achieve desired functionality, the application must be able to manipulate these triggers and send them to the collar. In our testing, we observed that the application has access to all the aforementioned values, and can send them to the collar with ~ 1 second of delay, based on internet connection strength. Additionally, the triggers that are handled automatically, such as Temp_Hazard, Indoor_Beacon_Triggered, and Predator_Detected properly automatically updated based on data received from the collar.

10: Administrative Overview

Below is a compiled version of all the administrative information covered in the document thus far. It includes a timeline of expected milestones, a summarized version of our part selections, and any other tables or diagrams that help illustrate executive decisions that went into the design of the project. The goal of this section is to analyze the product from a further perspective, and make sure that its completion is both realistically achievable and economically viable. Cost and marketability are very important to us, especially when making a product that is designed to be sold on the market, so our team has compiled this section in order to streamline and address our goals for the collar.

10.1: Project Milestones

The table below lists planned milestones that aided in the completion of the project. The table includes milestones for both Senior Design One and Senior Design Two. This table is purely for the benefit of making sure our team completed certain goals by a specified time to ensure the timely completion of the project.

Table 41: Milestones

Senior Design One Milestones		
Project Milestone	Start Date	End Date
Form Group	8/21/23	8/24/23
Discuss Project Ideas	8/24/23	8/31/23
Form Committee	9/11/23	9/14/23
10 Page Divide and Conquer Paper Due		9/15/23
Divide and Conquer Paper Review		9/19/23
Research Similar Products	9/15/23	9/20/23
MCU Research and Selection	9/19/23	10/10/23
General Component Research	9/15/23	10/15/23
Research Design Constraints	10/15/23	10/20/23
Selection and Ordering of Desired Components		10/21/23
75 Page Research Paper Due		11/3/23
Individual Component Testing	10/25/23	11/13/23
Base App Programming	10/22/23	11/15/23
Simultaneous Multiple Component Testing	11/13/23	11/20/23
Order Components	11/1/23	12/31/23
PCB Schematic	11/1/23	11/25/23
150 Page Final Senior Design 1 Document Due		12/5/23
Senior Design Two Milestones		
Order Prototype PCBs		1/12/24

Hardware and Software Testing	1/12/24	4/19/2024
Order Finalized PCB		3/04/2023
Complete Final Report	1/12/2024	4/23/2024
Final Fully Functioning Product Presentation	4/13/2024	4/19/2024

10.2: Hardware Requirements and Specifications

The following table lists the hardware requirements relating to our selected components. Upon completion of the project, every specification should be achieved and should have a measurable output showing that the desired specification was achieved. The requirements to be demonstrated are highlighted in yellow. The hardware requirements relate mainly to desired properties of the physical components and the accuracy of the physical components data collection.

Table 42: Hardware Requirements and Specifications. Requirements to be demonstrated are highlighted in yellow.

Component	Parameter	Specification
Temperature Sensor	Temperature detection in °C	± 2 °C.
Humidity Sensor	Relative humidity detection	$\pm 10\%$.
Wireless Transmission	Upload speed for general information	< 10 minutes
Wireless Transmission (cont.)	Upload speed for emergency notifications	< 45 seconds
Power Supply	Length of rechargeable battery life	> 1 hour
GPS	Geofencing/location tracking update time	Updates location at least every 30 seconds
DC Motor	Vibration	~150 Hz
Wide Field of View Camera	Angle	$\geq 300^\circ$ azimuthal field of view, $\sim 360^\circ$ radial field of view
Indoor Location Receiver Lens System	Angle	$\geq 90^\circ$ radial field of view

Indoor Location Receiver Lens System (cont.)	Accuracy	$\geq 90\%$
Transmitter Light Source	Wavelength	$900 \text{ nm} > \lambda > 2000 \text{ nm}$
White LED	Strobe light duration	1 minute

10.3: Final Part Specifications

The following is a summarized version of all our selected components as they relate to the previous table. For more detailed descriptions regarding the selection process and specifications of these components, please refer to the listed tables in the “Related Technology and Part Selection” section of this paper.

Table 43: Final Hardware Selections

Component	Component Identifier/Part Number	Detailed Specification Location
Temperature Sensor	SHT31-DIS-B	Table 3
Humidity Sensor	SHT31-DIS-B	Table 3
Wireless Transmission	ESP32 Microcontroller	Table 2
Power Supply	PRT-13851 Lithium-Ion Battery	Table 5
GPS	PA1616S	Table 4
DC Vibration Motor	Adafrui 1201 Vibration Motor ERM	Table 17
Strobe light	LED	Table 13
Strobe light	Collimating lens	Table 14
Strobe light	Reflector	Table 15
Wide Field of View Camera	OV5640 Camera Board	Table 16
Indoor Location System Transmitter LED	OED-EL-1L1 LEDs	Table 8
Indoor Location System Transmitter Collimating Lens	45-077 Lens	Table 11
Indoor Location System	10 mm Ball Lens	Table 12

Receiver Lens System (cont.)		
Indoor Location System Receiver Filter	SCHOTT RG850 Filter	Table 10
Indoor Location System Photodetectors	SFH 2200 Photodiodes	Table 9

10.4: Software Specifications

The next table lists the software requirements of the smart pet collar. The software requirements mainly relate to the programming required to maximize the users' experience when utilizing the smart pet collar. Upon completion of the project, the smart pet collar should achieve the requirements listed in the table below. The feature to be demonstrated at the end of the project is highlighted in yellow.

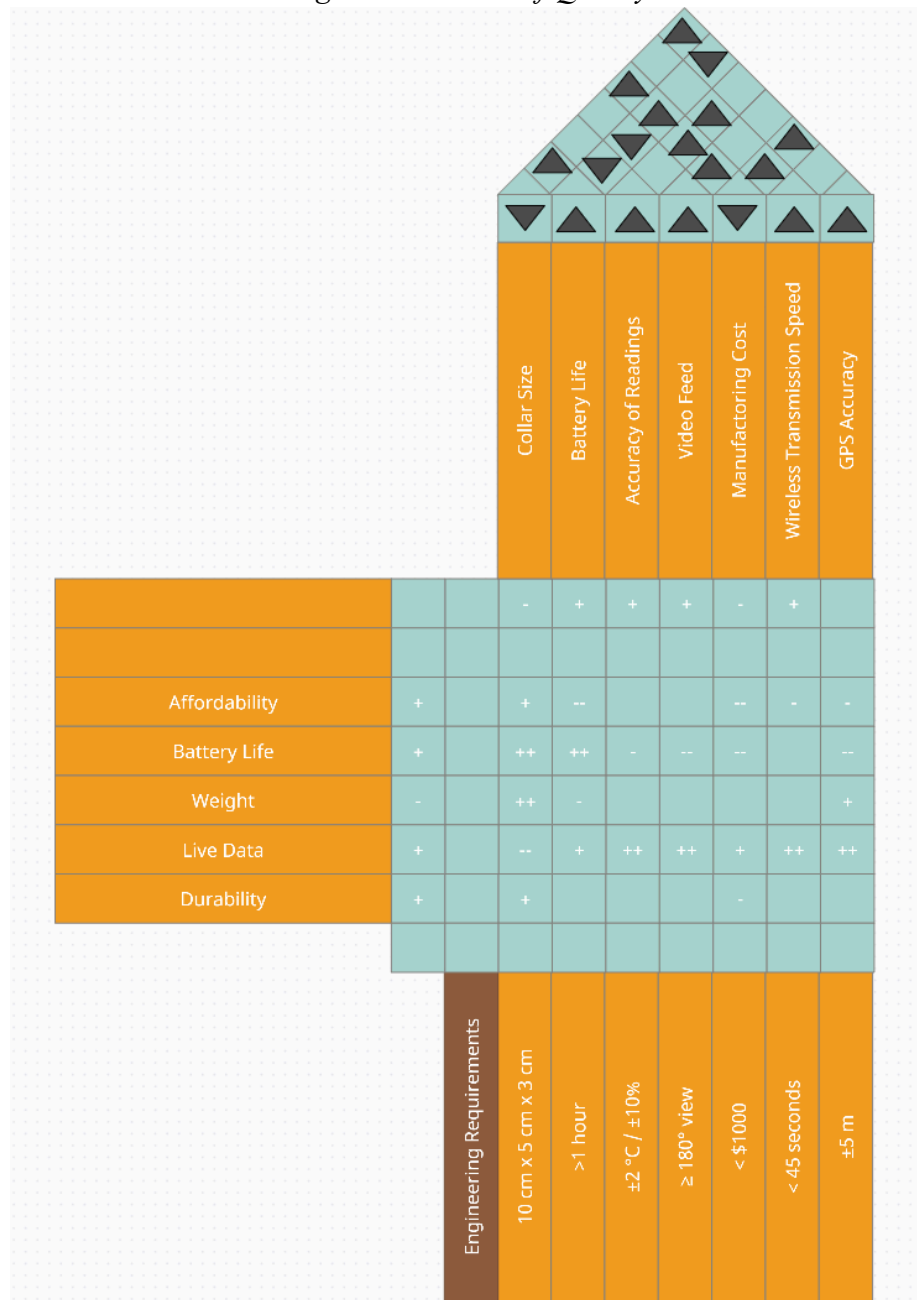
Table 44: Software Components and Specifications. Requirements to be demonstrated are highlighted in yellow.

Component	Specification
App	The app will be accessible to users to monitor their pets' temperature, humidity levels, relative location, and notify them of any detected predators. The app will also allow the user to manually trigger the defense LEDs, use the vibrations to get the animals attention, and see the remaining battery life of the collar.
Image Processing	The collar will be able to take images from the camera(s) and run image processing software to identify an anomaly from typical outdoor surroundings.

10.6: House of Quality

This diagram is the House of Quality. Further discussion about the figure is below.

Figure 58: House of Quality



The diagram above is used to show how the customer’s priorities for our product relate to our design priorities as engineers. The “+” and “-” symbols next to each priority indicate whether we strive to maximize or minimize the listed item. For instance, it is desirable to maximize the battery life and minimize the collar size. In the middle of the diagram, the “+” and “++” symbols indicate a positive and very positive relationship between attaining the intersecting priorities, respectively, while the “-” and “--” symbols indicate a negative and very negative relationship between attaining the intersecting priorities. For instance, there is a very positive relationship between obtaining a low weight, and a small collar size, since component weight is closely related to component size.

One of the biggest factors when it comes to meeting customer expectations while remaining realistically manufacturable is money. However, for our specific product, the size ends up being our number one area of concern. As shown in the diagram, the size of the collar has an effect on all of the top 5 customer requirements for the product. Being a product that is meant to be used by animals of all sizes, it is particularly important to keep the collar as small as possible, in order for it to remain comfortable for smaller animals. This size restriction, in turn, affects every other area of the product, as it forces us to optimize every bit of space we have to work with. As components get smaller, it becomes more expensive to maintain our desired level of quality for their outputs as well, so we must find a balance between size, cost, and accuracy. Another determining factor for our collar is going to be the customer’s desire for live data. As shown by the diagram, live data transmission affects nearly all areas of the collar’s design, so our team prioritized fast and accurate data transmission.

10.7: Project Budget

The budget for the project was provided by our sponsor, Ramon Jiminez, as well as personally funded by the group members. Our sponsor has afforded us a budget of \$1000, which we can use to purchase any components directly relating to the construction of the collar. The sponsor has also left the design and choice of components up to us. The table below shows the cost of the components we have chosen for the collar. The sub-total displayed in the table does not take into account delivery fees or taxes.

Table 45: Final Hardware Bill of Materials

Item Description	Vendor	Quantity	Price per Unit	Price
ESP32 WROOM Microcontroller	Amazon	5	\$5.60	\$27.99
PA1616D GPS Module	Adafruit	1	\$31.94	\$31.94
Adafruit Vibration Motor 1201	Digikey	1	\$1.95	\$1.95
OED-EL-1L1 LEDs	Mouser	10	\$0.43	\$4.30
OED-EL-1L2 LEDs	Mouser	10	\$0.35	\$3.54
SFH 2200 Photodiodes	Mouser	10	\$1.39	\$13.90
HOYA IR85N Filter	Edmund Optics	1	\$44.00	\$44.00

45-077 Lens	Edmund Optics	2	\$26.00	\$52.00
10 mm Ball Lens	MSE Supplies	1	\$16.20	\$16.20
SHT31-DIS-B Temp/Humidity Sensor	Digikey	1	\$5.42	\$5.42
2000 mAh Lithium-Ion Battery	Amazon	1	\$11.99	\$11.99
OV5640 Camera Board	Amazon	2	\$25.99	\$51.98
Wide Angle Lens	Amazon	2	\$45	\$45
SMD LEDs	Amazon	10	\$1.72	\$1.72
Collimating Lens	Thorlabs	1	\$24.92	\$24.92
PCBs v.1	PCBWay	10 (each)	\$5	\$136.83
PCBs v.2	PCBWay	5 (each)	\$5	\$74.45
Project Sub-Total				\$460.20

This project was under budget, so there was leeway to purchase replacement components when necessary as well as cover incidental costs such as shipping and delivery fees.

10.8 Contributions

As our group consists of more members than the average group, and our project is so complex and multifaceted, it is important that the work is evenly distributed and is assigned according to our individual strengths. The benefit of having a group is the ability to share the workload so that everything plays to our strengths. The below table summarizes the general tasks we accomplished and indicates the primary person who worked on it as well as the secondary. We worked on some tasks as a group, however someone took responsibility as the lead person.

Table 46: Table of Contributions

Task	Primary Person	Secondary Person
Microcontroller Comparison and Testing	Sara Wijas	Austin Fugate

Temperature and Humidity Sensor Comparison and Testing	Austin Fugate	Sara Wijas
Global Positioning System (GPS) Comparison and Testing	Austin Fugate	Sara Wijas
Power Supply Design and Testing	Austin Fugate	Sara Wijas
Indoor Location and Fencing System Optical Design	Rana Scherer	Nadia Khan
Indoor Location and Fencing System Testing	Rana Scherer	Nadia Khan
Strobe Light Design and Testing	Nadia Khan	Rana Scherer
Wide FOV Camera Sensor Comparison	Nadia Khan	Rana Scherer
Wide FOV Camera Optical Design	Nadia Khan	Rana Scherer
Wide FOV Camera Testing	Nadia Khan	Jesus Pagan Vela
Vibration Motor Comparison and Testing	Sara Wijas	Austin Fugate
Chest of Harness PCB Design	Sara Wijas	Austin Fugate
Back of Harness PCB Design	Sara Wijas	Austin Fugate
Indoor Location and Fencing PCB Design	Austin Fugate	Sara Wijas
GUI Design	Jesus Pagan Vela	Sara Wijas
Software Design	Jesus Pagan Vela	Austin Fugate
Image Processing Testing	Jesus Pagan Vela	Austin Fugate

11: Conclusion

Our project is SAFEPADS, a wearable protection and tracking device for animals of all sizes. It is able to track an animal outdoors using GPS sensors, a beacon-based indoor tracking system to monitor where a pet is inside a house, vibrational corrections for

misbehavior, temperature and humidity sensing to ensure a safe environment for the animal, AI-based predator detection using wide field of view cameras to monitor and safeguard the animal against nearby predators, strobe light defenses to deter attacks from predators, and a well fleshed out application to control all of the features on the animal.

Since our project boasts many complex features, we needed to work diligently to ensure that every goal is met in time for the conclusion of Senior Design II. We have kept track of the milestone dates and ensured consistent and efficient progress as a group. We have maintained communication throughout the group and our different components to make sure that every part of the project is getting attention and that nothing has fallen through the cracks.

Through this project, we have learned a lot about the design and manufacturing process. Our sponsor, Ramon Juminez, has been an invaluable guide. He has made sure we have kept on track and has given us insight into the real world production and what we can expect from projects once we graduate.

This project has given us the skills necessary to impress any employer, as we have now proven we can research components, factor in all of the different aspects of each, intelligently choose the right one, adapt when troubleshooting goes awry, and successfully build a project from scratch in a competitive timeline.

For our project, we required the use of multiple microcontrollers, LEDs, photodiodes, and more. We had originally ordered our chosen microcontroller, the ESP32-WROOM-32E, from Digikey, however it had ended up being backordered and we couldn't wait that long for it to arrive. We found a pack of 5 on Amazon and they arrived within 3 days instead.

The Indoor Location and Fencing system that we designed to monitor the location of the animal within a house had originally taken on a few different looks; eventually, we decided on a wall-plug-in receiver that implemented photodiodes to pick up on LEDs emitting from the sides of the collar. These receiver beacons then send the information to the app for the user to monitor. That way, the beacons can determine where in the house the animal is and can also tell if the animal is upstairs, downstairs, in the basement, etc. in a way that other tracking devices currently on the market (such as an AirTag) cannot currently function.

We ran into some difficulties testing the infrared LEDs we bought. Originally, there was supposed to be a collimating lens in front of the LEDs in order to project light more directionally with a higher irradiance directly at the photodiode. However, once we began testing this setup, we realized that the collimating lens wasn't functioning in the expected manner. Its usage in the design was reconsidered based on the testing results without it in place while also considering that, by removing the collimating lens, we are able to fit more LEDs onto the collar to compensate for the LED light's divergence.

The LEDs that were chosen had to be in a specific range so as to not be harmful to animals' eyes. For dogs, a wide range of wavelengths outside of the visible range is

acceptable, but cats may be sensitive to some near-infrared light up to 900 nm eyesight, which limits our options. We eventually chose an 940 nm infrared LED, the OED-EL-1L1.

Our project also required the use of a GPS module, wide field of view cameras, and an application for user control.

The GPS module was chosen from a selection of GNSS modules. It was important to choose a component that is easily testable; for example, the original component we wanted to go with was arguably better, however it would've required a custom PCB in order to test it. Thus, we decided to go with the PS1616S.

The wide FOV cameras were originally going to be the Mega 5MP SPI camera module, however we ran into difficulties purchasing that component and had to switch the design to the OV5640. This luckily ended up being a better choice, as the second model was much smaller and fit better onto our collar.

The application is the heart of this project. It is what allows the user to really experience our product; without the app, a lot of the functions would be useless. The user is able to manually trigger the vibration for corrections and can also trigger the defense system to protect the pet. The user will get notifications about potential predators detected nearby and will also get notifications if the animal is in too high or low of a temperature for extended periods of time. The user will also be able to see all of the outdoor and indoor tracking of the animal and can create a geofence to keep the animal within a specific zone.

We believe in keeping animals safe and providing pet owners with peace of mind. We believe that our project is the best way to accomplish that goal, as we combined features from existing products and added our own concepts to them to create a robust collar that can do things that no other product on the market can.

The path we walked felt daunting at many points but through our teamwork, preparation, and hard work, we have worked through many challenges. We've encountered obsolete and backordered parts, components that are incompatible or wouldn't work once they were tested, and many more challenges together.

Through this project, we have gotten better at practical skills such as researching and troubleshooting. We've also had hands-on experiences in a lab, testing components, building circuitry, and soldering components. Figuring out how to test surface mounted devices was one of the first challenges we faced, and through intense research and brainstorming, we were able to overcome it by soldering the devices onto premade breakout boards to give them header pins that allows them to fit into a breadboard for testing.

The purpose of Senior Design, after all, is not to develop a product for money or fame. The purpose is to teach us how to work with a multidisciplinary group to accomplish a

common goal, and to get real-life experience doing research and design (R&D) and production and troubleshooting together. We have completed this class stronger for the work that we have done in it, and we will leave with a sense of pride in having brought an idea from concept to reality. Through hard work and perseverance, we will be able to do whatever we set our minds to, and we will be stronger engineers for it.

12: Declaration

We hereby declare that we have not copied more than seven pages from a Large Language Model (LLM). We have utilized an LLM in a limited capacity for drafting and proofreading purposes.

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