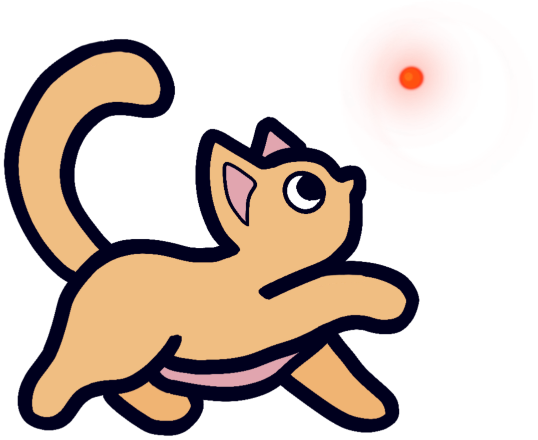
Senior Design II Report

Smart Laser Toy for Cats



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1 Executive Summary

This senior design initiative tackles a common challenge confronting today's cat owners: the struggle to provide substantial and interactive moments with their pets. Many cat owners can relate to the balancing act between a bustling professional life and the desire to offer quality time and stimulation to their domestic animals. Specifically focusing on cats, which require a holistic approach to well-being that includes both physical and cognitive stimulation, the group has designed an interactive toy to effectively address these challenges.

What is the main differentiator between market cat toys and the proposed design? There are three different features. First, the proposed cat toy is different from a normal laser pointer because it can change the shape of the laser. Since cats are curious animals with high intelligence and visual acuity, changing the laser's shape will increase their interest.

Second, the system integrates with a mobile app that offers expanded controls and adaptability. The app will have multiple features. The app will have a pseudorandom sequence that adds an element of unpredictability into the laser's path, closely mimicking the erratic movements of natural prey. The next direct manipulation of the laser's characteristics and has the capacity for pre-programmed remote interactions, ensuring your cat remains engaged even when you are not around.

The best feature of the proposed design is its inclusivity. The app will connect using a user-friendly, Bluetooth-supported interface. A requirement for this design is to consciously simplify the user experience to require minimal tactile interaction, making it ideal for individuals with hand movement constraints, seniors facing joint issues, or busy professionals.

The toy changes the standard laser pointer to a more comprehensive toy that includes several features; it's a comprehensive engagement solution for a pets well being. By addressing the specialized requirements of a broad spectrum of cat owners, this group's interactive toy pioneers a new standard in enriching the physical and cognitive lives of feline companions.

2 Project Description

The Smart Laser Toy for Cats is a device that integrates optics and electronics to deliver a portable toy that automatically interacts with a cat, once detected. The toy will allow a cat owner to stimulate their pet and keep the cat entertained without worrying about their day-to-day tasks without being disturbed.

2.1 Project Background

The project is an interactive cat toy that builds off of the idea of a laser pointer. The parts of the system are a laser diode system, a passive infrared motion sensor system, a camera system, a bluetooth based communication system, a phone application, and a power system that uses a battery management system.

The passive infrared system has four motion sensors surrounding the enclosure to account for the cat coming from any area of the room. The detection of motion then enables the camera system to activate and read the color of the cat collar tag that is illuminated by an LED and brightened by a Fresnel lens. This detection then activates the laser system. The laser system consists of optical apertures that enable the laser to change design and move as the cat plays with the laser.

The device itself is controlled by a phone application that allows the pet owner to change time settings of the laser system, see pet analytics, and change the scanning pattern of the laser. This will allow the user to play with the cat remotely through a mobile application if they do not want the automated mode. The phone application delivers signals through a bluetooth communication system. The project is powered by a battery source.

2.2 Project Motivation

In a typical household with cats, a cat is stimulated by manual motion of a laser pointer. This enables the cat to play with the laser, increase mental stimulation, and increase exercise. However, as modern society progresses, a homeowner may not always have time to play with the cat for long periods of time, especially when the cat needs to have more exercise throughout the day. The motivation for this project is to create a cost effective toy that adds more flexibility and user control to a traditionally fun toy for cats.

Furthermore, it is the desire of this group to make this toy more inclusive for those with hand restrictive mobility problems. As stated, a normal laser pointer is moved manually by the pet owner, this is not possible with people with health conditions like arthritis, where the moving of the hand or wrist can be excruciatingly painful, or for paralyzed owners, who are unable to move their hands. By having the laser system automated, it reduces user effort and allows the user to still play with their cat even though they are physically unable to move the laser.

While health conditions can be a large inhibitor for interacting with a cat as a pet owner, sometimes one may be extremely busy to dedicate an hour or more a day interacting with the cat. By creating an automated laser system that can also be enabled through a user-controlled app, this allows the pet owner to not only accomplish daily life tasks, but ensure proper stimulation and exercise of the cat on a daily basis. Moreover, this project is designed to increase the health of the cat by making an environment where exercise is increased while creating a more convenient for the owner and stimulating for the cat.

2.3 Goals

The overall goal of this project is to deliver an automatic laser toy for cats that requires minimum owner effort and allows the pet to be stimulated. The specific goals are broken down in the section below.

2.3.1 Core Goals

1. The toy shall be portable and lightweight.
2. A mobile application shall be created to allow the owner to communicate with the toy.
3. Wirelessly communicate between a mobile application and the device.
4. The use of optics and photonics shall be utilized to differentiate between multiple pets.
5. The toy shall automatically turn on when motion is detected.
6. A color detection system shall enable the laser system when it detects a cat.
7. The laser system shall generate different scanning patterns.

2.3.2 Advanced Goals

1. The device shall be enabled when a cat approaches from the front or sides of the device.
2. Implement optical beam shaping elements to optimize the shape of the laser.
3. The system shall provide owner analytics and insights into the owner's cat playtime behavior.
4. The collar tag shall be water resistant.

2.3.3 Stretch Goals

1. Allow the owner to create custom pattern sequences.
2. Make the mobile application cross-platform.
3. The toy shall automatically shut down when the cat reaches a "too-close" distance.
4. The device shall be waterproof.

2.4 Objectives

The Smart Laser Toy for Cats consists of many components that will enable the group to accomplish the goals of the project. The objectives to reach those goals are listed in the following sections.

2.4.1 Core Objectives

1. Design an enclosure that is less than 15 pounds and holds PCB, motion detection, battery, and laser system.
2. The mobile application and device will communicate via bluetooth signal.

3. The device will only operate for a cat using a color detection system that recognizes red, green, and blue colors from an LED collar tag, brightened and focused by the design of a Fresnel lens.
4. A passive infrared motion sensor will be designed to automatically turn on the color detection system.
5. Two wedge prisms will steer the laser diode into different scanning patterns.

2.4.2 Advanced Objectives

1. The mobile application has the following features: play time and number of times pattern changes.
2. One laser diode will be used to show scanning patterns on the floor through the design of a lens system.
3. Use four passive infrared sensors around the rectangular-shaped device to ensure maximum field of view for pet detection.
4. Use silicone adhesive to make the collar water-resistant.

2.4.3 Stretch Objectives

1. Passive infrared sensors will have a "too close" range setting that enables an automatic shut-down process when the cat is 5 centimeters away from the laser.
2. The mobile application will include custom sequences that the user can create, and cat profiles.
3. Use IPX-7 LEDs to make the collar waterproof.

2.5 Engineering Specifications

Component	Parameter	Specification
Laser System Power	Laser Power	1 mW
Laser System Wavelength	Laser Wavelength	630 - 690 nm
Passive Infrared System	Detection Range	0.5 to 1.5 ft
Passive Infrared System	Detection Wavelength	940 nm
Passive Infrared System	Response time	t < 15 seconds
Printed Circuit Board	Size	Size < 900 cm^2 (30 cm * 30 cm)
Printed Circuit Board	Purpose	House all non-optic systems
Bluetooth Based Communication System	Range	10 ft
Bluetooth Based	Response time	t < 30 seconds

Communication System		
Power System	Power Consumption	< 15 W
Power System	Runtime	10-15 minutes
Collar Activation System	Focal Length	20 mm
Collar Activation System	Range	0.5 to 3 ft
Mobile Application	Latency	$t \leq 200$ms
Laser Movement System	Play Area	645.2 in^2 (at 1 m distance)

Table 1: Engineering Specifications

2.6 Optical Schematic

The following figures demonstrate the optical schematics of the Smart Laser Toy for Cats and the path of the light rays.

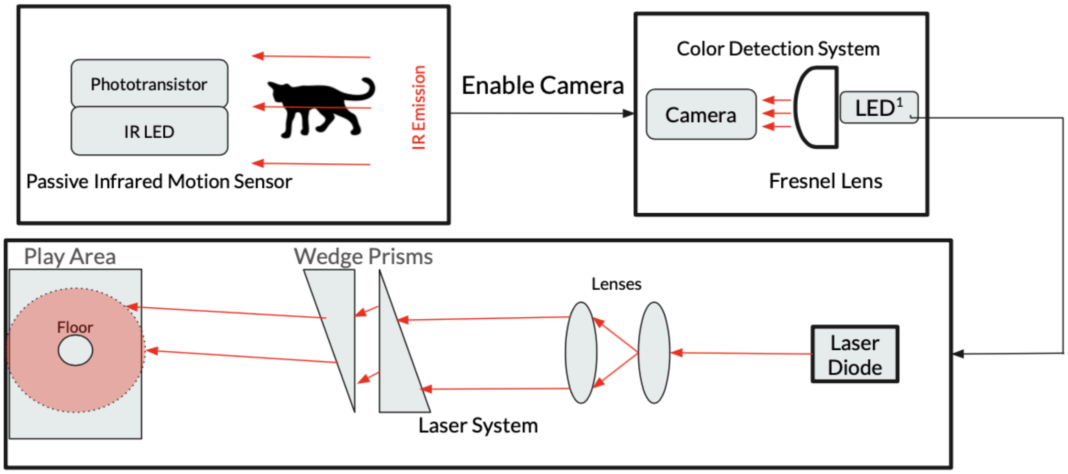
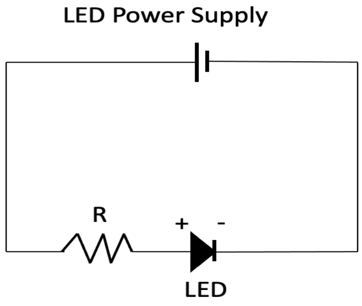


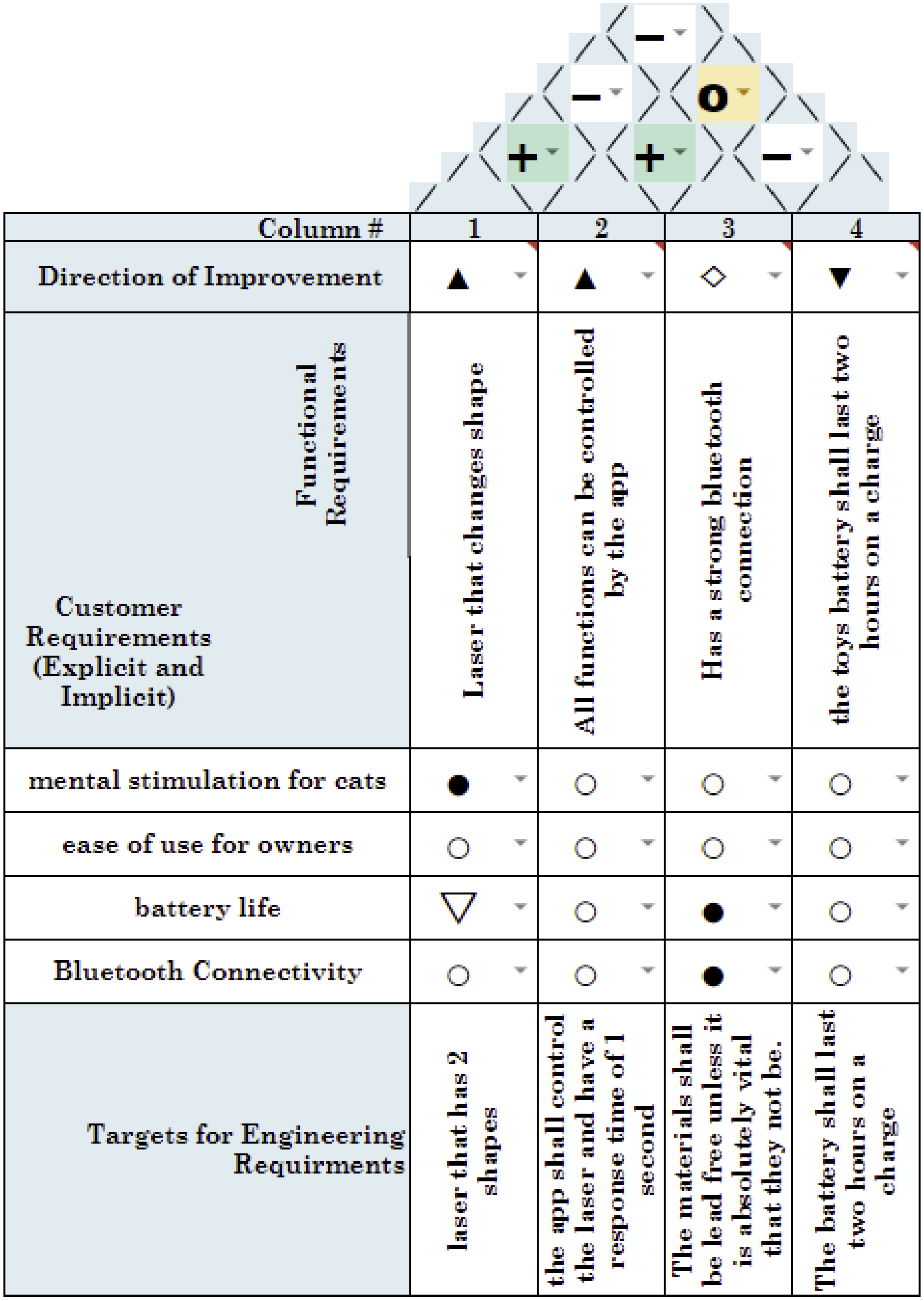
Figure 1: Optical Schematic of Smart Laser Toy for Cats



[1]*Figure 2: LED Power Supply of the Optical Schematic*

The schematics above show the general idea behind the Smart Laser Toy for Cats. Throughout the report, there are discussions about the technological investigations of each optical component in the schematic alongside calculations that lead to the exact schematic and components chosen. Figure 2 details the general wiring of an LED and in further sections it is shown how the resistance values were calculated and how this schematic was integrated into the circuit of the passive infrared motion sensor.

2.7 House of Quality



Column #	1	2	3	4
Direction of Improvement	▲	▲	◇	▼
Functional Requirements Customer Requirements (Explicit and Implicit)	Laser that changes shape	All functions can be controlled by the app	Has a strong bluetooth connection	the toys battery shall last two hours on a charge
mental stimulation for cats	●	○	○	○
ease of use for owners	○	○	○	○
battery life	▽	○	●	○
Bluetooth Connectivity	○	○	●	○
Targets for Engineering Requirments	laser that has 2 shapes	the app shall control the laser and have a response time of 1 second	The materials shall be lead free unless it is absolutely vital that they not be.	The battery shall last two hours on a charge

Figure 3: House of Quality Diagram

2.8 Project Diagrams

The following sections demonstrate the division of labor for all software and hardware components of the Smart Laser Toy for Cats.

2.8.1 Hardware Block Diagram

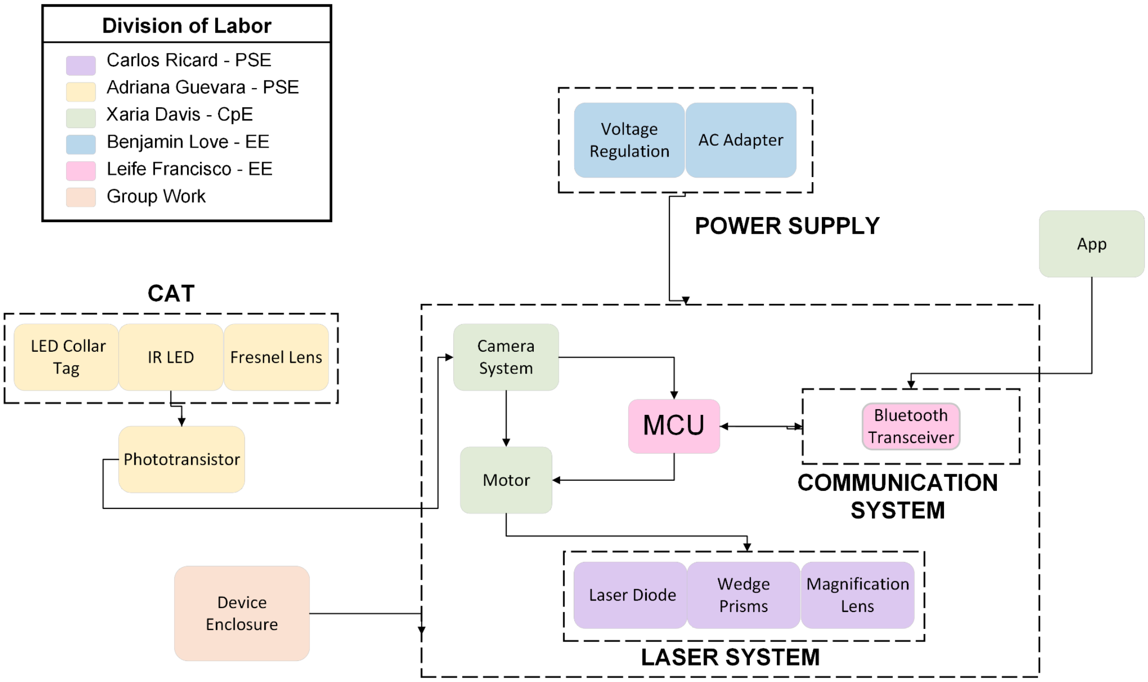


Figure 4: Hardware Block Diagram

2.8.1.1 Printed Circuit Board

The second major requirement required by the engineering department is to design, build, and test a printed circuit board (PCB). In the interactive cat toy project, it was decided that the PCB will house the power system, a communication system, a microcontroller unit, and other peripherals that are necessary to the success of the project. The microcontroller unit is an ATmega 2650. This is the microcontroller used in the Arduino. The purpose of this is not to purchase an Arduino, it is to use the Arduino Mega Rev3 as a reference design for the scope of the project. The Arduino Mega Rev3 will be used as a reference design because it is an open source hardware platform. Furthermore, Arduino's are renowned for their ecosystem, these microcontrollers offer the project flexibility, integrability with other peripherals, and are low cost. As an added benefit, the Arduino IDE is easy to use and provides a variety of open source code to use as examples and has a wonderful community of developers.

As stated previously, the reason the ATMega family was chosen for the design as the chipset for the microcontroller on the board is that it is widely available and accessible. These microcontrollers are widely used by enthusiasts, hobbyists, and developers. This means that there is a large body of knowledge widely online available for support. This wide accessibility means during the troubleshooting phase of the project the team will have an easy time finding hardware and software support when things go wrong.

Furthermore, the ATMega family offers more than enough processing power to handle the requirements without an unnecessary amount of excess. This means that the chip will be capable of giving the user an excellent experience while providing reliability and speed.

The Arduino family is most notably known for its incredible flexibility. Unlike purchasing a pre-built module, the printed circuit board will be tailored to the specific needs of the project. The reduction in peripherals which will preserve power and processing capabilities since the project will not require to add extra peripherals that other modules include.

Part selection requires market comparisons. To choose a microcontroller, market comparisons were done. The group compared the ATMega family microcontrollers to the STM family of microcontrollers. While the STM family of microcontrollers provides more processing power and memory, they lack open source hardware specifications, widely available peripherals, and have a difficult and expensive hardware abstraction layer. The main reason that the STM family of microcontrollers does not meet customer specifications is that the STMicroelectronics corporation does not offer a hardware abstraction layer like the ATMega family of microcontrollers does. The HAL has been secured by a paywall. Furthermore, this family of microcontrollers does not have an open source hardware reference design documentation.

2.8.1.2 Communication System

The communication system within the cat toy PCB serves three main tasks; to ensure seamless interaction between the mobile application and the device by transmitting data in a timely manner, to transmit data accurately, and to control the shape and mode the laser will operate in. In this section, the rationale for choosing bluetooth as the communication protocol for the cat toy project is discussed. Furthermore, how this communication standard meets hardware requirements, power efficiency, data rate, and overall system integration are discussed.

Initially, it was important to consider three short to medium range communication standards; Zigbee, Bluetooth, and Wifi. While these options were considered, Bluetooth was chosen as the best middle ground approach. First, Zigbee is traditionally used in IOT devices and consumes exceptionally low power. On the other hand, Wifi uses a large amount of power. Bluetooth is more energy efficient than wifi but slightly less than Zigbee and offers a middle ground.

Second, the cat toy requires continuous high bandwidth transmission to ensure timely and accurate control of the laser's shape and patterns. Zigbee uses low power but also has a low data rate. Since it has a low data rate, it does not meet our requirements for data rate. Bluetooth's ability to transmit up to three Mbps meets our demands and allows the cat toy to deliver an exciting experience for the user and cat.

The third reason to choose Bluetooth is that the antenna Bluetooth uses can be directly integrated into a PCB. For example, inverted F plane antennas are compact and known for their efficient performance. This makes them ideal for compact internet of devices like our cat toy. The use of this type of antenna allows us to integrate the entire communication system onto a compact portion of the PCB which will make sure the cat toy hardware and interface do not subtract from the overall gameplay experience while maintaining optimal connectivity.

In conclusion, Bluetooth was chosen based on various factors. Bluetooth offers efficiency, high data rate, simple network, a compact antenna, and direct connection to the hardware. All these features make Bluetooth the optimal communication protocol choice for constraints of the cat toy design project.

The paragraphs above describe the reason bluetooth was chosen over other short range communication protocols. To summarize, bluetooth was chosen over Zigbee and Wifi due to data rate, power, and the availability of hardware.

The final version of the printed circuit board uses an ESP32 WROVER E N8R8. The ESP32 WROVER E N8R8 includes a bluetooth module therefore the bluetooth module was changed from a NINA W102 to the ESP32 WROVER E N8R8.

2.8.1.3 Laser System

The laser system in this device utilizes a single laser and other optical components to display a beam on the wall. The system will display the beam in several locations on the wall at separate times in order to keep a cat constantly entertained. There are two main approaches that are in consideration at utilizing different techniques to accomplish this. One technique will utilize a diffraction grating and polarizer film to move the image, while the second would utilize wedge prisms to do the same. To ensure the components are secure within the device, the post that will hold the optical components will be 3D printed. The power output of the laser will be limited to 1 to 5 mW to match the output of commercial laser cat toys. It is important that the laser never exceeds 5 mW as it would be too dangerous to use for both the cat and cat owner's eye safety.

2.8.1.4 Motion Sensor System

The optical motion sensor of the smart cat toy serves to activate the camera system and in turn, activate the laser system to begin playing with the cat. The passive infrared (IR) sensor serves as a motion sensor to enable the camera system to turn on. This passive sensor consists of IR light-emitting diodes (LED) and a phototransistor; the phototransistor enables the optical signal received from the IR light emission to be converted to an electrical signal. The IR LED emits light and reflects the light back onto the phototransistor as the cat moves by it and the passive system activates the camera system. As the cat gets closer to the device, the IR LED will no longer reflect light onto the phototransistor and it causes the passive system to send a signal to the camera system that it must turn on.

The camera system is programmed to activate the laser system that enables the cat to play with the toy. Since some pet owners may have both cats and dogs, an LED of visible wavelength is placed on the cat collar behind a Fresnel lens to allow the camera system to know that a cat is present and ready to play. By designing the Fresnel lens to be in front of the LED tag, it diffuses the light to the camera system since the LED light is not dispersed widely throughout the room. This increases the brightness of the light to allow for color capture of the camera system. A large advantage of the Fresnel lens is that it has a short focal length so it can be placed near the LED tag and enable a smaller design to not be in the cat's way of daily activities. Once the camera system reads the specified LED color of the collar tag, the laser system is activated for a specified amount of time.

2.8.1.5 Power System

The power system that was originally designed was not used due to complications from the charge controller. The charge controller had large voltage and current fluctuations that resulted in an unstable system and was not able to be used. Therefore the group went with a much simpler power system that used two barrel jack connectors and linear dropout regulators that are housed on the printed circuit board.

The power system originally consisted of a battery composed of two lithium-ion cells, one linear voltage regulator of the low-dropout voltage (LDO) type, and a charge controller consisting of a single IC and additional basic circuit components. Further stretch goals discussed included an input power/battery bypass circuit to enable "charge and play" operation, or USB-PD (power delivery) integration to allow charging from a USB type C charger.

An integrated lithium-ion battery pack will be the primary power supply. Two cylindrical cells connected in series are desired here as introducing multiple cells in parallel reduces the degree of monitoring and control that the charger and battery management system (BMS) or equivalent devices have over the system. Conversely, series connection makes these jobs trivial, potentially allowing both to be accomplished with a single commercially available IC.

A BMS of some description is mandatory with lithium-ion batteries owing to their volatility and intolerance of overcharge and overdischarge. The primary job of the BMS is to cut off the supply and demand of current at the cell to prevent this, typically by measuring the voltage across the cell terminals.

Different voltages for subsystems of the toy will each require their own voltage regulator. There are two main types of DC voltage regulators, linear and switching. Linear regulators, which reduce a linear DC voltage input and maintain a linear output, are simple to build, provide smooth output voltage, and are relatively free of noise. However, they are also inefficient owing to their high resistance and thus of debatable choice for battery-powered applications. Switching regulators, which employ cycling the input voltage at a high frequency through transient components, have higher efficiency and less waste heat. Unfortunately, they are more difficult to design and have more noise to be dealt with. Owing to the additional design constraints with switching regulators, it has been decided that linear regulators will be employed for simplicity and reliability.

2.8.2 Software Flowchart

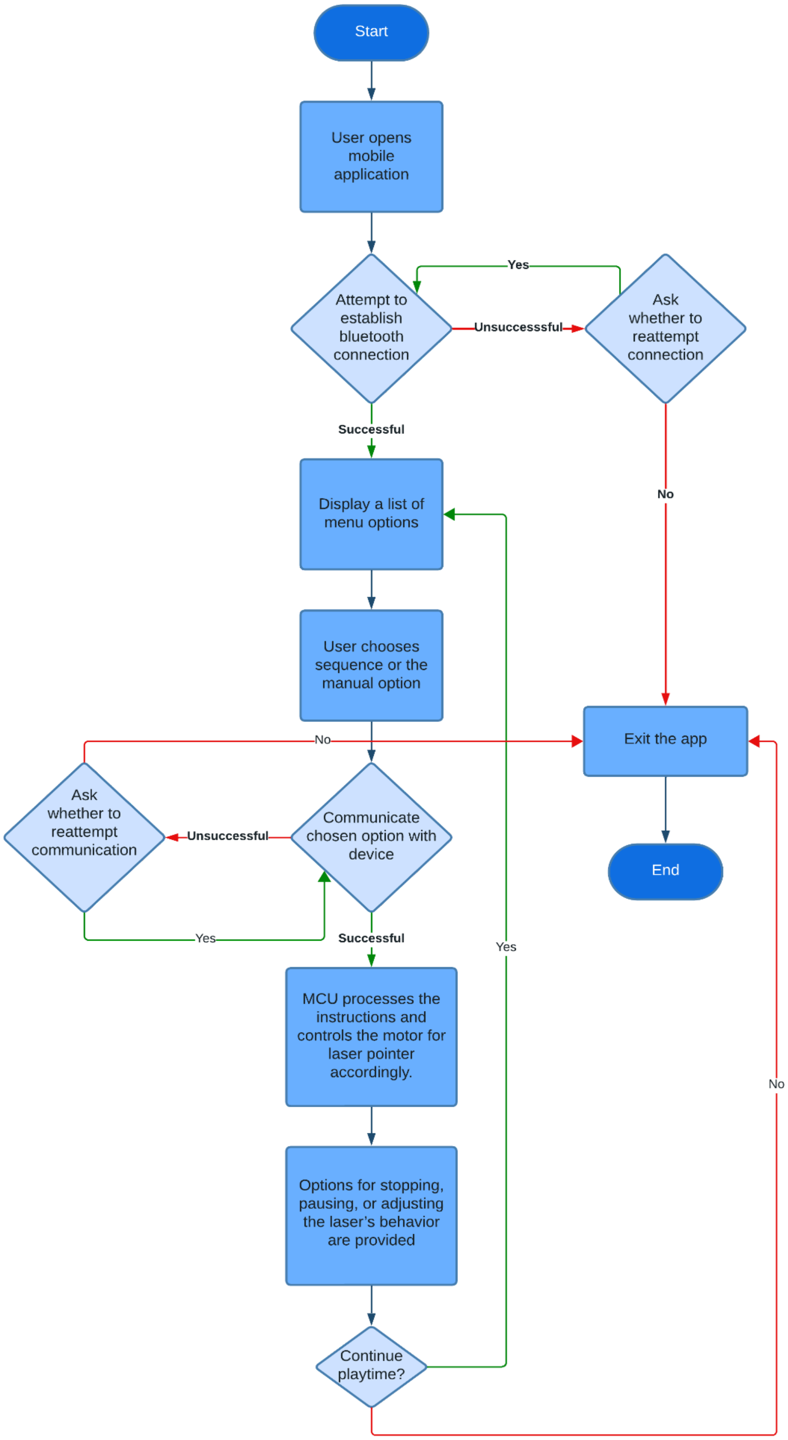


Figure 5: Software Flowchart Diagram

3 Related Work

Having household pets has always been an integral part of many families and societies. In today's societies, families and individuals tend to live very busy lifestyles, with sometimes little to no time to tend to their pets. Because of this, automated cat toys are not new to the consumer market, especially since playing with lasers is one of the most common ways to stimulate a household cat. Previous projects of the University of Central Florida Senior Design course sequence have created automated pet devices. The previous projects, alongside current market automated cat toys, provided a lot of research that was pivotal into the design of the Smart Laser Toy for Cats.

3.1 Existing Products

The following section lists the current market products that helped the group design the components and idea of the Smart Laser Toy for Cats.

3.1.1 PetSafe Bolt Automatic, Interactive Laser Cat Toy – Adjustable Laser with Random Patterns Small

This laser cat toy resembles a water bottle with a height of nine inches and a circular mirror housed in the top. The laser used in this product is a red laser that is housed at the base of the product and achieves random movements by rotating the mirror. The mirror points the laser in a downward angle, reducing the risks of the cat looking into the light source. The classification of the laser is listed as a III laser which means the power does not exceed 5 mW. The wavelength of the laser is in the 650 - 700 nm range as the product claims to be safe for a cat to use, this assists the group in deciding what laser to use for the Smart Laser Toy for Cats. The device has both an automatic and manual mode that can be selected when turning it on, each of which will last for fifteen minutes. This time was considered for the design of the project to ensure the device has an automatic shut off time. This product requires four AAA batteries to operate.

3.1.2 Saolife Automatic Cat Laser Toys, Interactive Laser Cat Toys for Indoor Cats/Kitty/Dogs, Cat Laser Toy Automatic

This product is an automatic laser cat toy that is housed in a spherical housing with a dark glass on the front, seen in. The spherical housing is motorized enabling the device to have several degrees of rotational movement, aiming the beam in a downward angle. The device has a suction cup on the underside of the base so that it can adhere to a window. The power output of the laser is listed as 3.63 mW, and is listed as a class 1 laser by FDA standards. The wavelength of the output laser beam is 650 nm, which is difficult for cats eyes to resolve. The product overcomes this problem with varying movement speeds and high output power. The product has an integrated rechargeable battery and an associated usb type-C cable for charging. The battery is stated to completely charge in two hours, with a battery life that lasts for about 2 days.

3.1.3 Friends Forever Interactive Laser Cat Toy

This laser is sold on Amazon, and other major retailers like Walmart, with the intent to be used as an automated toy for cats. This cat toy has an automated rotating laser point with adjustable scanning speeds that outputs in a 360 degree circular motion around the device. The device is approximately 8.25 inches high with the head being 4 inches in diameter, becoming slightly larger in a cone shape as it goes to the bottom of the device. It is battery-operated through the use of AA batteries and limits the cat to play in a small area circulating around the device. It automatically shuts off after 15 minutes.

3.1.4 Market Toy Comparisons

While it is evident that the Smart Laser Toy for Cats is inspired from current automated laser cat toys on the market. The device was designed with certain features in mind that are not found currently on the market, like a shut-off range for when the pet approaches the device too closely and motion sensing capabilities. The table below highlights key parameters amongst all devices and how the Smart Laser Toy for Cats compares to current market products.

	PetSafe Bolt	**Saolife Automatic Toy**	**Friends Forever Laser**	**Smart Laser Toy for Cats**
Motion Activated	No	No	No	Yes
Laser Scanning Pattern	Randomized	Randomized	Circular	Randomized
Placement	Ground	Higher ground	Ground	Higher ground
Rechargeable Battery	No	Yes	No	No
Manual Play Mode	Yes	No	No	No
Shut-off Time	15 minutes	10 minutes	15 minutes	10 minutes
Mobile App	No	No	No	Yes

Table 2: Market Products Comparison

3.2 Previous Senior Design Projects

There have been multiple senior design projects in the past that share the similar goal of automating a cat toy. The following explains previous projects featured in the college of engineering and computer science at UCF. These projects functioned as reference designs for the group's design of the Smart Laser Toy for Cats.

3.2.1 Autonomous Pet Entertainment System (A.P.E.S)

The Autonomous Pet Entertainment System (APES), designed by Group 8 between the semesters of Fall 2020 and Spring 2021, utilizes a roaming device with an embedded laser diode to interact with pets. The APES device was motorized to allow for movement. The Smart Laser Toy for Cats will take a different approach in order to make the system stationary. This allows the device to avoid issues that may arise from differing floor types, such as wood, tile, carpet, etc.

It should be noted that the Autonomous Pet Entertainment System was built by an engineering team during quarantine amidst the COVID-19 pandemic and, from the demonstration, appears to have only been tested on hard flooring such as wood and tile.

3.2.2 Opto-Smart Pet Feeder

The Opto-Smart Pet Feeder, designed by Group 9 between the semesters of Fall 2021 and Spring 2022, is an automatic pet feeder that uses optical motion sensors and color detection to enable the device so that pets can eat. While this project uses a photodiode and IR LED to design the motion sensor, it served as motivation to design a passive infrared motion sensor with the use of a phototransistor and IR LED. Alongside this, it also showed the ability to use LED collar tags to identify pets and this served as the idea behind using collar tags to identify cats in a household for the Smart Laser Toy for Cats.

4 Relevant Technologies

The following sections list and describe the major subsystems of the Smart Laser Toy for Cats and the components that integrate into each system.

4.1 Passive Infrared Sensor and Color Detection System

One optical system designed in the construction of the laser cat toy is the design of a passive infrared motion sensor and color detection system. Originally, the passive infrared sensor was designed using a phototransistor and one IR LED to detect motion by receiving the signal of the IR light as it reflects off objects in motion. The final version has a three by three array of IR LEDs and one phototransistor to increase detection distance. Once this signal is received by the phototransistor, it enables the camera system to activate and begin detecting colors off the pet collars. As long as the cat is wearing an LED of red, green, or blue light with a Fresnel lens, it enables the other optical system to activate the laser system that the cat will play with.

The following subsections delve into the optical components that are part of the passive infrared sensor and camera color detection system.

4.1.1 Phototransistor

A phototransistor is an optoelectronic device that converts light energy to an electrical signal and is intended to be a part of the design for the laser toy. A phototransistor is a type of a bipolar transistor, and although bipolar transistors are light sensitive, a phototransistor has been optimized for high light sensitivity. This makes it ideal for light sensing applications, as in a passive infrared (IR) sensor that was designed for the scope of this project. Since the sensor detects IR light, an IR phototransistor must be used since that is the only type that can trigger on with IR light. While a typical bipolar transistor has three terminals, base, collector, and emitter, the phototransistor only has two, emitter and collector. The base is made of IR-sensitive material, which means that voltage is not required and IR light will trigger the phototransistor to turn on.

The capabilities of the IR phototransitor lead to their use of detecting the presence or absence of IR light. To do so, an IR LED was used as part of the passive IR sensor. As the cat approaches the sensor, the phototransistor receives photons from the IR LEDs and produces a small amount of current between the emitter and collector. As the phototransistor receives a signal from the IR LED, it triggers the camera system to activate and begin differentiating between the cat collar color to determine if the laser system will be activated next or not.

4.1.2 Fresnel Lens

A Fresnel lens is a type of lens used in optical applications that improve the brightness of a light source by bending light to parallel rays with a common focal length. In fact, Fresnel lenses are particularly helpful in cases where short focal lengths are required. This was imperative to the scope of this project because a Fresnel lens is placed in front of a red, green, or blue LED on the cat collar to improve brightness and light dispersion so that the camera system can properly detect the light source. By having these features in place, the camera system enables the device in its entirety to distinguish between a cat or other animal. The Fresnel lens is also a smaller, lighter, and lower-cost lens compared to a traditional lens which is beneficial to the budget of the project and the comfort of the cat. A downside of the Fresnel lens is that it reduces the image quality of the source it is put over, but for the purpose of what is needed of the lens in the cat toy, it does not impair the function of light and color detection. Additionally, the lenses are created of concentric rings to provide the short focal length and can be molded from plastic enabling the low-cost and low-weight advantages that benefit the goals of this project. A precise drawing can be seen below in comparison to a plano-convex lens, where the rings will help collimate the light that enters from the flat side, and shows to be much thinner than a regular lens.

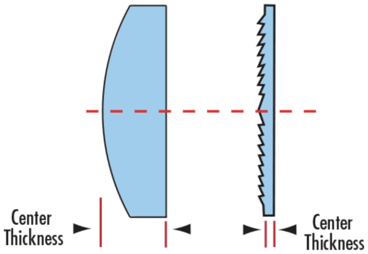


Figure 6: Comparison of Plano-Convex Lens (Left) to a Fresnel Lens (Right) (Courtesy of Edmund Optics)

4.1.3 LED

A light-emitting diode (LED) is an optoelectronic light source that is used in many optical applications. They are a type of semiconductor device that emits light so long as current flows through it. A visible light LED in red, green, and blue and an IR LED will be used throughout the construction of the cat toy. LEDs are illuminated through the movement of electrons in the semiconductor material that recombine with electron holes to emit photon energy to produce light. LEDs are most beneficial to use because they are low-cost, low-weight and integrate easily into electrical circuits. This is ideal since the goal of the project is to have a compact device that is portable and collar tags that are lightweight enough to not inhibit daily activities and comfort of the cat wearing the collar. While a single LED does not have enough illumination to be an easily detectable light source, the use of the Fresnel Lens eases the color detection properties of the collar at further distances.

4.2 Parts of A Digital Communication System

Since the bluetooth communication system is not studied extensively in most engineering courses it is a relevant technology that must be reviewed. Essentially any bluetooth system is a digital communication system. The parts of a digital communication system transmitter are shown in the figure.

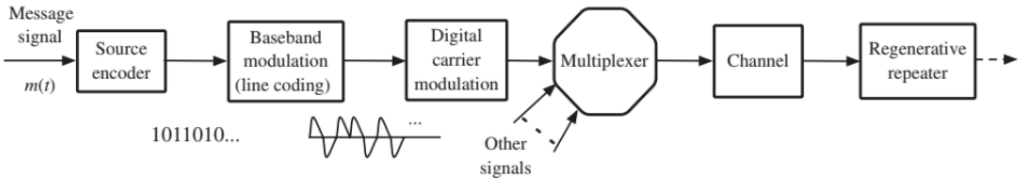


Figure 7: Digital Communication System (Courtesy of Modern Digital And Analog Communication Systems by B.P. Lathi)

The simplified version of any digital communications system is shown above. The source encoder, line coder, digital carrier modulator, and multiplexer are all contained in one unit inside the transmitter which is also inside the transceiver. Similarly to serial peripheral interface, universal asynchronous receiver transmitter (UART), and other embedded modulation schemes. Bluetooth has its own modulation scheme. It is specified by the Bluetooth core specification named V4.0.

4.2.1 Bluetooth Baseband Modulation

According to the bluetooth core specification the baseband modulation is a combination of gaussian frequency shift keying and differential phase shift keying. The figure below shows the way the baseband is modulated and the way the data rate packet is formatted.

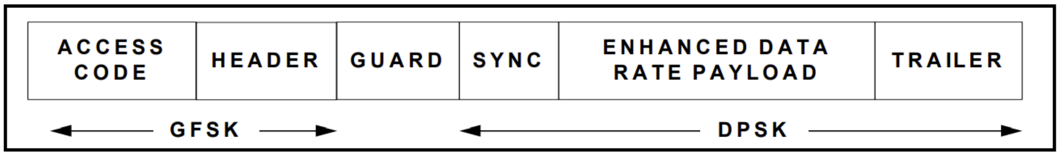


Figure 8: Baseband Modulation (Courtesy of Bluetooth Core Specification V4.0)

4.2.2 GFSK and DPSK Modulation

Gaussian frequency shift keying is a subset of frequency shift keying. Frequency shift keying encodes a one or a zero as a modulated signal with a different set of frequencies. Those frequencies are a set of frequencies that each represent a different message. However during the transition between a one and a zero when a shift in frequency occurs theoretically there is an instantaneous change in frequency that causes various problems in the receiver side of the transceiver. The figure below shows polar modulation.

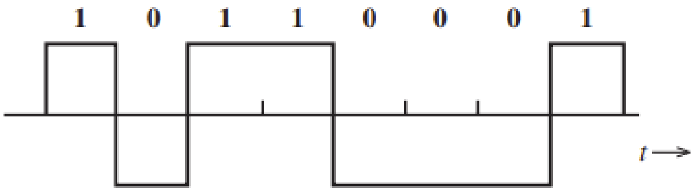


Figure 9: Polar Modulation (Courtesy of Modern Digital and Analog Communications by B.P. Lathi)

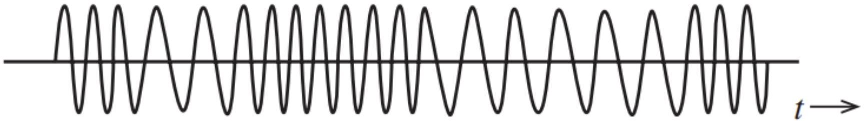


Figure 10: Frequency Shift Keying (Courtesy of Modern Digital and Analog Communications by B.P. Lathi)

The main difference between Gaussian frequency shift, kicking and frequency shift keying is that Gaussian frequency shift keying uses curved pulses. A figure is included below to show the difference.

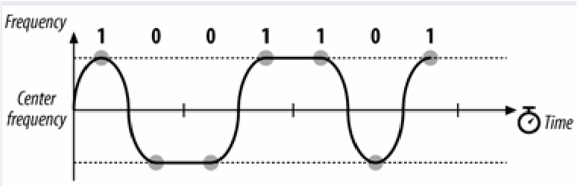


Figure 11: Gaussian Frequency Shift Keying (Courtesy of Digital Packet Radio Network System)

DPSK stands for differential phase shift keying. Phase Shift Keying is a digital carrier modulation scheme that encodes the information in the phase instead of the frequency. Differential Phase Shift keying only encodes a pulse when there is a change in phase. This saves on bandwidth however there is a cost in precision.

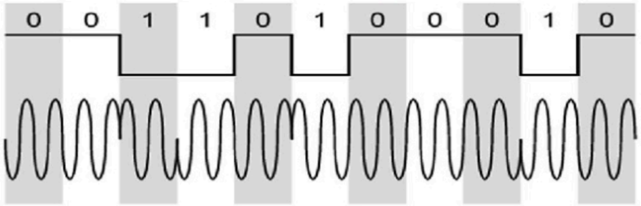
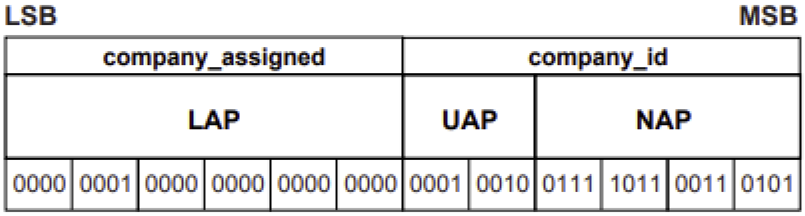


Figure 12: Differential Phase Shift Keying (Courtesy of Tutorials Point)

4.2.2.1 Bluetooth Device Addressing

The purpose of this paragraph is to paraphrase Bluetooth devices addressing standards from the Bluetooth core specifications V4.0. Since Bluetooth can form a piconet with multiple devices, bluetooth device addressing is an important part of a Bluetooth network, therefore a simple review of Bluetooth addressing is necessary and is not a widely understood technology.

Essentially, Bluetooth device addressing can be summarized by the picture below. The least significant bit or the right most hexadecimal code. Also named, the company assigned LAP or lower address part. The lower address part is the address that is assigned to each individual company. However, there are a block of 64 contiguous LAPs, reserved for inquiry operation**.** The most significant bit comprises two addresses, the UAP and the NAP. The UAP is the upper address part and consists of eight bits. The NAP is the nonsignificant address part consisting of 16 bits. The unique upper address is an organizational unique identifier, or in other words the unique upper address is a way to determine what organization manufactured the device. The non-significant address part is a series of bits that are manufactured defined, device, specific, and transmitted with every packet.



LSB MSB

company_assigned						company_id					
LAP						UAP		NAP			
0000	0001	0000	0000	0000	0000	0001	0010	0111	1011	0011	0101

Figure 13: Bluetooth Device Addressing (Courtesy of Bluetooth Core Specification V4.0)

In summary, the Bluetooth address is a 48 bit address that is transmitted with every packet. Those 48 bits are composed of three parts, the lower address part, the upper address part, and the non-significant address part. The lower address part is signed by the Institute of electrical and electronics engineers, IEEE, and its purpose is to provide a unique identifier for each manufacturer. The upper address part is also assigned by the Institute of electrical and electronics engineers and its purpose is to provide a unique identifier for each manufacturer's devices. The non-significant address part is assigned by the manufacturer, and its purpose is to act as a last unique identifier for each device. The reason that Bluetooth addressing is so important and has so many different addresses is that Bluetooth is able to form a PICO net with many devices. This necessitates a Bluetooth addressing system that has many original unique identifiers.

4.2.2.2 Access Codes

According to the below, Bluetooth core specification version 4.0, the purpose of the access code is to indicate "to the receiver, the arrival of a packet. It is used for timing, synchronization, and offset compensation. The receiver correlates against the entire synchronization word in the access code, providing very robust signaling". In other words, the access codes tell the receiver when a packet has arrived and make sure that the transmitter and receiver clocks are in time.

There are three different access codes; the device access code, the channel access code, the inquiry access code. The device access code has many parts that are not relevant to the project that has been extracted and handled by the manufacturer. Therefore, it is not important to discuss the parts of the device access code as this information is not pertinent to the design of the group's cat toy. The same rationale applies for the channel access code and inquiry access code.

4.2.2.3 Header

The packet header is the part of the data packet that is transmitted over the carrier frequency using Gaussian Frequency Shift Keying. Bluetooth has several parts. Each part has its own purpose. However, the individual details of how each part works shall not be discussed. What will be discussed is the purpose of each part and the data size of each part.

The packet header has six fields; LT_ADDR this is the logical transport address, TYPE this is the type code, FLOW this is the flow control, ARQN this is an acknowledgment indication, SEQN this is a sequence number, HEC this is a header error check. The total size of the packet header is 18 bits and the order in which each field is sent is shown below in the header format image.

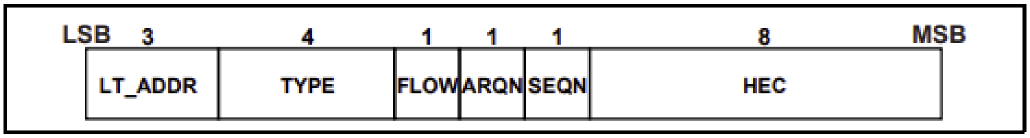


Figure 14: Header Device Addressing (Courtesy of Bluetooth Core Specification V4.0)

According to the Bluetooth core specification, the three bit LT_ADDR field contains the logical transport address for the packet. This field indicates the destinations that leave for a packet in a master to slave transmission slot, and indicates the source slave for a slave to master transmission slot. In simpler terms, this field contains the address for the device that must send or receive information. Next, according to the Bluetooth Core Specification the four bit TYPE code specifies which packet type is used. Furthermore, the Bluetooth core specifications explains why this field is important; this allows the non-addressed receivers to refrain from listening to the channel for the duration of the remaining slots. This allows the non-addressed receivers to refrain from listening to the channel for the duration of the remaining slots. In simpler terms, the purpose of this field is to make sure that other devices on a PICO net do not consume too much time, listening for information that is not important to them. In simpler terms, the purpose of this field is to make sure that other devices on a PICO net do not consume too much time, listening for information that is not important to them. Next, the purpose of the flow bit is used for flow control of packets over HCL logical transport. What this means is that a listener, or the device that is receiving information can receive packets in a way that does not consume too much space in the receive register of the bluetooth device. Next, the ARQN field is used to inform the source of successful transfer of payload data with CRC. Essentially what this means is that the Bluetooth device needs a way to know if data was successfully transmitted. This field shows the Bluetooth device if data was successfully transmitted. Next, the SEQN field orders the data. And finally the HEC data field checks the integrity of the entire header, according to the bluetooth core specification “if the header does not check, the entire packet is discarded”. Essentially the HEC data field is another way to make sure that data is accurately transmitted and if the calculated HEC is not correct then the Bluetooth device knows the data was not transmitted correctly.

4.2.2.4 Guard

According to the Bluetooth specifications, the data rate guard time is the period starting at the end of the last [Gaussian frequency shift keying] symbol of the header and ending at the start of the reference symbol of the synchronization sequence. In other words, the data rate guard time or the guard field of the enhanced data rate Bluetooth symbol package is a pause between header and Sinkfield of the standard enhanced data rate packet format.

4.2.2.5 Sync

The SYNC field of the standard enhanced data rate packet format purpose is to synchronize the packet timing that is transmitted, or received by the listening or transmitting device.

4.2.2.6 EDR Payload

The EDR payload is the enhanced data rate payload. The data rate payload is simply the information that needs to be delivered over the Bluetooth connection.

4.2.2.7 Trailer

According to the Bluetooth core specifications, the trailer adds two symbols to the end of the payload. The purpose of doing this is to ensure that when a device switches from transmit mode to receive mode, there is time for the transceiver clock to synchronize.

In summary, the baseband modulation used for bluetooth enhanced data rate packets are complex and include many parts. The parts are the access code, header, guard, sink, enhanced data rate, payload, trailer. Each of these parts of the baseband modulation scheme serve a distinct purpose, and help to ensure that the data received or transmitted is accurate. Each of these baseband modulation schemes serve a distinct purpose, and help to ensure that the data received or transmitted is accurate.

4.3 Power System Technologies and Considerations

In the planning stages of the project, various options for powering the toy were discussed. The original desired outcome was to have the toy be battery-powered, but the plan experienced problems in the testing stage. Therefore, it was decided to utilize a switching AC adapter in the final project instead.

Given that the toy was to be battery-powered as an early design goal, a suitable battery system was key to the function of the other systems. A battery and associated components need to do more than simply hold a charge. They must also provide adequate current, give a consistent voltage or predictable voltage range, keep the battery cell or cells at a safe state of charge at all times, and offer circuit cutoff in case of an electrical fault or extreme temperatures. In short, safety is important, and it starts with appropriate cell selection.

4.3.1 Power Supply Comparison

The following table shows a comparison of power options available to our project. These include an integrated rechargeable battery, user-replaceable alkaline cells, an external AC adapter, and an integrated AC adapter. The quantifiable features for comparison are runtime, typical supply voltage, the disposability of cells, and the dimensions of a typical unit. Note that the dimensions are of concern because of the supply's footprint in the enclosure.

As previously mentioned, integrated battery was the initial target, and in fact the dimensions shown are taken from the very battery holder used during testing. However, an external AC adapter was selected as backup owing to its lack of internal footprint and ease of integration into the rest of the project.

	Integrated Battery	Alkaline Battery	External AC Adapter	Integrated AC Adapter
Runtime	Limited	Limited	Infinite	Infinite
Internal Dimensions (approximate)	88 * 46 * 22mm	62 * 56 * 18mm	N/A	76 * 53 * 32mm
Waste Cells?	No	Yes	No	No
Supply Voltage	3.7v/cell	1.5v/cell	5v DC	120v AC

Table 3: Options and key metrics of different power supply technologies

4.3.2 Considerations for Number of Cells

One of the most fundamental design criteria with battery-powered devices is whether or not multiple cells are required. Using multiple cells in a pack, or group, can allow for greater current capacity, higher voltage output, increased device runtime, or all of the above. However, all of the multiple-cell options increase the complexity of not only the pack, but also the charging circuit and battery management system (BMS). Therefore, it is crucial that the use case of the pack dictates the use of multiple cells, or lack thereof. There are two ways to combine cells: series and parallel. Cells at this level are not much more than DC voltage sources, and are typically modeled as such. As basic circuit design goes, connecting cells in series adds the voltages of each cell together, and connecting them in parallel adds their currents. Notice that there is no mention here of whether the cell voltages are the same. This is a core part of the problem; Connecting multiple cells in any way requires additional and/or more complicated components to regulate voltage and current in each cell. This is referred to as "balancing," and is the act of matching the state of charge of cells as close as possible. Cells have a usable voltage range, with the voltage across the cell terminals dropping as they are discharged. If one cell has a voltage differing from the others in a pack, this causes problems. If they are connected in series, the lowest-voltage cell in the pack risks being over-discharged, which can destroy the cell. If they are connected in parallel, drastic differences in voltage can cause dangerously high surges in current through wiring and busbars as the cells "self-balance."

With all that said, this risk and additional work can be necessary if a project demands the power of a large pack. The largest constraint for power requirements will be the size and type of servo motors used in the polarizer system. Although there are high-quality single cells available that can output enough current, there are still reservations about the runtime. To improve runtime, two cells could be connected in parallel with adequate safety measures in place, or the project can be designed for two cells in series. The rest of the systems (Raspberry pi, microcontroller, laser diodes, etc.) have relatively low power consumption and thus are not as alarming. For this project, we have decided to utilize two cells in series to increase voltage output for the LDO regulators, which are step-down only, and provide optimal runtime.

4.3.3 Considerations for Battery and/or Charging Management

Battery cells, especially lithium-ion ones, require constant monitoring of themselves and the systems around them. The criteria are that the cells should remain within a safe state of charge (SoC) and state of health (SoH) at all times. This means no overcharge or over discharge, no current draw in excess of the pack's ability, and no operation outside of safe temperatures.

This is accomplished with a device called a battery management system (BMS). The BMS takes input from the cells in the form of voltage across each cell, current output of the pack, and (usually) temperature from at least one location in the pack. More sensors for extra data points can be added as required. These parameters have defined safe operating ranges, and the cells must operate within these parameters at all times to prevent thermal runaway or cell damage. To accomplish this, a BMS has control over the circuit connection at the cell terminals, usually via field-effect transistors. If any of the voltage, current, or temperature values breach safe operating parameters, the circuit is immediately opened.

Obviously, this project requires one. Upon further investigation into component selection for battery management as well as charging, it was discovered that most BMS solutions are for larger, more complex projects than a small toy or mobile device. For the purposes of this project, the relevant component type is actually a charge controller meant for portable devices such as bluetooth speakers and battery banks. Fortunately, these controllers are so ubiquitous that they are now available as a single integrated circuit that is responsible not just for the above tasks, but many also control charging as well. Additionally, although data output for software is an option, absolutely no code and/or debugging is necessary; The circuit can be built to run entirely via hardware, provided you select components accordingly. This is possibly the most crucial system of the project, but it has a simple, robust solution.

4.3.4 Considerations For Voltage Regulators

As the supply voltage from the AC adapter will be mismatched from the nominal voltage requirements of the microcontroller and/or bluetooth module, a voltage regulator will be required to convert from one voltage to the other. The criteria for regulators for this project are that they must accept an input voltage of 5 volts, have a nominal output voltage of 3.3 volts, and have very little output noise. This is because our project has sensors, a laser diode, and other electronic components like a Bluetooth module that require stable voltage sources. The two main classes of voltage regulators are linear and switching.

4.3.4.1 Linear vs. Switching Regulators

Linear regulators typically use resistance to lower the voltage from input to output. The name “linear” stems from the fact that the input voltage is not switched on and off to modulate the output. General benefits to linear regulators include low cost, ease of design, small footprint, low noise, and a wide range of acceptable voltage input. The biggest downside is typically efficiency; Using resistors as a form of voltage regulation wastes some measurable amount of energy as waste heat from the current fighting the resistance. Switching regulators use some form of modulation to switch the input voltage on and off over a period of time, then use transient components (such as capacitors) to “average out” the voltage at the output. This wastes less energy than linear regulators, but they create new problems. The first is that the act of switching introduces noise to the output voltage, which can cause problems with high-sensitivity components such as microcontrollers and sensors. The second is that switching topologies require many more components to operate. Some of these components must be external, such as large capacitors. Because of the increased noise and complexity of switching regulators, we are opting for a linear regulator type.

4.3.4.2 Linear Dropout Regulators

One common, simple type of linear regulator is the linear dropout (LDO) regulator. There are a few subsets, but all LDOs use a resistive voltage divider and an operational amplifier to step down an input voltage to a target voltage. The key benefit to LDOs is that since an op-amp gives closed-loop control over the output voltage, the target voltage is always seen at the output, even with fluctuations in input voltage. Given that many circuits require common voltages such as 5v and 3.3v, many LDO ICs are pre-tuned to one of these voltages. The range of input voltages, continuous and peak current draw, and packaging are properties of individual ICs, of which there are thousands on the market today. Owing to the importance of constant, low-noise voltage sources for the Bluetooth module and laser diode, we have decided to use LDO regulators in this project.

	Switching	Low Dropout	Linear (others)
Output Noise/Ripple	>10mV	<40μV	<40μV

Efficiency	>95%	60%	60%
Input/Output ΔV	>>2v	<2v	>2v
# of Components	5 or more	3	3

Table 4: Options and key metrics of different voltage regulator technologies

4.4 Laser Movement System Technologies

The necessity for a laser movement system is such that the laser diode's output must be manipulated into various movements, shapes, and patterns. The idea that was initially discussed was to accomplish this via static polarization filters that are manipulated mechanically, but this later evolved into the wedge prism design employed in the final design. Regardless, different motor types were investigated. The main requirements for the motors are that they must be as small as possible, have low power consumption, and have precise positional and/or velocity control with minimal inertia. Other constraints were available degrees of travel and ease of driving via the microcontroller, but these were more specific design choices that were dealt with as the project progressed.

4.4.1 Servo Motors

Various types of servo motors are being discussed. Conceptually, a "servo motor" is any motor that operates with closed-loop feedback in its control system (or at least is open-loop with a high degree of precision), but this is not a good enough distinction for this project. For example, a large, high-torque brushed DC motor used for drivetrain or rotary power tool applications is not a good fit, even if it has a rotational sensor on its output shaft. The power consumption, high RPM, and lack of precise angular position control are unacceptable. Thus, we need to be more specific.

Perhaps the motors most commonly associated with the term "servo motor" are so-called "hobby servos." These are devices that contain a very small brushed motor, gearbox, positional sensor, and a premade positional control board in a single box. Positional control means that they are controlled based on the angular position of the output shaft, and are typically used for linear actuation in model vehicles. There are many reasons why these motors would be desirable. The first is that they are very easy to use. Simply set the desired angle using a pulsed-width modulation (PWM) signal, and the output shaft moves to that angle. Second, the typical current draw is minimal, usually on the order of hundreds of milliamps. Third, the positional control is exceptionally accurate, and inertia is negligible due to the small size. Outside of these factors, the motors can have a finite or infinite field of rotation. These are referred to as fixed rotation or continuous rotation servos. Fixed rotation hobby servos have a finite field of rotational movement, typically 90 or 180 degrees. These are common as they are adequate for linear actuation of a lever, which is the most common use case. But as required, continuous rotation servos are also an option. These still use positional control for desired angle movement, but can do so infinitely with 360 degrees of rotation. After discussion of various options for laser movement, it was decided that continuous servos would be required for full implementation of the wedge prisms.

4.4.2 Stepper Motors

Another option that was discussed was the use of stepper motors. These are a kind of motor made specifically for positional control applications, and are common on computer-numerical-controlled (CNC) machine tools and similar applications. Stepper motors work by using around a dozen stator windings, as well as rotor positioning that is slightly geometrically opposed to the stator dimensions. In practice, by activating one stator winding segment, the rotor is “snapped” to a precise angle, which gives a very high degree of accuracy. However, they are more difficult to drive than hobby servos, often requiring a dedicated IC to manipulate the stator windings through each “step” of movement. Additionally, they tend to be much larger and have higher power consumption, even when stationary in order to “hold” their position. Owing to these issues, stepper motors have been ruled out in this project.

	Steppers	”Hobby” Servos
Method of Control	Limited	Limited
Current Draw	>1.5A/phase	<500mA
Size	42.3 x 42.3 x 48mm	22.6 x 12.2 x 30mm
Mass	350g	9g
Step Precision	<<1 degree	1 degree

Table 5: Options and key metrics of different motor technologies

4.5 Laser System

The laser system in our device is designed to enable the movement of a laser beam to entertain a cat. To accomplish this we utilized several optoelectronic components, as well as unique properties of light.

4.5.1 Laser Diode

The laser that is in this device is a laser diode (LD), a semiconductor device that works on the same core principles of traditional lasers. The laser diode has three primary components that allow it to lase: a pump source, a gain medium, and an optical resonator.

The pump source is used to provide energy to the laser system to generate photons. The generated photons then enter the system in an optical cavity that consists of two curved mirrors and a gain medium. Within the optical cavity, the generated photons interact with the gain medium which is usually made from materials with higher energy states. The generated photons excite the electrons in the gain medium and cause them to drop from higher energy state to lower states generating an identical photon in a process called stimulated emission. The new photons that are generated inside the optical cavity are reflected off of the curved mirrors that surround the medium. The photons continuously reflect off of the curved mirrors causing the number of photons to increase exponentially in a small amount of time. This continues until the optical power can overcome the refractive index of one mirror, meaning the system has begun to lase and a coherent monochromatic beam is emitted.

The three major components of the LD can be placed in a small module that acts similarly to a LED. The laser module utilizes a PIN junction, a similar semiconductor junction as an LED's PN junction with an additional region of intrinsic material. This material tends to have a lower quantity of electrons and acts as the gain medium for the photons that are trapped inside. The laser module is also covered with reflective material that is used to form the optical resonator. When enough electricity is added to the system, the device will begin to produce a coherent beam of light, as the photons that are trapped in the intrinsic region can overcome the reflectivity of the optical resonator. Once the laser is operational, the output power can be adjusted by controlling the input electrical current. The power output of the laser will be limited to 1-5 mW to match the output of commercial laser cat toys. It is important that the laser never exceeds 5 mW as it would be too dangerous to use.

4.5.2 Diffraction Grating

Originally, to achieve beam separation and movement on the wall several optical components were in consideration. One of these optical components was a diffraction grating; however, accurately moving the laser in a satisfying pattern proved too costly and difficult to implement this method. Diffraction gratings rely on the wave-like properties of constructive and destructive interference of light to separate light into several different diffraction orders. The constructive and destructive interference occurs due to the grooves or slit of the diffraction grating, much in the same way as the double slit experiment. Unlike the interference pattern generated by the double slit experiment, the diffraction grating produces separate and coherent rays of light. This is because the diffraction gratings have significantly more grooves or slits to create points of constructive interference on the peaks of the wave of light, and multiple points of destructive interference in between the peaks, leaving separate coherent beams of light.

When a laser beam comes into contact with a diffraction grating, the following equation can be used to describe the pattern:

$$d \sin \theta_m = m\lambda$$

Equation 1: Diffraction Grating Equation

Where d represents the spacing between slits in the grating, and θ_m is the angle of the diffraction order from the center beam. The variable m represents the diffraction order which can be and λ is the wavelength of light of the laser beam. The distance between the center laser and the diffraction order on the wall is used to create a right triangle visualized in Figure 15. The equation can now be simplified using the trigonometric relationship between sin(θ) and the sides of a triangle. The equation can be further simplified as the height between the center beam and the diffraction order (Z), and the distance to the screen L.

$$tan(\theta_m) = \frac{Z}{L}$$

Equation 2: Simplified Diffraction Grating Equation

In this device, the diffraction grating was intended to separate the laser beam into separate beams of light. The diffraction grating would be mounted on a motor that would rotate the diffraction grating to change the position of the diffraction orders on the wall. Diffraction gratings differ between each other by the number of equally-spaced slits that are measured in lines/mm. As the lines/mm increase, the distance between the diffraction orders increases. The points where constructive interference occurs would be the separate diffraction orders that are now coherent enough to look like separate laser beams enabling it to be used as a beam splitter in this device.

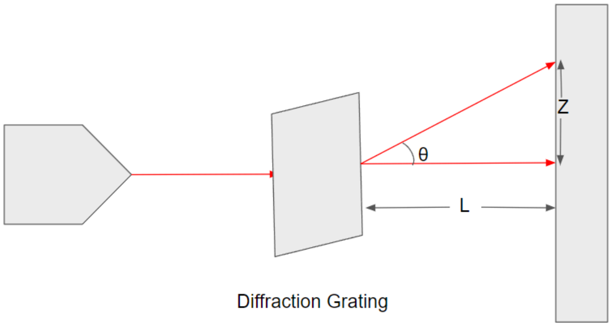


Figure 15: Diffraction grating effect

4.5.3 Polarizers

Optical polarizers are devices used to change the propagation orientation of light that passess through it. They work on the wave-like properties of light, and one's ability to interpret that as an oscillating electro-magnetic (EM) wave that propagates in free space. An EM wave has two distinct components, a strong electric field and a weak magnetic field that both oscillate in patterns that are consistent to a sinusoidal or cosine function. Both of these waves propagate in the same direction, however they are tangential to each other. There are many variations in amplitude, frequency, wavelength, and phase shift that give light unique orientations while propagating forward. The propagation can be visualized as a unit circle where the angle corresponds to the direction the light faceses. The electric field is typically used to determine the angle light is propagating at due to it being stronger than the magnetic field.

The orientation of polarizers fall into one of three categories: linearly polarized, circularly polarized, and elliptically polarized. In linearly polarized light, the electric field propagates in a single plane with a given amplitude. Circularly polarized light has two linear components that have the same amplitude but are perpendicular to each other. The propagation of the occurring electric field will be a circular motion. Elliptically polarized light is similar to circularly polarized light except the amplitudes of the perpendicular components are different causing the circular pattern to become an ellipse pattern. Light that is emitted from a standard light source is typically a collection of all polarization orientations and is referred to as randomly or unpolarized light.

Although most light sources emit randomly polarized light, lasers emit linearly polarized light. Typically, when randomly polarized light is incident to an optical polarizer, the new polarization of light is oriented in the same angle that the polarizer itself is angled as we can see from figure 16.

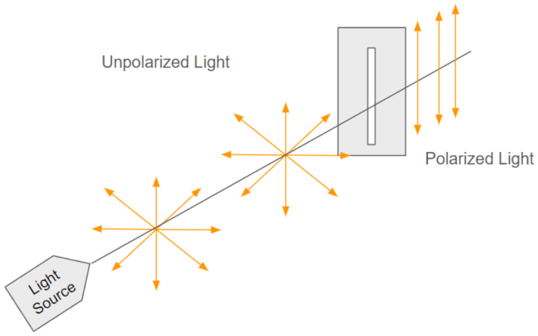


Figure 16: Polarizers effect on unpolarized light

When linear light is incident on an optical polarizer and it is oriented at the same angle of the optical polarizer, nothing will happen. When linearly polarized light is incident on an optical polarizer and it is not oriented at the same angle, the light that passes through has an angle as the polarizer and an optical power corresponding to Malus's Law, which can be described below by Equation 3.

$$I = I_0 cos\theta_i^2$$

Equation 3: Malus's Law

Where I_0 is the incident optical power on the polarizer and θ_i is the difference in the angle of the polarizer and the angle of the incident linearly polarized light.

Optical polarizers can be broken down into two categories, absorptive and beam-splitting polarizers. The absorptive polarizers have weak absorption at certain polarization directions while having strong polarization at other directions. A beam-splitting polarizer works by placing two special types of prisms next to each other so that the different polarization directions are propagating in different directions.

The polarizer was originally intended to work in conjunction with the diffraction grating to filter out all of the individual laser beams except for one, limiting the output image to one. The polarizer would be mounted with a motor to rotate it so it filters the different diffraction orders. This is due to the polarizing film filtering out light that is different polarization based on the orientation of the film. This means that while the polarizer is rotated, it can selectively filter out light that does not match its orientation.

For the polarization filter to display different diffraction orders, it would require a polarizer and motor for each of the diffraction orders of the laser beams. The motors would also need to work independent of each other to choose individual diffraction orders to display. The polarization and motor also require that the diffraction grating does not rotate as that would move the location of the diffraction orders away. Ultimately, the complexity of this approach did not justify the extra cost for unsatisfying laser movement, and led to our decision to pursue another approach.

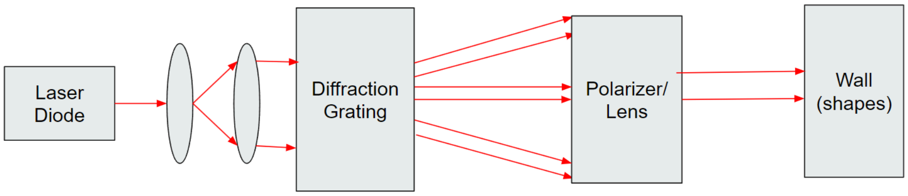


Figure 17 : Diffraction Grating/ Polarizer Design

4.5.4 Beam Shaping

The laser system was designed to increase the dimensions of the laser beam to ensure that the spot size can be sufficiently seen while rapidly moving. To accomplish this a simple beam expander setup was used. A Galilean design which requires two lenses, one positive and one negative, separated by the sum of their focal length was chosen for our device. As the beam is expanded and collimated, the beam divergence will decrease, making the image maintain its intended shape with minimum aberrations.

4.5.5 Lenses

Lenses are optical components that can be used to manipulate and shape light by expanding or focusing light away from a point. The area that is in front of the front surface of the lens is called the object plane while the area behind is called the image plane. The point the lens converges or scatters light toward is called the focal point. The distance between the back surface of a lens and the focal point is called the focal length. The optical power of a lens is measured in inverse meters in a unit called diopter and is equal to the inverse of the focal length. Lenses with very short focal length will have a high power and vice versa. When the focal length falls in the image plane behind the lens, the optical power will be positive, and the parallel light rays will be converged onto the focal point.

Lenses can also have focal points that fall in front of the object plane instead of just the image plane in relation to a lens. When the focal length is in front of the lens it results in the focal length to be negative, resulting in the lens having a negative optical power. Lenses with negative optical power will scatter light since there is no physical point behind the lens where the light will converge.

4.5.5.1 N-BK7 Optical Grade Glass

Optical borosilicate-crown glass (N-BK7) is a very pure universal optical glass that is one of the most common glass types used to produce high-quality optics in the visible spectrum. N-BK7 glass is known to have a refractive index of 1.51509, a smooth transmission, and low absorption in the entire visible spectrum which would be useful in our beam shaping designs. N-BK7 can come in many forms, which is useful for us as it enables us to utilize its properties in both lens and prism forms for our design. For our design all of the lenses and prisms consist of N-BK7 glass as its properties are ideal for our optical design within the laser system as well as its popularity within the industry makes it one of the more reasonably priced optical grade glass.

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4.5.5.2 Methods of beam expansions

There are two main telescopic lens systems that can be created with a pair of lenses. In both cases the system will be afocal where the focal point is located an infinite distance away from the lenses. Both methods have distinct characteristics that affect the overall portability of the entire device.

4.5.5.2.1 Keplerian Beam Expander

The first system that was under consideration was the Keplerian beam expander design, which utilizes two lenses with positive focal lengths. The lenses are separated by a distance equal to the sum of their focal lengths, and the output beam inverted with respect to the input beam. This happens because when the light is refracted through the input lens, it focuses to a point in between both lenses. The light begins to expand as it travels past the focal point until it reaches the output lens, at which point; the light is refracted back into a collimated beam with an expanded waist when compared to the input. To adjust the magnification of the system, lenses with greater focal lengths must be used since the distance between lenses is the sum of the focal lengths. Optical designs that utilize this method are generally on the longer side since the distance between lenses is equal to the sum of positive numbers.

4.5.5.2.2 Galilean Beam Expander

Much like the Keplerian design, a Galilean beam expander design utilizes two lenses, however; one has a negative optical power while the other has a positive. In this design, the distance between the lenses can be found by finding the difference in their focal lengths, making the design more compact. When the beam of a laser is incident on the first lens, it is refracted through the lens with negative optical power. The diverging beams produced by the negative lens expands the diameter of the beam waist until it is incident on the second positive lens. The Galilean design does not focus the light to a single point, enabling the output beam to maintain the same orientation in relation to the input.

Both beam expander designs accomplish the task of magnification and collimation utilizing two optical lenses. However, between both discussed methods for beam expansion, the Galilean beam expander provides more benefits that can be utilized in our design and was chosen for our project. The Galilean design requires less distance in between lenses in comparison to the Keplerian design, enabling us to create a more compact and portable design. Galilean design is also known to reduce spherical aberrations due to the lens used in the design.

4.5.6 Prisms

Prisms are optical elements that are made up of glass or transparent materials that are made with precise angles and plane faces. They are known for their property to refract light at varying angles away from the optical axis. A well known experiment that shows this phenomenon is separating white light into the different colors that it is composed of due to the differing wavelengths. This effect can be described by Snell's Law of Refraction:

$$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

Equation 4: Snell's Law

where n_1 is the refractive index of the material that light is traveling through and θ_1 is the angle incident on the front of the optical surface. Typically n_1 and θ_1 are known values, as well as the refractive index of the material, to calculate for the new propagation angle in the material in relation to the optical axis.

Prisms can also redirect light that is incident on it by reflecting the beam off the inside surface. Reflecting the beam can be done one of two ways, either by coating a surface with a reflective material, or by a phenomenon called total internal reflection. Total internal reflection occurs when the angle of incidence of the prism causes the angle of refraction to be 90°, causing it to reflect. Reflecting prisms utilize this property on one or more surfaces to deviate the laser beam by 90° or 180 °. For the Smart Laser Toy for Cats, a rotating prism that displaces the laser beam by right angle would not be engaging to a cat.

The geometry of the prism is a major factor to the functionality and characteristics of the optical component as it determines how light is redirected and how great the deviation. One geometry that is designed to steer a laser beam at angles of deviation of 10° or less, is a wedge prism. Wedge prisms are designed to be used as either a single component or as a pair, with a variety of patterns that can be traced depending on the number of prisms and the direction and speed of their rotation. When a single wedge prism is oriented with the thickest part of the glass in the top position and rotated, the laser will be deviated by a certain angle and trace a circle. When a second wedge prism to the optical system with the same orientation and rotation time, the angle of deviation will be doubled, resulting in a larger circle.We can also rotate the prisms in different directions and speeds to steer the laser beam into different patterns. We can use the equation 5 found on THORLAB to map where the beam will be steered within the play area, where r_1 and r_d are the radius of deviation of the prism, ω_1 and ω_2 are the rotation speed of the prisms, and t is the amount of time the system is active.

$$y(\omega_1, \omega_2) = (r_1 + r_d) * sin(\omega_1 t) + r_2 sin(\omega_2 t),$$

$$x(\omega_1, \omega_2) = (r_1 + r_d) * cos(\omega_1 t) + r_2 cos(\omega_2 t)$$

Equation 5: Risley Prism Rotation Equation

The two wedge prism method of moving the desired image was chosen for this project to refract the laser a certain angle away from the central axis of the system. Since a Risley prism is a wedge prism, it follows the same principles of refraction and equations to steer the laser beam.

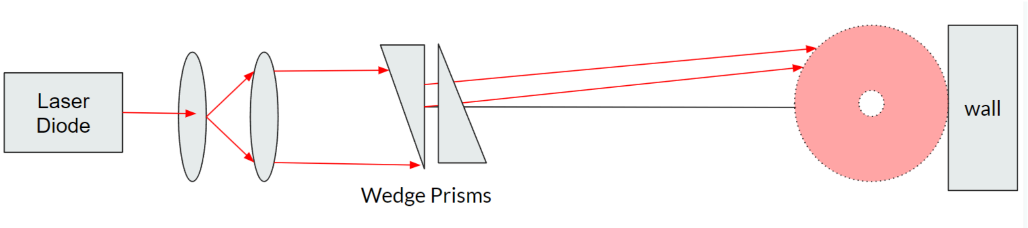


Figure 18: Risley Prism Design

4.5.7 Optical Mounts

The optical components that are utilized for this device are required to be securely mounted onto the optical axis without damaging the glass. For the Risley pair, the group needed to both mount it onto the optical axis as well as rotate the prisms. While we could have purchased optical mounts that are both stationary as well as mounts with motors integrated into them to achieve automatic rotation, it would be too expensive. Instead we decided to 3D print optical mounts that can hold the lenses stationary, as well as more complex mounts that can hold a motor to rotate the component it is holding. An example of the more complex mount can be seen in the following figure.

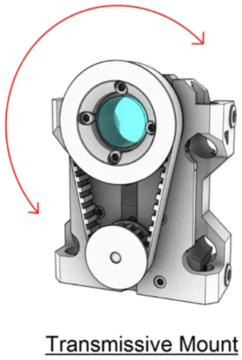


Figure 19: 3D printed optical transmissive mount(Courtesy of Optica Publishing Group)

5 Technology Investigation and Part Selection

The following section lists the technological investigations and part selections of the components that were integrated into each subsystem to design and deliver the Smart Laser Toy for Cats.

5.1 Bluetooth Module Part Selection

The following section describes the technological investigations conducted to select the bluetooth module.

5.1.1 Criteria for Parts Selection

Since the communication system is the backbone of the cat toy project, it is important to discuss the criteria used to select the bluetooth transceiver that will be a part of the printed circuit board design. There are two documents that provide standard documentation and explain the functionality of bluetooth. The first document is by the Institute of Electrical and Electronics Engineers and is named IEEE 802.15.4. The second is named the Bluetooth Core Standard v4.0. The criteria the group will use to select a bluetooth module or transceiver is as follows: the bluetooth mode, iPhone support, EMC/FCC certification, data rate, current consumption, evaluation board available, flash memory, cost, and built in antenna. The primary focus of the first paragraph will be why each of these criteria are important for selecting a bluetooth module and a transceiver.
There are two options for making a bluetooth communication system. The first is to choose a module that integrates an antenna and all other parts of the relevant system into a circuit board that can be integrated into the system using a shield (this is common using an arduino).

The second option is to integrate a bluetooth module into the same printed circuit board as a microcontroller. Due to space constraints the first option will be used. Next, it is important to discuss why each of the criteria is important to the overall system. The bluetooth mode that was chosen for this project is bluetooth mode v4.0. Bluetooth mode v4.0 was chosen because according to a quick Google search it is the mode that iPhones have had support for since the iPhone 4s which was released in 2011. Furthermore, Apple’s iPhone is selective about which type of bluetooth mode it uses. Different versions of Apple’s iPhone have supported different types of modulation modes at different times; for example iPhone 4s supported CDMA and iPhone 5 supported 4G LTE. Therefore since the main purpose of the bluetooth system is to connect with an iPhone it is important to make sure that the module or transceiver that is chosen for this project is compatible with the models of iPhone that the capture a large enough market share to ensure that many customers can be acquired without having to upgrade the customer’s current phone.

The next criteria that was selected for the bluetooth system is electromagnetic compatibility or federal communications commission certification. The reason why this is important is that this standard essentially makes sure that the module or transceiver that is chosen is compliant with rules and regulations in regards to electromagnetic compatibility. The next two factors that are important for the project are data rate and current consumption. The data rate and peak current consumption are inverse of each other. For this project it was determined that a high data rate is more important than a lower current consumption. Therefore a higher data rate will be prioritized over a low current consumption. This tradeoff was made to ensure low latency between the iPhone application and the system.

The next criteria that was selected for this system is that there should be an evaluation board available online. The reason that this is a requirement for the bluetooth transceiver is that the presence of an evaluation board means that the product has been proven to work and there is a reference design that the group can use to integrate the bluetooth system into the cat toy project. The existence of an evaluation board for sale makes the design of this part of the system simpler. Another way to increase the simplicity of the design is to buy a bluetooth module with a built in printed circuit board antenna. Antenna design is a complex field that often requires graduate level understanding of electromagnetic field theory as well as competency with esoteric complex design software. As a general rule of thumb in engineering, simpler is better therefore the group will aggressively pursue finding a bluetooth module that has an integrated Antenna. Another feature that would improve performance at the cost of increased complexity is the presence of flash memory in a bluetooth module. Flash memory allows the quick storage of the data that is received and then sent to the computing system that is on the printed circuit board microcontroller. However, the tradeoff with both these features is that they increase cost. Cost is the last factor on the list however it is one of the most important. Therefore the group has to make sure that the bluetooth module and transceiver integrated circuit are optimized for cost, complexity, integrability, and performance.

5.1.2 Reputable Manufacturers

Another separate criteria that is important is the reputation of the manufacturer. The reason why this is important is that there are many manufacturers of bluetooth modules that are extremely cost competitive; however, those manufacturers have been known to provide data sheets with unreliable information, and to grossly overinflate the performance of those modules. Therefore the group will restrict the bluetooth transceiver or bluetooth module to the following manufacturer; Vishay Semiconductor, STMicroelectronics, Analog Devices, Texas Instruments, Qualcomm, Qorvo, Semtec, Expressif, and other reputable manufacturers. The purpose of this is to ensure the quality of the product that is purchased gives the performance that is needed for the project.

5.1.3 Antenna Selection

There are two options for selecting an antenna. The first option is to use a built-in antenna that comes provided with a bluetooth module. The second option is to design and build an antenna for a specific purpose. The merits of both shall be discussed below.

The first option for the bluetooth communication system is to select a module with a built-in antenna. There are only two disadvantages to this option. The first is that buying the built in antenna is usually more expensive. The second disadvantage is that since the group would be purchasing the antenna then the group is limited by the budget available to what they can afford. However there are many advantages to purchasing the module. The first advantage is that purchasing a bluetooth module with a built in antenna is that the built in antenna has been tested. It has been tested to be reliable. It works with the bluetooth module integrated circuit. The second advantage of purchasing a bluetooth module with a built in antenna is that the built in antenna has been tested to have the omnidirectional radiation pattern that is required for this application. That means that the group will be reassured it works the way that Bluetooth Core Standard requirements require. The third advantage that purchasing a bluetooth module with a built-in antenna has is that it has been used by other customers for the same purpose that the project intends to use it for; as a communication system between an application on a phone and a microcontroller.

The second option is to design, build, and test an antenna. There are few advantages and many disadvantages to this option. First the advantages of designing, building, and testing an antenna is that this process is challenging, the opportunity to learn is large, and the antenna can be purpose built. The ability to build such an antenna would essentially allow the group to make a custom antenna that would provide a larger link budget and would give a chance at performance improvements. The disadvantages are as follows; the group would be required to test the antenna which requires specialized equipment, the group would need to make multiple designs and iteratively improve them which has the chance to increase overall design cost, and this process requires in depth knowledge that is provided by several design guides that are provided in the reference documentation. It is for the reasons above that the group decided not to build an antenna for this project. However in future iterations a higher gain antenna would improve the range of the communications protocol and allow the customer to be further away.

The purpose of the previous paragraphs was to provide context for the design criteria for the project. Furthermore, the secondary purpose of the previous paragraphs is that those paragraphs exposed the advantages and disadvantages of each option. Generally in engineering, there is always a tradeoff between systems integration and sub system design. Therefore, it is necessary to provide context for why the team chose to use systems integration as the main path for the project. After providing the context of the desired system quantities, the next step is to compare and contrast various modules that fit the design requirements. Since the previous paragraphs were long a summary of the system qualities that are desired are as follows: the system shall come from a reputable manufacturer, the system shall allow bluetooth classic, the system shall have a low peak current, the system shall have an evaluation board, the system shall be compatible with arduino and or ATMega 2056, the system shall have an integrated antenna module, and finally the system shall be in stock.

5.1.4 RF Transceiver Parts Selection Process and Summary

To locate an RF transceiver IC that met the project's criteria, DigiKey and Mouser search features were used. The search features that were used were discussed extensively above, but it is worth it to ensure that the features discussed above were the same as the features used in the search. In the Digikey and Mouser search the following criteria was used :

“TX/RX Only” , and under the protocol tab “Bluetooth v4.0”, “Bluetooth v4.1”, “Bluetooth v4.2”, “Bluetooth v5.0”.

The first module that was evaluated is the NRF51822-QFAB-R7 which is manufactured by Nordic Semiconductor. While Nordic semiconductor is a reputable brand the nordic semiconductor website did not feature an evaluation board for this particular model. Therefore, it was not selected.

The next module that fits the criteria is the NRF8001-R2Q32-R7. Again, while Nordic semiconductor is a reputable brand that includes high quality electronics, and solid design principles their website did not feature an evaluation board. This module did have a reference design that was purpose built as a shield for an Arduino. However, this is not adequate and does not meet the criteria.

The next module that had the criteria that fit the design was the BLUENRGCSP manufactured by ST microelectronics. While this board did an excellent job meeting the design criteria and requirements it is purpose built for the STMicrelectronics family of boards. Since these are not the MCU’s that the project will be based around then the RF transceiver IC was not chosen.

The QN9080-001-M17 made by NXP had all the features and met the requirements; however, it was too expensive. Therefore it was not chosen.

There are two modules that will be purchased and individually evaluated to ensure that the criteria on the datasheet meets the real world criteria.

First the CC2564 is a family of RF transceiver integrated circuits made by Texas Instruments. It features all of the features that are needed to meet the design requirements. Its strongest characteristic is the extensive documentation and the extensive reference designs available from Texas Instruments. A full evaluation board is available for purchase from the Texas Instruments website and included is a free and open reference design with all of the required parts. Furthermore Texas Instruments has provided extensive printed circuit board design guidelines as well as planar inverted F antenna design guides. Therefore this module will be purchased and used to build an evaluation board that can be tested for the criteria required by the project.

The second radio frequency transceiver integrated circuit that will be purchased is the NINA-W102-00B. The NINA-W102-00B is made by Swedish semiconductor U-blox. The semiconductor manufacturer is a reputable brand in the wireless communication module world. Furthermore there are arduino shields that are already built and available for the Arduino uno on the Arduino website and this radio frequency integrated circuit is the integrated circuit that is used. This is the reason that this board was chosen. Essentially it features an extensive reference design that has been vetted and used by millions of Arduino users.

Both of these RF transceiver ICs will be made into evaluation boards and tested in the lab to ensure they meet the design requirements. While the NINA-W102-00B is already used in an Arduino shield, its performance characteristics are extremely limited and lacking compared to the CC2564 RVMT from Texas Instruments.

The table below summarizes the discussion about which parts were selected and the various performance metrics that each component has.

Name	NRF51822-QFAB-R7	NRF8001-R2Q32-R7	BLUENRGCSP	QN9080-001-M17	CC2564	NINA-W102-00B	ESP32 WROVER-E-N8R8
Bluetooth Mode	BLE	BLE	BLE,v4.0	BLE, v5.0	EDR, BLE	Bluetooth V4.2	BLE, EDR, V5.0
Data Rate	1 Mbps	1Mbps (Max)	1 Mbps	2 Mbps	1 - 4 Mbps	1 Mbps	1-4 Mbps
Peak Current	16 mA	14.6 mA	8.43 mA	4.3 mA (at 1Mbps)	8 mA	130 mA	80 mA
Evaluation Board	No	No	No	Yes	Yes	Yes	Yes
Flash Memory	128 kB	No	64 Kb	256 Kb	No	16 Mb	512 Mb
Integrated Antenna	Yes	No	No	Yes, optional input	No	Yes	Yes
Cost	$4.64	$5.15	$1.83	$20.14	$6.84	$7.55	$3.00
Manufacturer	Nordic Semiconductor	Nordic Semiconductor	STMicroelectronics	NXP USA	Texas Instruments	U-blox	EXPRESSIF
In stock	22,155	3270	521	2273	2500	4939	1541

Table 6: Performance Metrics and Requirements of Bluetooth Transceivers and Modules

The final bluetooth module is the ESP32 WROVER E. Since this is also the microcontroller the schematic and changes will be included within the printed circuit board section.

5.2 Power System Research and Selections

The power system is a very important part of the project, but its operation should be as seamless and invisible to the user as possible. It has the responsibility to safely and reliably supply power from an onboard rechargeable battery or external AC adapter to the other systems. It was correctly anticipated that the multiple subsystems would need adjustments as testing commenced and problems were discovered, as generally a power system is fully developed last to meet the demands of the rest of a project. The following criteria and part listings were the important selections for the power system for the project, including cell selection, configuration of cells, charge controller selection, voltage regulator selection, and AC adapter selection.

5.2.1 Battery Cells

5.2.1.1 Cell Chemistry and Form Factor

There are a variety of cell chemistries on the market today, but one of the most common is the standard lithium-ion format. The exact parameters differ by exact makeup of cell components such as the anode and cathode material, but most have a nominal voltage of 3.7v and an operating range of 2.7v to 4.2v, and most related components are designed with these parameters in mind. Additionally, some individual cells available on the market have built-in protection circuitry. These are meant for systems which have a single cell and minimal electronics, or for a system whose cell is removable, such as a vaping device. These "protected" cells serve this role, but they are not to be used in this project. The reason is that the protection circuitry can interfere, conflict, or override with the other components that have their own safeguards in place, which can have disastrous consequences. This is especially true if a device uses multiple cells. For example in a parallel arrangement, if one cell shuts off on its own during charging, it can cause unexpected rises in current as the charging current redistributes through the other cells. Therefore, our cells will be unprotected as delivered.

One of the more basic decisions is form factor; What shape should the cells take? This shape can be highly specialized if a project demands it, but cells come in many "commodity" sizes that can be suitable for a wide variety of projects. One of the most common is the 18650 cylindrical format. The number designates cell dimensions of 18 by 65.0 millimeters. This size is used in a variety of off-the-shelf devices, and thus has not only many cells available, but ancillary components like cell holders as well. Additionally, 18650s can be either flat-top or button-top. Flat-top cells have a flat electrode surface on both ends, while button-top cells have a protrusion on one end reminiscent of that of a disposable alkaline cell. Electrically this makes no difference, but it is an important consideration when choosing a housing for the cells as most cell holders only hold one style.

5.2.1.2 Number and Arrangement of cells

The number of cells as well as their arrangement for a battery is dictated by two factors. The first is required system voltage. The nominal voltage of the battery must be roughly equal to that of the required system voltage. This will vary depending on the type of voltage regulators employed by the system. For example, if we are to use linear dropout (LDO) regulators, we must account for the fact that these regulators tend to be step-down only. If project requirements dictate one or more external 5v regulators directly powered by the pack, then the pack voltage must be greater than 5v at any state of charge. At a minimum voltage of 2.7 volts, this means that our project requires at least two cells in series at a minimum, fully discharged voltage of 5.4v. Although we are still deciding whether this will be the case (as opposed to internal 5v regulation in the charge controller), the design will be to have two cells in series just to be safe. Again, it is important to note that this minimum value changes with cell chemistry, so this may vary. The second factor for cell number and arrangement is the required battery capacity. To clarify, capacity is the rated amount of charge that the cells are rated to hold, independent of the present state of charge. Choosing cells with an unnecessarily high capacity rating can lead to higher than necessary cost, so it is important to choose capacity based on desired runtime. A common metric for capacity is amp-hours, which is conceptually the equivalent of the average current output of a cell if discharged over exactly one hour. For our project, we are aiming for a runtime of 30 to 60 minutes under normal operating conditions. Exact power consumption is to be determined, but current estimates place expected current draw at no greater than 2 amps peak, and continuous current will likely be slightly less than this. So a good "worst case" scenario would be to assume that for a maximum one hour runtime at 2 amps means that a total capacity of 1h * 2A = 2 amp-hours (Ah). When connecting cells in series, amp-hour ratings must be matched to each other. Additionally, series-connected cells see multiples of the voltage rating, but not the current. This translates to each of the two cells needing to be around 2 Ah in capacity. This is not a set criterion, but it serves as a good reference value, as many cells have rated capacity well beyond this and tend to be expensive. Additionally, this does not limit discharge to 2 amps, as most cells have a higher discharge current rating than their amp-hour rating when compared numerically.

5.2.1.3 Cell Criteria and Selection

Below is an assortment of cells available from reputable retailers. The main technical distinction between these cells is not only cell capacity, but also chemistry. However, the key deciding factor will actually be the reputability of the manufacturer, more so than with any other component in the entire project. The cells must not only be reliable, but also less prone to catastrophic failure such as thermal runaway. Large, well-known firms in the market have more stringent testing for their cells to mitigate these risks. Another key criteria will be cell chemistry, as the chemistry dictates charging parameters. That being said, many charge controllers allow for selection of these parameters anyway, including the selection for this project. Capacity will likely be a lesser factor in our decision as many capacities within range of the 2 Ah target are available, and exceeding the target is not inherently harmful.

The first cell examined was the PCFIR18650-1500 from ZEUS Battery Products. The big distinction for this cell is the chemistry; While the other two options shown here are the more standard lithium-ion chemistry, this cell is lithium-iron-phosphate (LiFePO4). This is a cell chemistry that includes its own set of pros and cons, but the key benefit is safety. The iron-phosphate chemistry is more robust and stable than lithium-ion, which could potentially make it safer for a toy. The main downside from a design perspective is that the chemistry has different charge and discharge curves, which has far-reaching effects with charge controller selection, as well as device operation. Because of the departure from this established norm, it would be more difficult to integrate these cells into the project, but it was an interesting contender.

The second cell examined, and ultimately the cell of choice, was the INR18650-25S from Samsung. This is an lithium-ion cell with a capacity of 2500mAh, which is reasonably within the desired capacity for the selection. Moreover, it is manufactured by Samsung, one of the largest names in the battery industry. The datasheet detail and organization reflects a commitment to quality and safety in the product.

The third cell examined was the NCR18650B by Panasonic. The benefit is that Panasonic is another well-known brand in the industry, so this is likely to be a quality product. Unfortunately, the datasheet was not as informative as that of the Samsung cell. For example, the maximum charge current was not listed. Although that limit certainly won't be encountered in this project, it was not a welcoming discovery. Additionally, the rated capacity is 3350mAh, 34% more capacity than the Samsung cell and likely unnecessarily large for this project.

Name	PCIFR18650-1500	INR18650-25S	NCR18650B
Capacity	1500mAh	2500mAh	3350mAh
Chemistry	LiFePO4	Li-ion	Li-ion (NCR)
Top	Button	Flat	Flat
Voltage (nominal)	3.2v	3.6v	3.6v
Charge Current (nominal)	300mA	1.25A	1.625A
Charge Current (max)	750mA	4A	Unknown
Discharge Current (max)	4.5A	10A	4.87A
Cost/1 Unit	$5.32	$8.99	$8.99
Manufacturer	ZEUS	Samsung	Panasonic
In stock	664	Yes, quantity Unknown	Yes, quantity Unknown

Table 7: Performance Metrics and Requirements of Battery Cells

5.2.2 Criteria for Charge Controller

The main criteria that were delegated to a BMS or equivalent component in this project were support for 2 cells in series, overvoltage protection, and thermal management while charging. An additional desired goal was to find a component that could balance the two cells while charging, as this would make the battery considerably more safe by eliminating mismatched voltages that may interfere with charging and discharging cutoff voltages. After some investigation, it was discovered that most of the BMS options on the market were hinger-end components with abilities beyond the scope of this project. The correct component for this job is actually a comprehensive charger IC, many of which contain additional features like thermal shutdown and cell balancing. Some of these components were compared. Despite the differing feature sets, it is important to note that all of the below components are designed for charging two cells in series from a nominally 5v input that is then boosted to the needed voltage internally. Additionally, they all have “basic” charging safety features such as overvoltage protection while charging and temperature monitoring via a negative temperature coefficient (NTC) pin.

5.2.2.1 Charge Controller Selection

The first component examined was the BQ25886 from Texas Instruments. This component is a 2-cell, 2 amp boost-mode battery charger IC. The highlights of this chip are the built-in USB protocol support, adjustable input current, and power path management. Power path management allows the chip, in the presence of a suitable power adapter (up to 3 amps at 5v), to select either the battery or the power adapter as the source for the system load. This was a stretch goal for the project which could be accomplished with this one device selection. In addition, this component is a standalone device, meaning that operating parameters are set by the value of external resistors that are connected to the system ground. This is also likely to be desirable as it means that configuration of the chip does not require additional programming from an external microcontroller. The power output to the other systems is routed through this chip, at battery voltage and/or the required charging voltage with no regulation. This means that external step-down voltage regulators will be required for the various 5v input requirements for most of the other systems. This will add complexity to the rest of the power system, but it is possible. Unfortunately, this component does not have balancing for the two lithium-ion cells, which is a desirable safety feature. This will likely disqualify this component from the completed project.

The second component examined was the BQ25887 from Texas Instruments. This is a product from the same family as the previous option, but with a different feature set. The primary benefit of this component is the presence of cell balancing via a “mid” cell terminal that can occasionally measure the difference in cell voltage during charging. The main downside is that unlike the other options, there is no controlled system output, meaning that there is no internal overcurrent or overdischarge protection. This is a very bad omission as it means that other components will need to be implemented to compensate for this. An extra consequence of lacking this feature is that this chip does not have a built-in power path option. Again, this feature is merely a stretch goal, but is still important to note for the sake of comparison. Finally, this chip requires external programming via I2C. This adds complexity and debugging issues due to not only needing an external microcontroller, but also necessitating the understanding and use of I2C messages specifically for this one device. With all of these issues taken into consideration, this component has been assessed to be the least desirable.

The third component examined was the MP2672 from Monolithic Power. This is a similar component to the BQ25886, but with some additional features. First and foremost, cell balancing is supported, which again is highly important. Additionally, an internal system output path with power path management is present, with recommended maximum currents of 2 amps in all directions. This allows the controller to select either the battery or external power adapter to power the system based on state of charge. An interesting feature of this chip is that it is the only one examined that supports BOTH I2C and standalone modes. This means that although we do not intend to use I2C and an external microcontroller for configuration as opposed to simple external resistors, the option would remain available to us with this chip. As with the BQ25886 chip, the controlled output appears to be the pack and/or charging voltage at any given time, so additional voltage regulation will be required for 5v systems downstream. This component's use will be contentious based on voltage regulator and current requirements for the rest of the project, but is nevertheless a strong contender.

The fourth component examined was the MP2639A from Monolithic Power. Unlike the other components on this list, the 5v supply is effectively "bidirectional," because it charges and discharges the battery via a common 5v line. This is accomplished via an internal structure that can control current flow. This was an unexpected but desirable feature because it potentially eliminates the need for several external 5v regulators to power the other systems in the toy. Additionally, this chip has adjustable thresholds for charge and discharge current, maximum cell voltage, and minimum cell voltage. This chip is standalone, meaning all of these parameters are fully adjustable via external resistors. There is no need for an external microcontroller. This component has been deemed desirable because out of all the components examined, it is the only standalone, bidirectional unit that also has balancing for two cells in series.

Name	BQ25886	BQ25887	MP2672	MP2639AGR
2s Balancing	No	Yes	Yes	Yes
V_{in} (max)	6.2V	6.2v	5.75v	5.75v
Output V	Battery Voltage	N/A	Battery Voltage	5v
Charge Current (max)	2A	2A	2A	2.5A
Discharge Current (max)	2A	N/A (no power path)	2A	5A
Interface	Standalone	I2C	I2C or Standalone	Standalone

Cost/1 Unit	$2.81	$5.48	$2.71	$3.67
Manufacturer	Texas Instruments	Texas Instruments	Monolithic Power	Monolithic Power
In stock	6,728	10,591	3,335	3,441

Table 8: Performance Metrics and Requirements of Charging Management ICs

5.2.3 Voltage Regulators

The following section is dedicated to the selection of a 3.3v voltage regulator that meets expected project requirements. General considerations are that DC-DC conversions must be made with voltages close in value to each other (this is exclusive to low-dropout topologies), must have electrical noise created by the conversion to be at a minimum, and be as simple and compact as possible. As discussed in relevant technology, this makes a clear case for a linear regulator format over a switching one. Linear regulators are able to supply steady, low-noise voltage with a minimum of external components, typically no more than one capacitor each on the input and output.

5.2.3.1 Criteria for Low-voltage Dropout Regulators

One of the most popular linear regulator types is the so-called “Low Dropout” regulator. Many linear regulators employ a transistor of some kind as part of their design, and this transistor inevitably has a minimum difference in potential required for stable operation. This minimum difference threshold is known as “dropout voltage.” This potential difference is important to quantify because below this difference, the transistor cannot operate with stability. Therefore, linear regulators of all types are usually specified with dropout voltage as their most important criteria. The name for LDOs originates from this general operating parameter because their dropout voltage is designed to be as small as possible. The power requirements for this project at present call for one or more 3.3v lines to power the microcontroller unit and similar components, with a 5v supply voltage directly from the internal voltage regulator in the all-inclusive charge controller.

Another relevant metric for LDOs in this project is the minimum output current requirement. Because these regulators are built with a transistor internally, considerations that would be given to the equivalent standalone transistor in a circuit should be given here. Specifically, transistors tend to have a nonlinear voltage-current relationship. The result is that our 3.3v regulator of choice’s minimum output current must be inspected at a specific output voltage. If testing reveals that current requirements are mismatched with the one selected regulator, then a different regulator can be substituted, or identical redundant regulators can be added as required.

5.2.3.2 3.3v LDO Regulator Selection

The first component examined was the AP2114HA-3.3TRG1 from Diodes Incorporated. This component is designed to supply a maximum output current of 1 amp, which is enough to power the microcontroller of choice, as well as one of the candidates for the

Bluetooth wireless module. The module in question has a current draw of over 100 mA, which is considerably higher than the others, but it is unknown at this time if it will be chosen. The dilemma is that the minimum current based on dropout voltage is a little difficult to discern. This is never a good sign in a datasheet. Therefore, this component is not a desirable choice.

The second component examined was the LM1117LD-3.3 by Texas Instruments. Like the first component, it is designed to supply a current of 800 milliamps. Specifications are very similar, but the important difference is that the dropout voltage is 1.2 volts as opposed to being on an order of millivolts such as with the other options. This is beneficial as it allows the regulator to operate as close to its dropout voltage as possible. Additionally, documentation is superior thanks to being manufactured by a reputable brand. Finally, it is slightly cheaper per unit compared to the previous option. Unless current requirements increase and a single larger regulator is not deemed mandatory, this will be the component of choice.

The third and fourth components examined were the TCR2EF33LM from Toshiba Semiconductor and Storage and the TLV70033DDCR from Texas Instruments. These regulators are designed for an output current of no more than 200mA, and offer the lowest dropout voltage out of all the options. Although they are attractive for these reasons, they may be too anemic to power all of the devices necessary. Additionally, the Texas Instruments component is 45% more expensive, which seems excessive.

One final note is that regulators with higher currents were briefly examined, but were immediately deemed undesirable. The size and cost of the components were exponentially higher for a moderate increase in current, and it is doubtful that such downsides would outweigh the benefits.

Name	AP2114HA-3.3 TRG1	LM1117LD-3.3	TCR2EF33LM	TLV70033DD CR
Output Current	1A	800mA	200mA	200mA
Supply Voltage	2.5v-6v	<15v	1.5v-5.5v	2v-5.5v
Dropout Voltage	450mV-750mV	1.2V	150mV-200mV	175mV-250mV
Size	6.3mm * 3.7mm * 1.8mm	6.3mm * 3.7mm * 1.8mm	2.8mm * 2.9mm * 1.1mm	2.2mm * 2.4mm * 1.1mm
Cost	$0.37	$0.35	$0.33	$0.48

Manufacturer	Diodes Incorporated	Texas Instruments	Toshiba Semiconductor and Storage	Texas Instruments
In stock	106,817	70,737	140,577	39,473

Table 9: Performance Metrics and Requirements of Low-Dropout Voltage Regulators

5.2.4 AC Adapter

The last core component of the power system is the power adapter. As the system uses a mix of components operating on 5 volts and 3.3 volts DC, there must be some means of using AC power from the wall to supply power to the toy. Since a 3.3 volt regulator is already specified, all that is needed is a 5 volt input. Additionally, the charge controller options (all of them, not just the primary selection) contain an internal 5v boost converter to step up a 5v supply to the battery voltage for charging purposes. Therefore, a 5v direct current power supply, commonly called an AC adapter, is required.

5.2.4.1 Adapter Criteria

To start, the most important criteria is that the AC adapter will be external. Placing the high-voltage AC components inside the toy introduces too many problems. First, carrying 120v AC from the wall to the toy creates a larger shocking hazard to cats and other home occupants. Second, placing the associated power electronics inside the toy will take up precious space and potentially create additional EMF compatibility problems for the other systems. As a result, very few small consumer electronic devices contain built-in AC adapters.

Another important decision is whether or not the adapter will be some form of USB connection. Many devices today of all kinds are recharged using USB connections due to the ubiquity of such chargers. For this iteration, we are opting to avoid this as it introduces compatibility problems with the multiple charging standards, both consortium and de facto. Additionally, the charge current of the selected controller is programmable, but not easily adjustable via USB, which reduces the odds of being able to negotiate current requirements with a USB adapter anyway. For this reason, all below AC adapter options feature a simple, standard barrel jack connector. Dimensions for the connectors are listed below, but this will functionally be inconsequential.

Finally, a note on current requirements. The charge controller options have maximum programmable charge currents of 2 to 2.5 amps, but some of the controllers can handle more for “charge and play” functionality in which the adapter both powers the device and charges the battery. This is a stretch goal for this project, but may end up being abandoned due to potential safety risks for the cat and/or operator during use of the toy. However, a maximum supply current of 3 amps is being specified just to be safe.

5.2.4.2 AC Adapter Selection

The following table shows three options for an AC adapter for the project. All power supplies are 5v with a rated output power of 15 W, but all three have different form factors. Owing to the similarity of the three supplies, the deciding criteria has become the form factor.

The first power supply examined was the PSC15R-050 by Phihong USA. This supply is the least expensive of the bunch, but there is a caveat. This is a "multi-blade" supply whose input is selected by a removable adapter to make it usable with wall sockets around the world. None of these adapters are included. Additionally, it mounts vertically when inserted into a US-style wall outlet, which obstructs insertion in a power strip in some situations.

The second power supply examined was the SWI18-5-N-P6 by CUI Inc. This supply is designed to plug directly into a NEMA 1-15 socket, which is the common household socket in the US. Additionally, this adapter has a horizontal orientation, which forgoes the issues with power strips with the first adapter. Therefore, this adapter is the one of choice.

The third power supply examined was the GST18A05-P1J by Mean Well USA Inc. This is the only power supply on this list that is a "desktop" style instead of "wall mount." This means that the supply is contained in a standalone box that uses a separately-sold cord to carry AC to the box. Additionally, it is the most expensive option. This is an improvement over the first option, but still undesirable.

Name	PSC15R-050	SWI18-5-N-P6	GST18A05-P1J
Form	Wall, vertical	Wall, horizontal	Desktop
Input Connector	Multi-blade	NEMA 1-15P	IEC 320-C14
Output Connector (Dimensions)	2.1mm ID * 5.5mm OD * 10.0mm L	2.5mm ID * 5.5mm OD * 9.5mm L	2.1mm ID * 5.5mm OD * 11.0mm L
Cost/1 Unit	$12.99	$16.87	$17.18
Manufacturer	Phihong USA	CUI Inc.	Mean Well USA Inc.
In stock	4,540	611	7,089

Table 10: Performance Metrics and Requirements of AC Adapters

5.3 PCB Parts Selection

Due to electrostatic discharge problems that resulted in a batch of ATMEGA 2560's being extremely sensitive, the group's initial design did not work with the ATMEGA 2560. The group then switched to an ESP32 WROVER-E-N8R8. This module did work and was able to provide the functionality the team needed. The ESP32 WROVER is a system on chip and provides everything any microcontroller project will need. Therefore the project's printed circuit board only needed a linear dropout regulator and other passive components.

Since the project is using an Arduino Mega as a reference design the project will use components similar to the Arduino Mega however the project will use different components so that the printed circuit board is optimized for this project's use case.

The core components of the Arduino Mega are the two microcontrollers and an LDO. The two components that will be preserved from the reference design are the ATMEGA16U2-MU and the ATMEGA2560-15AU. The ATMEGA16U2-MU will be preserved and used on the board as a microcontroller unit to provide a universal serial bus to serial peripheral interface connection and for low to medium computations. The second reason that the ATMEGA16U2-MU will be preserved and placed on the printed circuit board microcontroller unit integrated circuit design is to preserve board space. The third reason ATMEGA16U2-MU will be preserved and used on the printed circuit board is that it will ensure that not all the peripheral connections on the primary microcontroller unit are not used. The second part of the reference design that will be preserved and used on the printed circuit board design is the ATMEGA2560-15AU. The reason why the project needs the ATMEGA2560-15AU is that the ATMEGA2560-15AU provides substantially more memory than the ATMEGA16U2-MU, and has a larger read access memory size. The third core component of the reference design board is a low dropout regulator integrated circuit. The cat toy project will use a low dropout regulator integrated circuit however the low dropout regulator integrated circuit will not be the same. The reason for this is the low dropout regulator integrated circuit has poor characteristics when compared to LT1965. Essentially the low dropout regulator integrated circuit used by the reference design has poor performance characteristics when compared to industry standard low dropout regulator integrated circuits that are available for a similar price.

The passive components are inductors, resistors, capacitors, dual inline package pins (usually n = 8). All of these passive components will be used. However, the only characteristic that will be preserved in the final design is the value of the passive component. All passive components will be kept to above a standard electronics surface mount package size. The standard electronics surface mount package size the project will use is the 0603 size. The reason behind this is that the size of all other electronic components below this size is too small for an inexperienced team member to solder onto a printed circuit board.

Furthemore another consideration that should be made for electronic components are supply chain problems. A criteria for all electronic components that must be met is that the component must be available as an individual component and have no lead time. The second supply chain consideration that will be made for the electronic components is if the components come from a trusted manufacturer.

The table below provides a summary of the design criteria and the components that were chosen.

For the final version of the third printed circuit board the group changed to an ESP32 to make software development easier and make bluetooth connection easier. The second reason the group changed was to reduce cost. The table below reflects the changes made.

Name	ATMEGA16U2-MU	ATMEGA2560-15AU	ESP32-WROVER-E-N8R8
Purpose	USB to serial interface, peripheral task scheduler, provide connections to peripherals via ethernet, USB, PCIE	General Computing, functions as the main MCU for all compute intensive tasks.	General Computing, Functions as the main MCU for all compute intensive tasks, integrate bluetooth module
Cost	$3.24	$14.31	$3.00

Table 11: Primary Components

5.4 Passive Infrared Sensor Part Selection

The passive infrared sensor was designed using a phototransistor and IR LED. The following selections highlight the research and part selection of those components.

5.4.1 Phototransistor Selection

The Smart Laser Toy for Cats uses phototransistors as part of the passive infrared sensor to convert light energy to electrical signals. More specifically, infrared phototransistors are used as they are just like regular phototransistors, with the sole difference being that they block visible light while passing IR light through a built-in filter. A large advantage of phototransistors is that they have nearly instantaneous output since they are fast-acting, while remaining inexpensive and small in size.

The most common type of phototransistor material is silicon which enables a wavelength of 190 nm to 1100 nm. Phototransistors also have a peak wavelength where they are most sensitive, this peak spectral response is typically around 840 nm, which made an IR LED the perfect light source for this design. The IR LED will be emitting between 800 nm to 980 nm. It was decided to integrate the MTD8000M3B-T phototransistor into the design of the Smart Laser Toy for Cats because it has the widest viewing angle, which enabled the group to achieve wide motion sensing capabilities.

	Phototransistor		
	TEST2600	**MTD8000M3B-T**	**OP560C**
Voltage (Collector Emitter Breakdown)	70 V	20 V	15 V
Collector Current, I_C	50 mA	30 mA	9.8 mA
Wavelength	950 nm	880 nm	935 nm
Viewing Angle	60°	160°	56°
Max Power	100 mW	N/A	100 mW
Orientation	Universal	Top View	Side View

Table 12: Phototransistor Specifications Comparison

5.4.1.1 TEST2600

This phototransistor, part number 751-1061-ND, is manufactured by Vishay Semiconductor Opto Division on DigiKey for $1.05. It has a wavelength range of 850 nm to 980 nm, with universal orientation. The specifications in comparison with all the other phototransistors are provided above in table 12.

5.4.1.2 MTD8000M3B-T

The phototransistor, part number 1125-1147-ND, is manufactured by Marktech Optoelectronics on DigiKey for $3.72. It has a wavelength of 880 nm, with a top view orientation. The specifications in comparison with all the other phototransistors are provided above in table 12.

5.4.1.3 OP560C

The phototransistor, part number 365-1073-ND, is manufactured by TT Electronics/Optek Technology on DigiKey for $1.47. It has a wavelength of 935 nm, with a side view orientation. The specifications in comparison with all the other phototransistors are provided above in table 12.

5.4.2 IR LED Selection

The Smart Laser Toy for Cats uses IR LEDs to operate the passive infrared motion sensor. Since the wavelength is already specified by the phototransistor, we purchased an IR LED of 880 nm wavelength to integrate into the sensor. The IR LED sold by onsemi, QED223A4R0, was chosen as the IR LED integrated into the passive infrared motion sensor. It has the widest viewing angle and has the most intensity for under a dollar.

	880 nm IR LED		
	XTHI12W	**WP710A10SF4C**	**QED223A4R0**
Forward Voltage	1.3 V	1.3 V	1.7 V
Current	50 mA	50 mA	100 mA
Radiant Intensity, I_e	12 mW/sr	7 mW/sr	25 mW/sr
Viewing Angle	20°	34°	40°

Table 13: IR LED Specifications Comparison

5.4.2.1 XTHI12W

This IR LED has the part number 1497-1059-ND, manufactured by SunLED and sold on DigiKey for $0.69. The LED has a central wavelength of 880 nm and a 20° viewing angle. The specifications are compared above in table 13.

5.4.2.2 WP710A10SF4C

This IR LED has the part number 754-2227-ND, manufactured by Kingbright and sold on DigiKey for $0.58. The LED has a central wavelength of 880 nm and a 34° viewing angle. The specifications are compared above in table 13.

5.4.2.3 QED223A4R0

This IR LED has the part number QED223A4R0CT-NDD, manufactured by onsemi and sold on DigiKey for $0.86. The LED has a central wavelength of 880 nm and a 40° viewing angle. The specifications are compared above in table 13.

5.5 Color Detection System Part Selection

The following section details the criteria and parts selection for the color detection system of the Smart Laser Toy for Cats.

5.5.1 Camera Selection

The camera is the component that detects the colors it is programmed to associate with “cat”. Once the camera determines that one of the programmed colors (red, green, or blue) is present, then it enables the laser system to turn on for cat stimulation and entertainment. The camera detects all colors in the visible spectrum, and then specifically reads the RGB pixels to determine the color on the collar tag.

The camera that was originally going to be chosen with best compatibility to the original microcontroller unit of the device, the Arduino, is the Arducam IMX291. The camera with a wider FOV was ideal so that the cat could be detected from any angle. However, to mitigate the costs of the project, we proceeded with a Pi Camera Module 2, with the specs listed below.

	Camera			
	OV5647 Mini Camera Module	**Pi Camera Module 2**	**Arducam IMX291**	**Arducam OV2640**
Module Compatibility	Raspberry Pi	Raspberry Pi	Windows, Linux, Mac OS, Raspberry Pi	Arduino, Raspberry Pi
Video Resolution	1080p	8 MP	1080p	2 MP
Camera Size	2.4 cm x 2.5 cm	2.4 cm x 2.5 cm	3.4 cm x 3.8 cm	4 cm x 4.3 cm
Port	CSI	CSI	USB	SPI
FOV	60°	62.2°	160°	60°

Table 14: Camera Specifications Comparison

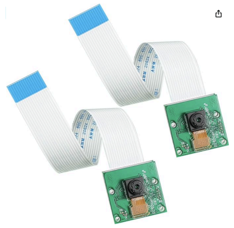


Figure 20: OV5647 Mini Camera Module (Courtesy of Amazon)

Figure 21: Arducam IMX291 Wide-Angle Camera (Courtesy of Amazon)

Figure 22: Arducam OV2640 Camera (Courtesy of Amazon)

5.5.1.1 OV5647 Mini Camera Module

A camera considered for the system is the OV5647 Camera Module.This camera is sold in a set of two for $8.99 on Amazon and is compatible with Raspberry Pi’s of model A, B, B+, 2, 3 B+, and 4. It has a video resolution of 1080p, and is easily integrated into the Raspberry Pi through the 6-inch ribbon and 15-pin insert that connects to the camera connector on the module. This specific camera was used for the Fall 2023 Senior Design Optics Discussion midterm demonstration and showed good capability in video capture and color detection. The camera specifications are compared above in table 14.

5.5.1.2 Arducam IMX291

The Arducam IMX291 camera is a USB-connected camera module sold for $49.99 on Amazon. This camera is compatible with Windows, Linux, Mac OS, or Raspberry Pi through the USB-port, this allows for no extra drivers to be installed. It has a video resolution of 1080p and wide-angle view which is beneficial for the goal of wide camera color detection. The camera specifications are compared above in table 14.

5.5.1.3 Arducam OV2640

The Arducam OV2640 camera is a camera module sold for $25.99 on Amazon. The camera is compatible with Arduino and Raspberry Pi boards. This is connected through pins, has 2 MP video resolution and comes with an IR block filter to only allow visible light to be viewed. The camera specifications are compared above in table 14.

5.5.2 LED Selection

The LED on the collar tag serves as the main color component for the camera. An LED was used as opposed to paint or colored paper because LEDs are brighter in nature. Therefore, in situations where the ambient light may be dimmer, it can still be detected as colors that do not come from a light source darken without proper room or ambient lighting. It is beneficial to use an LED because they are low in power consumption.

The LED requires a battery source and resistor to be connected to the component itself to work. As the LED disperses light in a way that can reduce its brightness from a far distance, a Fresnel lens will be placed over it to increase brightness of the colored-light and direct the light rays to be detected from a farther distance. To have a deeper understanding of the LEDs and calculate important information, the following equation is used.

$$R_s = \frac{V_s - V_{LED}}{I_{LED}}$$

Equation 6: LED Resistor Calculation

Equation 6 allows for the calculation of the proper resistance value to ensure a properly working LED system. The variable R_s is the resistance value in Ohms, V_s is the voltage of the source in volts, V_{LED} is the voltage drop across the LED in volts, and I_{LED} is the current that goes through the LED in Amperes.

5.5.2.1 RGB LED

A possible LED option was to use an RGB LED that controls color based on forward voltage applied to the LED to change color, has a viewing angle of 50 degrees and 20 mA current. This is a convenient option as it was used in the Photonics Senior Design Discussion midterm demonstration during Fall 2023. As the voltage is what is controlled, this was still a viable option to be considered for the final design of the device. While this option is good to consider, the group has decided not to move forward with this LED type because it has four leads as opposed to a single color LED that has two. A four lead LED adds complexity to the design of the LED collar tag and can mean it will be bigger to accommodate for the multiple leads. The goal of the collar tag is to be small and comfortable for the cat.

		RGB LED		
		WP154A4SURE QBFZGC	**WP154A4SEJ3V BDZGC/CA**	**COM-11451**
Forward Voltage	**Red**	1.9 V	2.2 V	2 V
	Blue	3.3 V	3.3 V	3.5 V
	Green	3.3 V	3.3 V	3.5 V
Wavelength	**Red**	630 nm	625 nm	620 nm
	Blue	465 nm	470 nm	460 nm
	Green	525 nm	525 nm	515 nm
Luminosity	**Red**	400 mcd	2600 mcd	1000 mcd
	Blue	900 mcd	1800 mcd	1200 mcd
	Green	1700 mcd	2000 mcd	1500 mcd

Table 15: RGB LED Specifications Comparison

5.5.2.1.1 WP154A4SUREQBFZGC

The RGB LED, part number 754-1615-ND, sold by DigiKey and manufactured by Kingbright is sold for $1.82. It has a forward voltage to trigger the colors as follows: 1.9 V for red, 3.3 V for green, and 3.3 V for blue. The wavelengths are 630 nm for red, 525 nm for green, and 465 nm for blue. The specifications are compared above in table 15.

5.5.2.1.2 WP154A4SEJ3VBDZGC/CA

The RGB LED, part number 754-2153-ND, sold by DigiKey and manufactured by Kingbright is sold for $2.04. It has a forward voltage to trigger the colors as follows: 2.2 V for red, 3.3 V for green, and 3.3 V for blue. The wavelengths are 625 nm for red, 515 nm for green, and 470 nm for blue. The specifications are compared above in table 15.

5.5.2.1.3 COM-11451

The RGB LED, part number 1568-1199-ND, sold by DigiKey and manufactured by SparkFun Electronics is sold for $0.95. It has a forward voltage to trigger the colors as follows: 2 V for red, 3.5 V for green, and 3.5 V for blue. The wavelengths are 620 nm for red, 515 nm for green, and 460 nm for blue. The specifications are compared above in table 15.

5.5.2.2 Single Color LED

An alternative option to the RGB LED was to use single color LEDs. This was a good alternative because the RGB LEDs have four leads that pertain to each color and are activated by a certain voltage. The single color LEDs only have two leads, which will only control the color selected when purchasing. This provided simple design constraints and measurements when creating the LED collar tag. The group decided to move forward with single color LEDs because of their two lead design. This allows for less complexity in the design of the collar tag and is a smaller, more comfortable design for the cat. The group decided to proceed with the highest intensity LEDs which will ensure the greatest likelihood of the camera detecting the color without major issues: WP7113SEC/J3, 151054GS03000, and LTL2V3TBS3KS.

	Red LED		
	XLUR12D	**WP7113SEC/J3**	**C5SMF-RJF-CT0W0BB1**
Forward Voltage	1.9 V	2.2 V	2.1 V
Current	10 mA	20 mA	20 mA
Wavelength	617 nm	625 nm	621 nm
Luminosity	39 mcd	8000 mcd	2640 mcd
Viewing Angle	30°	20°	100° x 40°

Table 16: Red LED Specifications Comparison

	Green LED		
	WP63GD	**151054GS03000**	**EALP05RDDGZ01**
Forward Voltage	2.2 V	3.4 V	3.3 V
Wavelength	568 nm	522 nm	525 nm
Luminosity	16 mcd	10000 mcd	5000 mcd
Viewing Angle	60°	30°	20°

Table 17: Green LED Specifications Comparison

	Blue LED		
	LTH3MM12VFR4600	**LTL2V3TBS3KS**	**NTE3186**

Forward Voltage	12 V	3.2 V	4.5 V
Current	12 mA	20 mA	20 mA
Wavelength	467 nm	470 nm	465 nm
Luminosity	1200 mcd	3700 mcd	40 mcd
Viewing Angle	30°	30°	60°

Table 18: Blue LED Specifications Comparison

5.5.2.2.1 XLUR12D

This single color LED is designed for the color red. It has the part number 1497-10-31-ND, manufactured by SunLED and sold on DigiKey for $0.28. The LED has a central wavelength of 617 nm. The specifications are compared above in table 16.

5.5.2.2.2 WP711SEC/J3

This single color LED is designed for the color red. It has the part number 754-1379-ND, manufactured by Kingbright and sold on DigiKey for $0.70. The LED has a central wavelength of 625 nm. The specifications are compared above in table 16.

5.5.2.2.3 C5SMF-RJF-CT0W0BB1

This single color LED is designed for the color red. It has the part number C5SMF-RJF-CT0W0BB1-ND, manufactured by CreeLED, Inc. and sold on DigiKey for $0.17. The LED has a central wavelength of 621 nm. The specifications are compared above in table 16.

5.5.2.2.4 WP63GD

This single color LED is designed for the color green. It has the part number 754-1474-ND, manufactured by Kingbright and sold on DigiKey for $0.37. The LED has a central wavelength of 568 nm. The specifications are compared above in table 17.

5.5.2.2.5 151054GS03000

This single color LED is designed for the color green. It has the part number 732-11407-ND, manufactured by Würth Elektronik and sold on DigiKey for $0.27. The LED has a central wavelength of 522 nm. The specifications are compared above in table 17.

5.5.2.2.6 EALP05RDDGZ01

This single color LED is designed for the color green. It has the part number 2368-NTE3186-ND, manufactured by NTE Electronics, Inc and sold on DigiKey for $1.48. The LED has a central wavelength of 525 nm. The specifications are compared above in table 17.

5.5.2.2.7 LTH3MM12VFR4600

This single color LED is designed for the color blue. It has the part number LTH3MM12VFR4600-ND, manufactured by Visual Communications Company and sold on DigiKey for \$1.16. The LED has a central wavelength of 467 nm. The specifications are compared above in table 18.

5.5.2.2.8 LTL2V3TBS3KS

This single color LED is designed for the color blue. It has the part number LTL2V3TBS3KS-ND, manufactured by Lite-On Inc. and sold on DigiKey for \$0.57. The LED has a central wavelength of 470 nm. The specifications are compared above in table 18.

5.5.2.2.9 NTE3186

This single color LED is designed for the color blue. It has the part number 1080-EALP05RDDGZ01TR-ND, manufactured by Everlight Electronics Co Ltd and sold on DigiKey for \$0.51. The LED has a central wavelength of 465 nm. The specifications are compared above in table 18.

5.5.3 Fresnel Lens Selection

The Fresnel lens was the final component of the color detection system that plays an integral role in the camera's ability to detect the LED color on the collar tag. Due to the LED's nature of dispersing light and not producing parallel rays of light, the Fresnel lens will be used to enhance the brightness of the LED and enable the camera to detect the color from a farther distance. It is also beneficial that the Fresnel lens requires a small focal length to focus the light. There are several equations that are beneficial in calculating the proper focal length, radius of curvatures, and material of the lens. These include, but are not limited to, the following equations below.

$$P = \frac{n_{lens} - n_o}{n_o}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Equation 7: Lensmaker Equation

$$P = \frac{1}{f}$$

Equation 8: Power and Focal Length Relationship

$$M = \frac{-Image\ Distance}{Object\ DIstance}$$

Equation 9: Magnification Equation

$$\frac{1}{f} = \frac{1}{Object\ Distance} + \frac{1}{Image\ Distance}$$

Equation 10: Imaging Equation

$$R = \frac{I_R}{I_L} = \frac{n_2 - n_1}{n_2 + n_1}$$

Equation 11: Fresnel Loss Equation

To provide a comfortable fit for the cat, the lens is no longer than 2” and has a maximum depth of 1.5”. Through various calculations using the above equations, a good focal length calculated was 25 mm. Although the calculations led the group to look for a focal length of 25 mm, upon discussing with the CREOL advisor, Dr. Delfyett, the focal length can be adjusted, within range, and the wavelength does not matter as much as the lens itself because the goal of the lens is to brighten and disperse the light farther than the singular LED. Since resolution is not important in this case, the wavelength does not weigh a high priority. The 5-pack Fresnel Lens sold by Amazon provides the most cost effective lens that meets the specifications the group is looking for, within range. By choosing this option, it allowed the Smart Laser Toy to remain cost effective since Fresnel lenses are typically a less expensive alternative.

	Fresnel Lens		
	FP125	**HMC_461_CTP**	**SSFNLR30NEW**
Material	Optical-Grade Acrylic	Polycarbonate	PMMA (Acrylic)
Wavelength	588 nm	N/A	N/A
Thickness	1.5 mm	3.63 mm	2 mm
Focal Length	25 mm	N/A	20 mm
Diameter	25.4 mm	15.75 mm	30 mm
Quantity	1	1	5
Cost	$25.04	$2.96	$34.00

Table 19: Fresnel Lens Specifications Comparison

5.5.3.1 FP125

A Fresnel lens of 25 mm focal length and 1” diameter that was considered is the FP125 lens, manufactured and sold by Thorlabs. This lens costs $25.04, is designed for 588 nm wavelength, and is 1.5 mm thick. The specifications can be seen compared above in table 19.

5.5.3.2 HMC_461_CTP

A Fresnel lens, part number HMC_461_CTP-ND, is manufactured by Visual Communications Company and sold on DigiKey for $2.96. The designed wavelength is not specified and the thickness is 3.63 mm. The lens also comes with a mount already made to fit. While this is an option, the data sheet provided is insufficient on the specifications and makes it difficult to decide on this lens. The specifications can be seen compared above in table 19.

5.5.3.3 SSFNLR30NEW

A Fresnel lens considered is the 5-pack Fresnel lens with 30 mm diameter and focal length of 20 mm manufactured by Six Seasons Store and sold on Amazon. The 5-pack costs $34.00 and the wavelength is not specified. The specifications can be seen compared above in table 19.

5.6 Laser Movement System Part Selection

As our project contains a laser that will require manipulation, a mechanical system must be employed to do this job. There are rotational and linear options for movement of the laser, but the final scope of the project calls for rotational movement of two wedge prisms. This rotation will be driven by motors that require a high degree of accuracy for positional control, preferably with no external feedback. These prisms will be spun continuously to deflect the laser at an angle, so this system requires motors that can rotate infinitely.

“Hobby” servo motors, sometimes also referred to as “RC” servo motors, are small, self-contained units that contain a motor, gearbox, and control module. These motors are compact, are easy to operate, are highly accurate and quick, and consume very little power. Compared to similar technologies such as stepper motors, they are a better fit for a small, low-power project where size, complication, and power consumption must be kept to a minimum.

5.6.1 Criteria For Motor Selection

Hobby servos come in two main classifications: Fixed-rotation and continuous-rotation. Fixed-rotation servos, sometimes also known as positional rotation servos, have a finite field of movement. The exact value varies, but these servos commonly have degrees of freedom between 90 and 180 degrees. The position is controlled by inputting a PWM signal at a specified frequency, which gives absolute control over the position with no external sensors required for feedback. Continuous servos, as the name implies, are free to rotate continuously. This is necessary for some applications, but an important caveat is that the control is relative, meaning movement is commanded as “move this many degrees” as opposed to “move to this exact angular position.”

For this application, it is necessary to use continuous-rotation servos as choosing fixed ones would limit the laser’s field of movement for generating the necessary patterns. This was a later development in the project, so a substitution had to be made because the selected motor was fixed-rotation. Fortunately, servo product families typically have fixed and continuous versions of the same motor, which made a substitution quick and easy.

5.6.2 Motor Selection

The first motor examined was the SER0006 from DFRobot. This is a fixed-rotation hobby servo with 180 nominal degrees of freedom. The largest benefit to this motor is clarity. The motor is made by a reputable brand, with a comprehensive datasheet that clearly lists the capabilities of the motor. Many hobby servos do not have this, even if the component is stocked by a reputable supplier. Additionally, it appears to be the best performer of the bunch, with the lowest no-load speed and the lowest reported current draw under a typical load. Finally, it has by far the lowest cost, undercutting the other two contenders by more than half. This motor ended up being the choice for a fixed-rotation servo, but the equivalent continuous version (part number SER0043) ended up being procured for the final project.

The second motor examined was the FXX-3037-TOP from Terasic, Inc. Immediately, a problem arose. The motor is recognizable via photograph in the datasheet, but it is identified by a different part number and without the manufacturer name. Although it's possible that all of the motors on this list have undergone some form of rebranding, this is an especially bad example of a component of dubious origin. Unfortunately, the specifications and pedigree of many motors were like this. Additionally, it appears to be a good technical candidate with 120 degrees of freedom and high build quality for "rugged" applications, but this is not without compromise. It's nearly double the volume of the other motors and has considerably more current draw under load. This makes it unacceptable to this project in a technical sense.

Finally, the ROB-09065 was examined. This motor is provided by SparkFun Electronics, a well-known hobbyist electronics storefront. It features 160 degrees of freedom and a size and a working current draw comparable to that of the DFRobot motor. Unfortunately, despite being a similar candidate, it is nearly double the price with no real justification. The datasheet also does not list any figures for current, regardless of load. It is likely an acceptable value in reality, but is too perilous to take a chance on.

Name	SER0006	FXX-3037-TOP-ND	ROB-09065	SER0043
Degrees of Freedom	180 degrees	120 degrees	160 degrees	Continuous
No-load Speed	0.12s/60 degrees	0.17s/60 degrees	0.15s/60 degrees	0.12s/60 degrees
Working Current	<500mA	500mA-900mA	Unknown	<500mA
Size	22.0mm * 12.5mm * 29.5mm	40.7mm * 19.7mm * 42.9mm	23.1mm * 11.7mm * 29.0mm	22.0mm * 12.5mm * 29.5mm

Cost	$3.62	$12.00	$9.95	$4.00
Manufacturer	DFRobot	Terasic Inc.	SparkFun Electronics	DFRobot
In stock	308	29	92	162

Table 20: Performance Metrics and Requirements of Fixed-rotation Servo Motors

5.7 Laser System Part Selection

The following section describes the technological investigations and part selection for the laser system of the Smart Laser Toy for Cats.

5.7.1 Laser Diode Selection

From the laser specifications and commercial cat laser toys, it was known that the power output of the laser diode would be around 5 mW or less. The group also knew the output wavelength of the laser should be in the red range of visible light, as this is the color that cats can see the safest. Green light is easily absorbed by a cat's eye and can cause harm to them. With sufficient brightness and fast enough movement, cats will be entertained by laser induced images.

5.7.1.1 VLM-650-03

With this in mind, there were three main options for laser diodes that were in consideration for the laser system. The first laser diode is from Digikey, the VLM-650-03 LPT 650 nm solid state module manufactured by Quarton Inc.. This laser can be adjusted between less than 1 mW to 2.5 mW for $18.25.

5.7.1.2 VLM-520-LPT

The second laser was also from the Quarton store page on Amazon, the VLM-520-04 LPT green laser diode. Unlike the first module, this laser does not have an adjustable output power, however it can be adjusted with the use of polarized film. This laser also outputs a beam that is green which is not ideal for cats to see and costs $19.95.

5.7.1.3 1054 Laser Module

The third laser that was under consideration was found on Digikey, the 1054 laser module, manufactured by Adafruit Industries LLC. This laser has a power output of 5 mW and a wavelength that is within the 'red' range of visible light for the price of $5.95.

Each of these lasers that were under consideration can be classified as either a class II or class III laser that could be used in a cat laser toy. Each of these lasers are compact, and have similar dimensions when compared to one another with the module length measuring 20 mm. For the Smart Laser Toy for Cats, the VLM-650-03 LPT laser module was chosen due to its meeting all safety standards, and its significantly lower price point.

Laser Diode Comparison				
Laser Diodes	**Output Power**	**Wavelength**	**Classification**	**Price**
VLM-650-03 LPT	< 2.5 mW	650 nm	IIIa	$18.25
VLM-520-04 LPT	< 1 mW	520 nm	IIa	$19.95
1054	< 5 mW	650 nm	IIIa	$5.95

Table 21: Laser specification comparison

5.7.2 Diffraction Grating Selection

Below is the part selection process we used for the diffraction grating in our project before ultimately deciding to pursue another method of beam steering. The triangle that is formed and trigonometric properties were used to calculate the distance between first diffraction order and the laser beam located on the center axis. To do this, the group calculated the angle of diffraction (θ_m) for the wavelength of the incident laser beam (650 nm) for each diffraction grade spacing. Commercial diffraction gratings are sold in a variety of spacings ranging from 500 lines/mm to 13500 lines/inch, each having a noticeable effect on the angle of deviation between the first diffraction order and the optical axis. Due to the portable design of the Smart Laser Toy for Cats, the distance between the diffraction grating and the wall will change depending on where the owner places the device. For this reason, the distance between the first diffraction order and the optical axis will change affecting the play area of the device.

Diffraction Grating Comparison						
Diffraction Grating	**d**	**m**	**Displacement at device entrance**	**1 m away**	**5 m away**	**10 m away**
500 line/mm	$2x10^{-6}$	18.97°	5.156 cm	34.37 cm	1.719 m	3.437 m
13500 line/in	$1.881x10^{-6}$	20.21°	5.522 cm	36.81 cm	1.841 m	3.681 m
1000 lines/mm	$1x10^{-6}$	40.54°	15.29 cm	1.019 m	5.095 m	10.19 m

Table 22: Diffraction Grating Specification Comparison

5.7.2.1 500 lines/mm

To begin we calculated the value d found in Equation 12 by converting the diffraction spacing to lines/m and taking the inverse.

$$d = \frac{1}{Diffraction\ Spacing\ (lines/mm)}$$

Equation 12: Distance Between Two Fringes

The calculated value of d was used to solve for θ_m for the first diffraction order m=1 by manipulating Equation 1, the diffraction grating equation. By doing this, it was found that θ_m is equal to 18.97° for a wavelength of 650 nm. The calculated angle was then used to determine how wide the opening of the Smart Laser Toy for Cats is by using Equation 2, the simplified diffraction equation, by using the distance between the diffraction grating and the end of the optical track, which is about 0.15 mm, being equal to L .

Once this was done, the distance between the first diffraction order and the optical axis at the end of the optical track was found to be 5.156 cm. This meant the design of the device would need to have a circular hole with a radius of 6 cm to not impede any of the laser beams. The group then placed the diffraction grating an arbitrary distance away from the wall that the different orders will be displayed on to calculate the spread of diffraction orders. Due to the portable nature of the Smart Laser Toy for Cats, the play area of the device will vary depending on the distance away from the wall. To compare the size of the play area, the three arbitrary operating distances were chosen to be 1, 5 and 10 meters. To start, the group used the distance between the first diffraction order at the first arbitrary distance of 1 m to acquire a general range of the play area that was calculated using Equation 2. Doing this, the group found that the play area of the Smart Cat Laser Toy is a circle with a radius of 34.37 cm at 1 m. The process was then repeated for the second arbitrary distance of 5 m, resulting in a play of a circle with radius 1.719 m. Equation 2 was then used at a distance of 10 m to find the resulting play area would have a radius of 3.437 m.

5.7.2.2 13500 lines/in.

The steps to calculating the angle θ_m for this diffraction grating for a laser that has the wavelength of 650 nm are identical to the previous one. The group first converted the line spacing of the diffraction grating so that it is in units of lines/m using Equation 1, calculating a value of 531496.063 lines/m . The next step was to calculate the value of d by taking the inverse of the line spacing, so that the resulting value is in units of m/lines. This yielded the value d that equals 1.881×10^{-6} m/lines, enabling us to solve for the diffracted angle of the first diffraction order. To do this, the value of d that was calculated for this diffraction spacing was plugged into the equation, the wavelength of the laser that is incident on the component, and m=1 to find the distance between the first diffraction order and the optical axis where the center beam is located. Once this was done, the angle of deviation was found to be equal to 20.21°. Next, the group took this angle and calculated the minimal opening needed for the Smart Cat Laser Toy by utilizing the relationship that $\tan(\theta_m)$ has with the ratio of the sides of a triangle. By utilizing this approach, it was found that the opening would need to be the shape of a circle with the radius of 5.522 cm. The group then utilized the same process to calculate the distance between the original laser located on the optical axis and the first diffraction order by substituting the distance to the end of the optical track to the various arbitrary operating distances. Once this process was complete, it was found that for an operating distance of 1 m, 5 m, and 10 m that the first diffraction order will be located 36.81 cm, 1.841 m, and 3.681 m.

5.7.2.3 1000 lines/mm

As previously stated, before the angle of deviation for a diffraction grating with this line spacing can be found, the group must first find the distance between two of the gratings. The group began by converting the line spacing to be in units of lines/m, which is equal to 1,000,000 lines/m. The inverse of this number was then taken to find the value d, which in this case leaves us with a value of $1 \text{x} 10^{-6}$ m/lines. Next, the group calculated the angle of deviation for the first diffraction order by plugging in the associated variables to equation 1 yielding an angle of 40.54°. This value was then used to find the minimum opening needed in the device to allow for the separated diffraction orders to pass through. To do this, the distance between the diffraction grating and the end of the optical path length was used to calculate the distance between the diffraction order and optical axis by utilizing the same trigonometric ratio as before. Taking the product of $\tan(\theta_m)$ and the distance from the diffraction grating to the entrance, it was found the value to be equal to 15.29 cm. The group can now utilize the same process to determine the play area of the Smart Cat Laser Toy at any arbitrary distances by multiplying $\tan(\theta_m)$ by the distance the incident laser will travel before it reaches a wall. Once this was complete, it can be seen that for operating distances of 1 m, 5 m, and 10 m, the first diffraction order will be located 1.09 m, 5.095 m, and 10.19 m.

5.7.3 Polarizer Selection

Below is the part selection process that was used for the polarizers in our project before ultimately deciding to pursue another method of beam steering.There are two main form factors for absorptive polarizers: a lens or a film. When a polarizer is in the form of a lens, have a film on the surface of optical grade glass. Both forms that a polarizer can take can be rotated 90°. There are several advantages and disadvantages to each form factor of the polarizer that must be considered before selecting which should be implemented in the design.

Polarizer selection				
Name	**Thickness**	**Dimensions**	**Extinction Ratio**	**Price**
LPVISE050-A	2.1 mm	⌀ 12.7 mm	1000:1	$89.09

Polarizer Lens				
WGF HC11N Wire Grid Polarizing Film	0.08 mm	12.5 x 12.5 mm	4250:1	$45.00
LPVISE2X2 polarizing film	0.3mm	50.8 x 50.8 mm	1000:1	$9.54

Table 23: Polarizing Filter Specification Comparison

5.7.3.1 LPVISE050-A Polarizer Lens

The LPVISE050-A Polarizer lenses found on THORLABS have a polarization efficiency of 99% or about a 1000:1 extinction ratio for light in the 500-700 nm wavelength. These types of polarizers are known to be sensitive to stress when mounting it to an optical system. This sensitivity could lead to a reduced polarization efficiency, allowing more light to be transmitted through it at any orientation. The composition of the polarizer being optical grade glass means that the price is rather expensive, costing $89.09 excluding tax and shipping. This design would have required three polarizers that are mounted by a motor to change the orientation of polarization, making polarizers that utilize optical grade glass too expensive.

5.7.3.2 WGF HC11N Wire Grid Polarizing Film

Alternatively, the absorptive polarizer can take the form of a thin square sheet of film. The Wire Grid Film (WGF) HC11N wire grid polarizing film that is found on Edmund Optics is an optical component that comes in a thin sheet. This polarizing film has an extinction ratio of 4250:1 for wavelengths of light in the 400-1200 nm range. Because this polarizing film utilizes a wire grid design, it will reflect light that does not have the proper polarization while transmitting light that does. This enables the polarizer to act as a polarizing beam splitter. The film has a thickness of 0.08 mm with the dimensions of 12.5 x 12.5 mm, making this component on the smaller side and would limit the size the waist of the laser can be expanded. The wire grid of this polarizer is exposed and could sustain damage, affecting the performance of the component. This component is sold at the price of $45.00 per sheet not including tax and shipping. The Smart Laser Toy for Cats will require multiple polarizers that are large enough to block the transmission of the expanded laser beams, meaning; this component was too expensive for the dimensions. The film can be bought in larger dimensions. However, the price point rises as well.

5.7.3.3 LPVISE2X2 Polarizing Film

The LPVISE2X2 polarizing film that is found on THORLABS has an extinction ratio or 1000:1 for light that is found in the 500-700 nm range. Unlike the lens polarizers, polarizing film is not sensitive to stress when mounting and can even cut to a custom size and shape. Polarizing film has the potential to slightly diffuse the light that is transmitted through it and will not maintain the collimation of large input beams. The price for a 2” x 2” sheet of LPVISE2X2 polarization filter can be purchased on THORLABS for $9.54.

At this price point we are able to purchase multiple sheets for a fraction of the cost of the lens polarizer. However, since the diffraction grating was not used in this device, this polarizer was not chosen for this design.

5.7.4 Prism Selection

By utilizing the property of refraction of light through a prism, the group was able to accomplish beam steering in a way that would entertain a cat. Due to the diverse form factors of prisms, a laser can be manipulated in multiple different directions. Several prism geometries have shown characteristics that could prove useful to the design.

Prism Comparison			
Prism	**Prism Type**	**Angle of Deviation**	**Dimensions**
1° Commercial Grade Wedge Prism	Wedge Prism	1°	3.00 mm thick
N-BK7 Right-Angle Prisms, Uncoated (350 nm - 2 µm)	Right Angle	90°/180°	3 x 3 x 3 mm
Round Wedge Prisms, 6° Beam Deviation	Wedge Prism	6°	8.11 mm thick

Table 24: Prism Specification Comparison

5.7.4.1 2° Commercial Grade Wedge Prism

The company Edmund Optics sells a wedge prism on their website that will deviate a laser beam that is incident on its surface by 2°. The prism consists of N-BK7 optical grade glass and an optical power of 1.74 diopters. The prism is coated with a material that enables it to operate with light in the 400-700 nm range of light. Because this component is a wedge prism, a second identical prism can also be added so that the laser beam can be steered into several different patterns of varying complexity by rotating them. The prism can be acquired for $24.95 per unit before shipping and tax. For this prism to operate, a specialized mount will need to be sourced that enables the rotation of the lens without impeding the path of the incident laser beam.

5.7.4.2 N-BK7 Right-Angle Prisms, Uncoated (350 nm - 2 µm)

This right-angle prism can be found on THORLABS website and consists of N-BK7 optical grade glass. Due to the prism's geometry, it can utilize the principle of total internal reflection to deviate the laser beam by either 90° or 180° depending on which surface that it is incident on. While deviating the laser beam by 90° would not be useful for our design as it would result in a play area that is too large when rotated, deviating it by 180° has a major benefit. This is because the laser would need to reflect off two of the internal surfaces of the prism and would be displaced a distance from the incident beam. This would mean that a simple motor can be placed behind the prism and manipulate the laser beam without concern of it blocking the optical axis. We would only need one of these prisms from our design and can purchase one for the price of $42.51 per unit.

5.7.4.3 Round Wedge Prisms, 10° Beam Deviation

This prism is a wedge prism that can be found on THORLABS website and consists of N-BK7 optical grade glass. Due to the geometry of the prism, the laser light that is incident on its front surface will be refracted by 10°.The prism is uncoated and can operate with light in the 400-700 nm range of light. The prism has a diameter of 25.4 mm and a thickness of 8.11 mm. As stated with the previous wedge prism, we can rotate the component to trace a circle around the optical axis, or add a secondary prism to create more complex patterns. For this design we would at most require two and each individual wedge prism can be acquired for $40.09. A special mount would be needed to rotate this component without the motor impeding the path of the laser beam. This prism was ultimately chosen for our device as it would allow for satisfying beam movement at a reasonable price point.

5.7.5 Lens Selection

As stated before, the laser system in this design would require the laser beam to be expanded to dimensions large enough for us to utilize a stencil of an image. Once the group had decided on which method we would pursue to expand the laser beam, the next step was to determine the dimensions of the laser to determine the scale that the beam needs to be extended. Through testing of the VLM-650-03 LPT, it was found that the diode's spot size is an ellipse that is about 4 mm and when measuring the shorter end we found that it was about 2 mm. For the purposes of the design goals, it could be imagined as a 2x3 mm rectangle spot size and proceed with calculating the spot size for various magnifications. While there are optical beam expanders that can be purchased commercially that can adjust the magnification of the system, they are too expensive to be utilized in this design. How much the beam can be expanded is also determined by the focal lengths of the lenses in the system and can be expressed in the following equation.

$$m_{12} = \frac{f_2}{f_1}$$

Equation 13: Beam Expansion Ratio

Where f_1 and f_2 is the focal length of the first and second lens respectively. The lenses that can be utilized in a galilean beam expander can be any combination of biconcave, biconvex, plano concave, and plano convex lenses. In this design, we utilized plano concave and convex lenses as they are known to reduce spherical aberrations.

Galilean Beam Expander Comparison

Magnification	Lens	Focal Length	Distance Between Lenses	Price
2x	LC1054	-25 mm	25 mm	$44.69
	LA1131	50 mm		
	48-678	-15 mm	15 mm	$54.25
	45-085	30 mm		
3x	LC1054	-25 mm	50 mm	$44.24
	LA1608	75 mm		
	48-678	-15 mm	30 mm	$54.25
	49-879	45 mm		
4x	LC1054	-25 mm	75 mm	$43.43
	LA1509	100 mm		
	48-678	-15 mm	45 mm	$54.25
	45-435	60 mm		
5x	LC1054	-25 mm	100 mm	$43.43
	LA1986	125 mm		
	48-678	-15 mm	60 mm	$55.25
	32-479	75 mm		

Table 25: Lens Magnification Comparison

5.7.5.1 2x Magnification

With 2x magnification the group would have a laser spot size of 4x6 mm rectangle which would be able to produce a simple image or pattern with a stencil. To achieve this magnification the group needed to find a combination of lenses whose focal length has a ratio that equals 2. The first lens needed would be one with a negative focal length to refract the light making it the plano concave lens in the system. For the case of the Smart Laser Toy for Cats device design, it was decided to utilize the LC1054 plano concave lens found on THORLABS. This lens consists of N-BK7 optical grade glass, has a focal length of -25 mm, a thickness of 4.7 mm, and the face has a diameter of ½”. To determine the corresponding plano convex lens we manipulated equation 13 and took the multiple of -25 mm and 2 to find that we needed a focal length of 50 mm. The LA1131 plano convex lens found on THORLABS has this focal length with a diameter of 1” and is made of N-BK7 glass. With this combination of these lenses the group calculated the distance they should be spaced by taking the sum of their focal lengths and found that it should be a distance of 25 mm.

If the goal were to achieve 2x magnification while reducing the distance between lenses, lenses with different focal lengths needed to be found. While it was desired to reduce the distance between the lenses as much as possible, space for both the mounts and motors that are utilized in this design must still be left. The first lens in the system would be the 6.0mm Dia. x -15 FL, Uncoated, Plano-Concave Lens found on Edmund Optics, which has a focal length of -15 mm, a diameter of 6 mm, and is made of N-BK7 optical grade glass. While Edmund Optics does offer plano concave lenses that have focal lengths as low as -6 mm, we were avoiding this option because spherical aberrations increase with shorter focal distances. We took the focal length of the lens and equation 13 to find the focal length of the plano convex lens needed to achieve the desired magnification, finding it to be 30 mm. We intended to use the 12.0mm Dia. x 30.0mm FL Uncoated, Plano-Convex Lens, which has a focal length of 30 mm, a diameter of 12 mm, and is made of N-BK7 glass. With this lens combination it was found that the distance between the lenses is 15 mm, which is roughly half of the distance as the other 2x magnification configuration.

5.7.5.2 3x Magnification

When the beam spot size of the laser was multiplied by a factor of 3, the new dimensions calculated were that of a 6 x 9 mm rectangle. Similar to the 2x magnification, we utilized the same plano concave lens with the focal length of -25 mm because it is easier to find lenses with focal lengths in multiples of 5. The same approach as before was taken with equation 13 to find the focal length needed to achieve the desired magnification and found it to be 75 mm. The LA 1608 plano convex lens has a 75 mm focal length with a diameter of 1” and is made of N-BK7 optical grade glass. Taking the sum of these focal lengths to find the spacing of the lenses, the distance is 50 mm.

To reduce the distance between lenses, the same approach was as before utilized with shorter focal lengths. The 6.0mm Dia. x -15 FL, Uncoated, Plano-Concave Lens we used before for 2x magnification, can be used again in this scenario. Equation 13 and the focal length of the initial lens were then used to find the required focal length of the corresponding plano convex lens. Doing this, we found that the focal length we need is 45 mm and the 15.0mm Dia. x 45.0mm FL, Uncoated, Plano-Convex Lens fits this criteria. We then found the distance between lenses by taking the sum of the focal lengths, finding it to be 30 mm. With this spacing, the group can achieve the magnification. However, there is an increased chance of spherical aberrations. With this configuration, the group can reduce the distance between lenses by 20 mm.

5.7.5.3 4x Magnification

A 4x Galilean beam expander would have a new laser spot size that can be visualized as a 8 x 12 mm rectangle, which would be able to produce a large enough image to create a significantly more complex animal. Like the previous magnifications, the group utilized the LC 1054 plano concave lens for the first lens with a negative focal length of -25 mm. The group then used equation 13 to find the corresponding focal length needed to achieve 4x magnification, and found that it is 100 mm. It was found that the LA1131 plano convex lens has a focal length of 100 mm and a diameter of 1” which could be utilized for this magnification. With this lens combination, the distance between lenses can be calculated by taking the sum of the focal lengths and finding that it is equal to 75 mm.

To achieve 4x magnification while also reducing the spacing between lenses, the group utilized the same approach as before. The 6.0mm Dia. x -15 FL, Uncoated, Plano-Concave Lens that was used before as our initial lens is used again as it is the shortest distance for focal length that we can select before spherical aberrations become a concern. Using the focal length of the initial lens and equation 13, it was found that the focal length of the plano convex lens needed for this magnification is 60 mm. The lens found that fulfills these conditions is the 15.0mm Dia. x 60.0mm FL, Uncoated, Plano-Convex Lens with a focal length of 60 mm, a diameter of 12 mm, and is made of N-BK7 optical grade glass. The spacing between the lenses in this configuration of lenses was calculated with the same method as before to find that it is equal to 45 mm. Comparing the spacing between lenses needed for both 4x magnification lens configuration, it can be seen that this second design reduces the distance by 30 mm.

5.7.5.4 5x Magnification

At 5x magnification, the beam spot that would be incident on the lens system would be expanded to the dimensions of 10 x 15 mm rectangle, which is ample enough of a size for a cat to see while moving rapidly. The same negative focal length of -25 was used and like the previous magnifications, the group utilized the LC 1054 plano concave lens. Utilizing equation 13, the necessary focal length to achieve 5x magnification was calculated, and it was found that it is equal to 125 mm. The LA1986 plano convex lens found on THORLABS has a focal length of 125 mm and a diameter of 1” and can be utilized for this beam expander design. The distance that the lenses must be spaced to achieve the desired magnification was calculated to be 100 mm. The distances between the lenses can be seen increasing by 25 mm, and will continue to so long as we continue to utilize the same plano concave lens. To keep our design portable, the group cannot afford to continue to use the same initial lens if further magnification is needed.

To reduce the distance between the lenses one can begin by selecting the initial plano concave lens with a negative focal length. For this purpose, the 6.0mm Dia. x -15 FL, Uncoated, PlanoConcave Lens found on Edmund Optics is utilized. The focal length of this lens and equation 13 is then used to find the necessary focal length to achieve this magnification, finding it to be 60 mm. On Edmund Optics, it was found that the 25.0mm Dia. x 75.0mm FL Uncoated, Plano-Convex Lens has the correct specifications of 75 mm focal length, a diameter of 25 mm, and is made of N-BK7 optical grade glass. The spacing between the lenses was calculated by taking the sum of the focal length, finding it to be equal to 60 mm. Comparing the spacing between the lenses for both 5x magnification configurations, it is found that this configuration reduces the spacing by 40 mm.

For the design of the Smart Laser Toy for Cats, the spot size would need to be expanded large enough so that it can be seen by a cat while moving at a rapid speed. As stated before, the largest limiting factor for the entirety of the laser system is the spacing between the lenses. With this in mind, it can be seen that either lens configuration achieving 5x magnification would be the ideal option for beam expander. Taking a look at both of the lenses, the difference in lens spacing is reduced by 40 mm. As the magnification for both lens combinations is the same, the spacing between the lenses could cause more spherical aberrations and required testing before fully understanding how that affected the laser system.

5.7.6 Optical Mount Selection

The optical mounts that can be purchased online can take many different forms such as fixed and adjustable mounts. The mounts that can be purchased online range in price depending on the complexity of the mount with fixed mounts being the cheapest option. On the THORLAB website, we found a pair of fixed lens mounts that can be used to hold the lenses for the lenses in the beam expander. These mounts are made for specific lens diameter however the price of the product is consistent with all diameters at $16.58. The more complex optical mounts such as the adjustable lens holder serve the same function of the fixed lens mounts with the added benefit of adjusting the diameter of the lens that can fit in the mount, enabling us to purchase multiple identical mounts to hold different sized lenses; however, the price of one of these mounts is about $50 per mount. The Risley pair could also be placed on the optical axis by using the adjustable mount; we would not be able to automatically rotate the prisms. To do this the group would need to utilize an optical mount with the integrated servo motor to mount and rotate the prisms; however, the price of one of these mounts is in the price range of $700-$1000, making it prohibitively expensive.

If the group were to 3D print the mounts that are needed for our design, the group would be able to mount the lenses with the same effectiveness as the mounts sold by optics companies for a fraction of the price. As the 3D printed lens mount can take similar forms to the lenses that can be purchased online, they could also be designed to look drastically different from traditional mounts, which would simplify the components needed for the device to function. For example, the biggest challenge of the implantation of the galilean beam expander would be the precise alignment of the lenses on the optical axis, and because the lenses we are using have drastically different diameters, the group would not be able to place them into an optical tube that keeps lenses of the same size inside of it aligned. However with 3D printing, it is possible to print an optical tube that shifts in diameter from one end to the other, in order to mount both lenses with different diameters inside of it with no problem. From this it can be seen that instead of needing a mount and stand for each lens in the galilean beam expander, one 3D optical tube and a stand to hold the components can be used. The same approach can be utilized to mount both of the wedge prisms inside a 3D printed optical tube with grooved band around the outside. The group can then utilize a motor that is placed either under or off to the side of the optical prisms with 3D printed gear that is meshed with the ridges on the optical tube. This would enable the rotation of the prism at the same speed and direction to achieve 4° beam deviation while only using one mount and one motor. For 3D printing optical mounts, a computer file with the proper dimensions are required, and can be found on open source file websites.

From all of this, it can be clearly seen that although store bought optical mounts function extremely well for their intended purposes, they are too expensive and would require an amount for each specific component to function. We decided to 3D print the mounts because we would be able to mount the lenses securely to the optical axis while designing in a way to reduce the amount of required components in the device. In the case of the wedge prisms, there was no choice but to 3D print our mount as it would be too expensive to purchase one that has an integrated motor for rotation. For this reason it has been decided to utilize 3D printed mounts that we designed ourselves.

6 Design Constraints and Standards

The following sections list the design constraints and standards of the Smart Laser Toy for Cats.

6.1 Design Constraints

The purpose of this section is to detail the constraints related to the Smart Laser Toy for Cats that impacted the design process, build schedule, and other areas. Ensuring that these constraints are understood and acknowledged enabled the successful completion of the device for the market.

6.1.1 Economic Constraints

On the current market, automated laser cat toys can range anywhere from \$6.99 to \$39.99. However, further inspection of the devices revealed that they are automated but cannot differentiate between different types of animals, nor present different patterns on the wall or floor. The devices only have a randomized point moving around. The original budget for the design was approximately \$150, it increased due to high costs of lenses and other products. Although the budget allocated for the design is much higher than the current market prices, the design created has features not currently found on the market. Features like app integration, pet differentiation, and laser patterns make the product different from current automated cat toys.

Alongside enhanced features, the device was funded out-of-pocket. This caused the budget for the Smart Laser Toy for Cats to be more constrained and less expensive options were opted for. Options such as library rentals, 3D printing, and items previously owned by group members were used whenever possible. Lastly, to ensure that all purchased materials were accounted for and transparent within the group, a bill of materials was used to keep track of purchases to ensure the device remained in budget and funding was a shared responsibility.

6.1.2 Time Constraints

A major constraint in both the design of the device and gathering of the materials was time. The build and demonstration of the device had a strict timeline created by University of Central Florida professors in the College of Engineering and Computer Science, alongside the College of Optics and Photonics. In Senior Design I, the Photonic Science and Engineering students performed a midterm demo eight weeks into the semester, and a final demo fourteen weeks into the semester. These demos demonstrated working optical systems that were integrated into the design of the final product. The tight timeline of the demos led the team to account for early ordering of supplies to account for possible delays and ensure the design of the device was accurate to not order more items than necessary. Scheduling as a group was also a time constraint due to the limitations every individual had with class schedules and work schedules. As a group, it was decided to meet once a week to update progress and address any concerns regarding the design process. Overall, the timeline of the two-semester senior design course and individual schedules of each group member led to a couple time constraints to deliver a final, working device.

6.1.3 Social and Political Constraints

While social constraints may not be the most prominent of all the constraints, there are some factors involved that directly impacted the scope of the design and device overall. The Smart Laser Toy for Cats targets consumers with an active or busy lifestyle, consumers who work from home, and consumers with physical limitations or constraints that reduce their hand mobility.

For the consumers who live a very active and busy lifestyle, the device must be plugged in. The device has an AC adapter so that it can receive power. While, this device has one of the target audiences to be those with busy lifestyles, if the device is not plugged in, it will not power on and therefore it can not be used for the cat. A large constraint for the consumer is to always ensure it is connected to power, since the ability to use it with a rechargeable battery is a stretch goal. It is also in the user's responsibility to ensure the cat is playing with the device as the laser moves. If the integrated or chosen setting for the laser display is not preferred by the cat, the cat may not even be using it. Being distracted in a work from home setting, or not being in the house due to busy scheduling, can prohibit the owner from knowing that the cat is not using the Smart Laser Toy for Cats as intended. The pet owner will need to ensure that the correct laser display is being used for the cat's preference.

For the consumers who have hand mobility restrictions and limitations, a large constraint will be their ability to plug in the device and use the integrated app to control the device. While the device is motion sensored and is aimed to have little to no human interaction to power on, there may be time that troubleshooting may be needed, as with any electrical or automated device. This can include anything from plugging in the device, powering it on, or manually shutting it off. With hand mobility restrictions, this could present a challenge and outside help may be needed to assist with these constraints.

After careful consideration of political constraints the Smart Laser Toy for Cats imposes on the consumers, it was determined that there are no political constraints that apply to the scope of the design or use of the device.

6.1.4 Ethical, Health, and Safety Constraints

The Smart Laser Toy for Cats has several ethical, health, and safety constraints to consider since the device interacts with cats and the pet owners may also use the device to configure it.

The main component of the Smart Laser Toy for Cats is the laser that is used to motivate the cat to interact with the toy, this poses many safety constraints in regards to eye safety for the cat and any other pets or humans who may be in the line of sight of the ray. To mitigate the risks associated with laser use, the device will be using an eye-safe, Class 3A laser to comply with laser safety standards and prioritize ocular safety. Alongside eye risks is also the LED lights used for the passive infrared motion sensor and LED collar tag. Like the laser, the device follows LED safety standards to mitigate any and all risks associated with the use of LEDs in a device interacting with animals and humans.

Another component considered with the health and safety of the pets and humans, was fire safety hazards associated with the use of electrical components in the device. To mitigate the risk of an electrical fire, the device is enclosed in an enclosure that vents air well and reduces water from entering in the event there is liquid near the device. The design of the enclosure and wiring within the device was carefully considered to reduce fire risks. Furthermore, the collar tag will not be within the device, and therefore the tag is at a minimum, water-resistant to prevent the LED from damaging to protect the safety of the pet since they will be wearing it around their neck.

A large ethical consideration was the privacy protection of the user since a mobile application will be created to allow cat owners to interact with or configure the device without being physically present in the room. Since there is pet information on the application, a goal of the design was to include password protected user profiles so that if the mobile device is misplaced by the owner, the application cannot be used by anyone other than the owner.

6.1.5 Manufacturability Constraints

The Smart Laser Toy for Cats has many working components that were designed and built by the members of the group. This led to purchasing smaller components that were integrated into the design and working elements of the device. Factors such as supply-chain issues, shipping times, and material resources were considered when taking manufacturability constraints of the device into account.

To mitigate potential supply-chain and shipping issues, the group pre-ordered components that were integrated into the design of the device in the first semester of the senior design course sequence to ensure that they were available when the build of the Smart Laser Toy for Cats began in the second semester of the sequence. The University of Central Florida also had resources available to students that were considered to reduce costs of materials associated with the build and so shipping times or supply-chain issues were not a problem.

Material resources were also a constraint that was considered. The enclosure of the device was designed in SolidWorks and built using wood because it is safe to harness electrical components since the electrical components may generate some heat while the device is being used. Material resources were a constraint because there is an ongoing wood shortage.

6.1.6 Sustainability Constraints

The materials and items used in the design and build of the Smart Laser Toy for Cats were chosen and manufactured for longevity. The goal of the end result was to provide a device that is able to be used for several years without issues arising from the mechanical, electrical, optical, or software design of the device. Sustainability constraints considered were choosing materials and components that would ensure productivity continues after pet interactions, accidental spills on or near it, and accidental drops of the device while owning the toy.

During the design and build of the Smart Laser Toy for Cats, factors like quality of material selection, component purchase and design of the enclosure were being carefully considered to mitigate factors that could reduce the lifespan of the device while in use. The group wanted to produce a device that is sustainable for busy lifestyles and people with hand mobility restrictions. Alongside the overall lifespan of the device, by using materials and components of good quality reduced waste and repair costs for the owner and manufacturer.

6.2 Standards

The purpose of this section is to list the standards that were followed in the build and design of the Smart Laser Toy for Cats. This ensures the safety of the users who interact with the design, which wass a major goal of the project.

6.2.1 IEEE Bluetooth Standard 802.15.1

Since a significant part of the senior design project depends on bluetooth connectivity the standard that acts as the glue to our entire ecosystem is the bluetooth communication system. The standards that apply to the group's project are IEEE 802.15 and the Bluetooth Core Standard. From these documents, the technical requirements were discerned, along with guidance on potential design constraints that impact functionality and compatibility.

At a glance, IEEE 802.15.1, is simpler and more straightforward, it is for these reasons the group chose to use IEEE 802.15.1 as a reference to understand how the bluetooth physical layer, baseband, MAC function. While Bluetooth Core Standard is more recent to off the shelf market technologies and is a more detail oriented explanation, it's evident that the Bluetooth Classic's core functions and requirements have not changed significantly over the years. Because the core principles of the transmitter and receiver designs remain relatively unchanged,it is more useful to use the IEEE 802.15.1 standard to understand bluetooth and used it as a guide to right design requirements to pick out off the shelf bluetooth transceivers for our design.

The IEEE standard details the requirements for transmitters. The first relevant are the class power requirements for the antenna. It is important to note that there are three primary power classes: 20 dBm, 4 dBm, and 0 dBm. For the project design, which prioritized a reliable connection up to 10 feet, the second class, operating at 4 dBm, emerged as the optimal choice. Given that Bluetooth technology is inherently designed to facilitate connections over a range of approximately 10 meters (roughly 30 feet), the group's part selection provides a significant margin. This ensures a stable connection even if there are potential interferences or real-world constraints that might compromise range. The second reason that class 2 requirement for an antenna was chosen is that according to the IEEE standard class 1 receivers require received signal strength indicators. This adds another layer of complexity to the design of the receiver which would add cost. These are two examples of how the institute of electrical and electronics engineers 802.15.1 document helped us verify design requirements.

The second system that the IEEE 802.15.1 standards document helped us understand was the characteristics that the receiver should have. The main characteristics of a receiver are its sensitivity and noise suppression. Most of the noise suppression is done using the inherent signal processing characteristics. However, one interesting characteristic of bluetooth wireless receivers is that the required sensitivity of the antenna is negative 70 decibels per milliwatt, or negative 70 dBm.

Like most digital receivers every Bluetooth device is equipped with an internal system clock, which is fundamental in governing its data transfer timing and hopping sequences. This clock is derived from a consistent, unadjusted native clock that always remains on. The uniqueness of the Bluetooth clock system lies in its synchronization method: rather than direct synchronization, devices synchronize by adding offsets to their native clocks. However, this synchronization is temporary. Given the free-running nature of native clocks, offsets need regular updating to maintain synchronization. Synchronization is an important characteristic that maintains proper communication between the controller device and the listener device. It is an important characteristic to look for in a bluetooth module or transceiver which allows us to understand if the part we will buy is going to perform in the necessary way to maintain a good connection.

It's worth noting that the Bluetooth clock doesn't correspond to real-world time. In terms of specifications, it uses a resolution of at least 312.5 µs and operates at 3.2 KHz.

When multiple Bluetooth devices come into close proximity, they form a mini network, known as a piconet. Within this network, one device takes on the role of the master, setting the tone for timing and frequency hopping. For seamless communication, slave devices adjust their clocks based on the master's clock which is shared with them. It's essential to recognize the significance of specific Bluetooth timings—312.5 µs, 625 µs, 1.25 ms, and 1.28 s—as they are the backbone of data transfer processes. For instance, the master-to-slave data transmission initiates during specific slots, defined by these timings.

For a project like a Bluetooth-connected cat toy, understanding these nuances is paramount. Whether the toy or the app assumes the role of the master, synchronization is key. Being well-acquainted with these timings and synchronization processes not only facilitated smooth communication but also assisted in troubleshooting and refining any potential delays or issues.

6.2.2 IEEE/ANSI C63.4-2014

The standard C63.4-2014 is a standard about EMC. EMC is electromagnetic capability. Electromagnetic capability is another term for how much energy is radiated by wires when they conduct electricity. EMC standards pertain to the interactive cat toy project. The cat toy heavily relies on radiation mechanisms to provide entertainment and communications. These radiation mechanisms are bluetooth and a laser that changes shape. Furthermore, high frequency transients occur during the switching phase of switched mode power supplies.

The standard C63.4-2014 is a standard about EMC. EMC is an acronym for electromagnetic capability. There are three parts of our system that have the potential to radiate energy. The three parts are the bluetooth communication system, the laser system, activation system, and the power system. The bluetooth communication system had the largest potential to provide EMC problems.

The reason why the bluetooth communication system presented this problem is that the bluetooth communication system is a radio system that has a specific frequency. Since all transceivers which are essentially radio systems rely on radiative transfer of energy using antennas it is actually radiating and therefore we need a criteria to select parts that provide appropriate EMC levels. The problems that come from EMC non-compliance are after this.

The second system that has the potential to cause EMC problems is the laser system. This system is also a system that uses the radiative transfer of energy to send high energy photons that emit light. This light emission may cause noise, electromagnetic interference, and electromagnetic compatibility problems with nearby sources that also rely on radiation as a mechanism of energy transfer or information transfer to function. An example of this is turning on a microwave next to a cell phone. The microwave if it is not properly shielded will radiate and disrupt the bluetooth signal since they are at the same frequency. While it is unlikely something like this will happen. The guide provides us with a benchmark for understanding how the laser system may affect other systems around it. The third system that could have EMC problems is the power supply system. The power supply system will use a combination of switched mode power supply's either boost or buck converters. Both of these converters rely on switching and during that time high frequency transients occur on the power lines. These high frequency transients are small in amplitude but we need to make sure that none of the noise that inadvertently will be introduced to the system will cause EMC problems.

The first reason that EMC is such a large problem that must be accounted for in our design is noise. The size of our system has to be small. Since our system needs to be small to be convenient any high frequency transients that occur have a huge potential to cause noise. This noise can disrupt the function of the receiver in the bluetooth system, the laser, the laser diode activation, the printed circuit board, and the memory within the printed circuit boards microcontroller.

The second reason that EMC/EMI needs to be considered in our design is parts selection. In the last paragraph we discussed noise and how the potential it has to affect various parts throughout our board. The standards provided by C63.4-2014 will give us a benchmark that helps us pick parts that can handle any noise or electromagnetic interference that will be produced.

The third reason the EMC/EMI needs to be considered in our design is that it gives recommendations on how to minimize EMI/EMC through proper circuit design and layout design. The institute of electronic and electrical engineers and American standards institute guide C63.4-2014 provides shielding techniques and grounding techniques to prevent electromagnetic interference and electromagnetic capability.

6.2.3 LED Safety Standards

LEDs were used in the construction of the Smart Laser Toy for Cats. LEDs are commonly used light sources in modern appliances that are being integrated in current products or replacing older light sources in products already in the consumer market, like household lighting fixtures. Nonetheless, there are safety precautions accounted for in the use of LEDs within appliances and products, especially for the ocular safety of the pets interacting with the toy.

For the design of the Smart Laser Toy for Cats, traditional IR LEDs and RGB LEDs are used. These are considered to be a safe light source and do not pose hazards to the eye of any potential pets and humans interacting with the toy. In the scope of this project, low risk LEDs were used, otherwise known as an “exempt group”. IEC/EN 62471 Eye Safety standards categorize the risk groups as the following:

Risk Group	Philosophical Basis
Exempt	No photobiological hazard
Group 1 (Low-Risk)	No photobiological hazard under normal behavioral limitations
Group 2 (Moderate-Risk)	Does not pose a hazard due to aversion response to bright light or thermal discomfort
Group 3 (High-Risk)	Hazardous even for momentary exposure

Table 26: Risk groups based on the emission limit and permissible exposure time

Due to animal and human exposure being involved within the scope of this project, only exempt group LEDs will be utilized to comply with LED safety standards in accordance with IEC/EN 62471. The permissible exposure time for an exempt group is approximately 10,000 seconds, which is equivalent to 2.8 hours. It is not anticipated that the cat will be playing with the device for several hours given the activeness of pets. Therefore, the use of the IR and RGB LEDs pose little to no threat to the photobiological safety of humans and pets interacting with the device.

6.2.4 Laser Safety Standards

When choosing a laser diode it was important to decide the beam wavelength and power output. For the wavelength of light that is emitted from the laser, it was important to choose a wavelength that is both safe for cats eyes and can be easily seen. Like humans, cats are sensitive to the green color wavelength (495 nm - 570 nm), but they lack sensitivity to interpret wavelengths at higher and lower ranges. While this does mean that a cat’s eye can resolve green light best, it is also more hazardous to them. This is because the color detecting cones found in their eyes are more sensitive to the yellow-green wavelengths of light. The light of an extremely low power green laser could harm a cat's eyes if it was to look into the beam more than a red laser of higher power due to this sensitivity. Commercial cat laser toys tend to emit a beam that is red (650 nm -700 nm) despite that color being difficult for cats to see. This is due to the movements of the laser dot that is produced causing cats to perceive it as small prey. For the power output, it is important that the laser is not powerful enough to cause damage to the eyes

The United States Food and Drug Administration (FDA) is the agency that is responsible for regulating laser products, and has an established system to determine how hazardous a product is. While the FDA's safety classification is meant with human eyes in mind, it can also be used as a guideline for cat laser toys. According to the FDA's system, lasers that are hazardous to human eyes when looked at directly over a long period of time are classified as class II/IIa with a power output limited to less than 1 mW. Class III/IIIa lasers can be hazardous when viewed directly faster than class II, they still present a low risk of injury and have a power output of 1-5 mW. Commercial cat laser toys tend to have a power output ranging from less than 1 mW to 5 mW, or can be classified as class II and III lasers. With that in mind, the laser diode that was chosen for this design does not exceed 5 mW of power.

Class FDA	Class IEC	Laser product Hazard	Product Examples
I	1, 1M	Considered non-hazardous. Hazard increases if viewed with optical aids, including magnifiers, binoculars, or telescopes	● Laser Printer ● CD Player ● DVD Player
IIa, II	2,2M	Hazard increases when viewed directly for long periods of time. Hazard increases if viewed with optical aids.	● Barcode scanner
IIIa	3R	Depending on power and beam area, can be momentarily hazardous when directly viewed or when staring directly at the beam with an unaided eye. Risk of injury increases when viewed with optical aids.	● Laser pointers
IIIb	3B	Immediate skin hazard from direct beam and immediate eye hazard when viewed directly.	● Laser Light Show Projectors ● Industrial Lasers ● Research Lasers

IV	4	Immediate skin hazard and eye hazard from exposure to either the direct or reflected beam; may also present a fire hazard.	● Laser Light Show Projectors ● Industrial Lasers ● Research Lasers ● medical device lasers for eye surgery of skin treatments

Table 27: FDA Laser Hazard Classification Table

6.2.5 Commentary on Standards for Pet Products

As the device is tantamount to a consumer product, relevant consumer standards for electronic and laser devices must be adhered to. Since the primary use is as a toy for cats, this obviously required considerations for the safety of the cats first and foremost. This immediately led to an interesting discovery: Outside of edible products such as food and treats, the United States has no universal safety standards or regulations on products for pets. This is obviously unacceptable in a toy as complex as ours, especially when a laser and/or lithium-ion battery are factored in.

Although there is no governance per se, some veterinarians have recommended considerations when shopping for pet toys. These include, but are not limited to:

- Does the toy meet the federal safety standards for (human) children's toys, ASTM-F963? Some pet toys are tested to this standard.
- Does the toy meet the State of California's Proposition 65 standards? This governs the presence or absence of harmful chemicals such as volatile organic compounds (VOCs).
- Does the toy immediately appear to be well-made and durable based on first visual and tactile impressions?
- Are there any parts that are sharp, jagged, or unnecessarily protruding that could injure a pet?
- Are there small parts that could be a choking or suffocating hazard if dislodged or released, such as polystyrene beads?

Although some of these criteria are subjective and perhaps a little too vague, they nevertheless gave a sense of what an educated consumer would expect from a quality pet toy.

7 Software and Hardware

The following sections describe the software and hardware development process to design and build the Smart Laser Toy for Cats.

7.1 Software Development Process

Software development refers to the process of planning, designing, programming, testing, debugging, and maintenance of software applications. At the fundamental level, software refers to a collection of instructions, data, and programs that enable a computer or a computing device to perform specific tasks or functions. The software development process refers to a systematic and structured approach to software development. There are many different methodologies developers choose from, but the key aspects remain the same:

- Understand the project requirements
- Design a blueprint for the software
- Build a model for prototyping and simulation
- Code in the appropriate language
- Conduct testing
- Deploy to production environments
- Conduct maintenance
- Create comprehensive documentation
- Ensure the project stays on schedule

The software development process is critical for creating high-quality, reliable software that meets the needs of users while maintaining efficiency and effectiveness in development efforts. It is important to note that it is possible to combine multiple methodologies when working on a project. Combining methodologies offers various benefits, like improved adaptability to project needs and efficient resource allocation.

7.1.1 Different methodologies

The existence of multiple software development methodologies is beneficial because of the diverse nature of software projects. Each software project encompasses unique sets of requirements, timelines, and complexities. One methodology may excel in a certain context but is unsuitable in another. It is also important to note that team dynamics may be a big influence when it comes to choosing the methodology, or methodologies, for a project. Having a variety of different methodologies allows developers and project managers to choose the best approach based on the project requirements. Some of the most popular software development methodologies include: Agile, Waterfall, Lean, and DevOps.

7.1.1.1 The Agile Methodology

The Agile Methodology emphasizes customer feedback and the ability to respond to requirement changes and any stage of the development process. It is a flexible and iterative approach to software development that prioritizes collaboration, adaptability, and delivering incremental value to customers. It breaks down the project into smaller, more manageable chunks, called sprints, that generally last 1 - 4 weeks. After each sprint, teams reflect to see if there is anything that can be improved and adjust their strategy for the next sprint. Regular feedback loops, daily stand-up meetings, and continuous improvement through retrospectives are integral to Agile. It also promotes transparency, self-organization, and a customer-centric mindset. This approach allows for faster and more frequent deliveries, enhancing the project's flexibility and alignment with evolving customer needs.

Scrum is an Agile methodology that prioritizes flexibility and adaptability in the software development process. It gets its name from an important component in rugby. During a scrum, rugby players work with their team to move the ball forward. Similarly, during a scrum the software development team works together to move their product forward. Like Scrum, Kanban is another popular approach rooted in agile methodology. Kanban focuses on visualizing work, managing workflow, and optimizing productivity. In Kanban, tasks are represented as cards on a board, each column representing a specific stage of the workflow. This allows for teams to easily visualize the progress of the project and allocate resources accordingly. A hybrid of Scrum and Kanban, Scrumban combines the flexibility of Kanban with the structure of Scrum. This approach allows for teams to benefit from Scrum's iterative approach while maintaining the flexibility to adapt the workflow.

7.1.1.2 The Waterfall Methodology

The Waterfall Methodology follows a linear software development approach. As the name suggests, it is characterized by its sequential progression through predefined phases, mimicking the flow of a waterfall. Unlike Agile and other iterative methodologies, Waterfall follows a strict, one-directional flow from requirements analysis, design, implementation, testing, deployment, to maintenance. This makes the Waterfall methodology perfect for projects that have clear and stable requirements. Each phase is meant to flow seamlessly into the next, so there is no way to continue to the next phase without the deliverables of the previous and current phases. This results in an emphasis on thorough documentation and planning. This approach allows for a comprehensive understanding of the project scope and requirements before moving forward. However, because of its rigidity, it is challenging to accommodate any changes in requirements or adapt to any unforeseen issues once a phase is complete.

7.1.1.3 The Lean Methodology

The Lean Methodology in software development is a unique approach focused on optimizing efficiency and minimizing waste throughout the development process. It draws inspiration from lean manufacturing principles, aiming to create value for the customer while eliminating unnecessary steps and resources. What sets Lean apart is its emphasis on continuous improvement, empowering teams to regularly assess their processes and make adjustments for enhanced productivity and quality. This methodology prioritizes delivering a Minimum Viable Product (MVP) quickly to gather feedback and iteratively refine the product. Additionally, Lean promotes a culture of collaboration and cross-functionality, encouraging teams to work together seamlessly, share knowledge, and remain adaptable to changing requirements. Placing a strong emphasis delivering value and reducing waste allows Lean to stand out as an efficient and customer-centric development process.

7.1.1.4 The DevOps Methodology

The DevOps methodology is a transformative approach in software development that combines software development (Dev) with information technology operations (Ops). This methodology emphasizes a feedback-driven iterative process, encouraging teams to learn and improve continuously. It aims to shorten development cycles and accelerate the delivery of software through continuous integration, delivery, and monitoring, as well as automation. DevOps ensures that both development and operations are aligned with business objectives, leading to faster deployment, quicker feedback loops, and the ability to respond swiftly to changing requirements. DevOps encourages learning from failures and using them as opportunities for growth and enhancement. This makes it stand out as a dynamic and responsive approach in the realm of software development methodologies.

7.1.2 Chosen Methodology

The chosen methodology for this project is a combination of Agile, specifically Scrumban, and Lean. Scrumban allows for the organization of tasks into sprints, allowing the developer to focus on specific goals, making the project feel more manageable. Additionally, Kanban’s visualization tools are invaluable in tracking progress and facilitating a flexible schedule.

Incorporating Lean principles is crucial for this project, as it is ongoing with multiple teams depending on the software to complete their parts. By initially delivering a basic functional application and iteratively refining it, the project can align with the multidisciplinary aspects, allowing the electronics and photonics teams to work appropriately. This hybrid methodology enhances productivity, efficiency, and the ability to deliver a high-quality product amidst a complex project landscape.

	Agile	Waterfall	Lean	DevOps
Approach	Iterative	Linear	Iterative	Iterative
Flexibility	High	Low	High	High
Visualization	Kanban	Gantt	Value Stream Mapping (VSM)	None
Speed of Delivery	Fast	Slow	Fast	Fast

Table 28: Comparison of Development Processes

7.2 Mobile Application Development

The following sections lists the process to develop the mobile application that allows pet owners to interact with the Smart Laser Toy for Cats remotely.

7.2.1 Understanding User Needs and Expectations

When creating a software application, it is crucial to first identify the fundamental requirements of the target audience. This project aims to create a Smart Laser Toy for Cats. The “smart” aspect of this project involves a mobile application that connects to the device via bluetooth, and gives the owner control of which scanning pattern is being played. The application also features an intuitive interface to ensure ease of use, especially for individuals who have limited mobility or impaired vision. Implementing clear visual cues, easy navigation, and adaptive features makes the application inclusive and user-centric. Understanding the needs of the user is essential for crafting an application that will seamlessly integrate with the Smart Laser Toy for Cats and enrich the overall experience for both the pet and the owner.

Recognizing the uniqueness of each pet and owner, the project emphasizes the integration of features that enable customization and personalization. For example, if an owner finds that there is a specific pattern that a pet enjoys, they will also have the option to favorite that pattern for further easy access during another play session.

Owners can explore and select from a number of sequences. Whether it’s a swift and sporadic movement to captivate an active cat or a gentle, slow movement for a more reserved pet, the app strives to offer a wide range of options for a captivating playtime experience.

7.2.2 Overview of Mobile Operating Systems

A mobile application is a software application written for use on a mobile device. With 6.3 billion smartphone users, and 1.14 billion tablet users, the mobile development market continues to grow at an increasing rate. A typical mobile application utilizes a network or bluetooth connection to work with remote computing resources. When creating a mobile device, one of the first things to consider is the target device platform. The fundamental decisions of the application development, like the base coding language and library frameworks, depend on the mobile platform, or operating system (OS), that is being used. There are two dominating device platforms in the world today, Apple iOS, and Google Android. Native iOS applications are written using the Swift or Objective-C programming languages, and are incompatible with the Android OS. Native Android applications are written using the Java or Kotlin programming languages, and are incompatible with iOS. Understanding the different mobile OS platforms is of prime importance for developers as it directly impacts how the applications are developed, designed, and deployed.

7.2.2.1 Apple iOS

Since its establishment in 2007, iOS has continued to revolutionize the way we interact with our devices. Since then, Apple has consistently been evolving, striving to meet the changing demands of consumers, solidifying their position as a front runner in the mobile

OS landscape. iOS is known for its simple, intuitive, easy to use interface and its strict security guidelines. This entices a wide variety of people, especially those who may not be “tech savvy”. When using iOS, it is common to have everything readily available at the click of a button, without the need for extra personalized configuration. Apple aims to make using their devices an easy and anxiety free experience for all users.

iOS emphasizes data privacy and security. The iOS ecosystem is meticulously designed to ensure that user data remains protected and under the user’s control. Features like Face ID and Touch ID provide secure yet convenient authentication methods. iOS’s privacy-centric approach is more pertinent than ever, with data breaches becoming increasingly common. A recent survey shows that almost 50% of people are considering switching to Apple from Android because of the “perceived superiority” in security and privacy.

Currently, there are almost 2 million apps available for download in the Apple App Store. iOS offers a robust and sophisticated development environment. For native iOS applications, Apple created Swift, a powerful and intuitive programming language that is fast, easy to learn, and features modern syntax. Apple’s integrated development environment (IDE), Xcode, provides a comprehensive set of tools that aid in app creation, testing, and debugging.

7.2.2.2 Google Android

The Android operating system was established in 2008 by Google. Since then, it has dominated the field of mobile operating systems, solidifying its position as the most popular OS today. Currently, there are over 3.3 billion Android users worldwide, with 1.57 billion android devices sold in 2022 alone. Consequently, Android holds an impressive 71.8% share of the global mobile market.

Android has not only revolutionized the way smartphones operate, but how developers create mobile applications. One of the hallmarks of Android is its open-source nature. This means that the source code can be accessed and modified, making it an appealing option for developers who like to alter code to suit their needs. The open source nature of android also attracts non-developers who seek to maximize customizability of their mobile phones. There is also a sense of security among users; open source code means that individuals have the ability to spot and fix vulnerabilities that the original developers may have missed. On the other hand, this openness also means that these vulnerabilities are open to exploitation.

Another reason Android stands out is for its affordability. When Apple attempts to create a budget device, it is in relation to the expensive prices of other Apple devices. In contrast, even budget Apple devices are relatively expensive compared to a wide variety of Android devices available, ranging from budget-friendly options to high-end flagships.

Android’s App Store, the Google Play Store, features a whopping 2.87 million apps available for download, almost 1 million more than the Apple App Store. Java and Kotlin are the primary programming languages for developing Android applications. Kotlin, introduced by Google in 2017 as an official language for Android development, has gained traction due to its conciseness, safety features, and full interoperability with Java.

Moreover, Google's Android Studio provides a robust and comprehensive Integrated Development Environment (IDE) for Android app development.

7.2.2.3 Different Development Approaches

In the realm of mobile app development, there are four different approaches to consider:

- Native Applications
- Hybrid Applications
- Cross-platform Applications

Each approach features a unique set of advantages and disadvantages. The selection of an approach impacts user experience, native feature integration, cost, timeline, deployment, and maintenance.

7.2.2.3.1 Native Applications

Native Applications are applications written to run on a specific operating system. If a developer wants to create an application exclusively for iOS, they would write it using the Swift or Objective-C programming languages. Likewise, if a developer's target is Android, they would use the Java or Kotlin programming languages.

There are several reasons why a developer might choose to develop a native application. First and foremost, if the application only needs to run on a particular operating system, there's no need to design it for multiple platforms. For instance, Procreate, an award-winning digital illustration app, is exclusively available on the Apple App Store for iOS and iPadOS. CNET has recognized Procreate as the best overall iPad drawing app of 2023. When questioned about the absence of Procreate on Android, the founders and developers explained that the app was purposefully tailored for use on the iPad Pro. iPads offer superior hardware and touch gestures compared to most Android tablets. The founders and developers of Procreate firmly believe that developing the app for Android devices would compromise the quality of their application.

One advantage of choosing to develop native applications involves the speed at which the application runs on the hardware. Native apps deliver the best performance, as the application is optimized for the specific operating system it's running on. This optimization also allows for native applications to run more smoothly, making them look and feel like a natural part of the device, effectively enhancing user experience.

Another advantage of native app development lies in the seamless interaction with the device's hardware. Since these apps are developed for a specific platform, developers can directly access the device's camera, GPS, microphone, and other hardware, faster than if the application were not native.

Lastly, in terms of development, native applications inevitably come with an easier debugging process. There are fewer dependencies to track, meaning there are fewer elements beyond the developer's control and consequently fewer bugs to worry about.

Despite the numerous advantages of native application development, a significant drawback lies in the need to create distinct codebases for each platform. This implies that for a single application concept, developers must build two separate native applications—one for iOS and another for Android. This duplication of effort can be time-consuming and resource-intensive. Moreover, once the app has completed the initial development phases, it will need to be maintained and updated, which also requires a lot of effort. Employing two different development teams to work on the applications (or the same team for an extended time), is also costly.

7.2.2.3.2 Hybrid Applications

As the demand for feature-rich and versatile mobile applications continues to rise, developers are actively seeking efficient ways to create apps that seamlessly function across various platforms while minimizing development efforts and costs. When targeting both the iOS and Android operating systems, the traditional approach of developing two separate native applications can be both time-consuming and costly. In response to these challenges, hybrid mobile application development has emerged as a potent solution, providing a middle ground between native and web-based applications.

Hybrid mobile applications are developed using web technologies like HTML, CSS, and JavaScript, encapsulated in a native container. This allows for developers to write a single codebase that can be deployed for use on multiple devices, while still maintaining a consistent user experience across devices. The native container acts as a bridge, allowing access to device functionalities like camera, GPS, and contacts, which was previously possible only in native applications.

One of the main advantages of hybrid development is code reusability. Developers can write a single codebase for the application's core logic and UI. This dramatically reduces the amount of time developers spend creating the application compared to creating separate native apps. The ability to reuse code for iOS and Android, the two dominant platforms, significantly enhances development speed, making hybrid development an attractive choice for many.

Another advantage stems from hybrid applications' cost-effective nature. Requiring only a single codebase substantially reduces the overall development cost, making it attractive to smaller businesses, startups, or individual developers with limited resources. Additionally, maintenance is simpler and more efficient since updates and bug fixes need to be performed on only one codebase instead of two.

One of the main disadvantages when it comes to using the hybrid-approach is the sacrifice of performance. Hybrid applications generally don't offer the same level of performance and user experience as native applications. Since they rely on a native browser, they come with numerous user interface (UI) issues. The user may be faced with an application that is slow, laggy, and very frustrating to use. Though having one codebase can be advantageous, it also means one wrong change can lead to disaster, potentially even allowing glitches to occur.

It is worth mentioning that hybrid applications may seem easier to implement, and they may be depending on the use case, but they also generally increase the complexity of the application. Creating a hybrid platform means writing code that works a specific way on one platform, but may not work the same way on another. Considering the developer is only working with one codebase for multiple operating systems, the code becomes more complex than if it were to be spread across multiple code bases. Additionally, when using technology that is not directly supported by the platform, there will be roadblocks that need to be worked around, adding even more complexity to the code.

When done correctly and in the right circumstances, hybrid mobile application development presents an effective solution for creating cross-platform applications. As the technology continues to advance, the capabilities and performance of hybrid development frameworks will improve, making them an increasingly attractive choice for developers aiming to deliver high-quality applications across multiple platforms.

7.2.2.3.3 Cross-platform Applications

Cross-platform mobile application development shares similarities with hybrid development. Fundamentally, both approaches rely on a single codebase to deploy an application across multiple platforms. In hybrid development, the codebase is written using web technologies (HTML, CSS, JavaScript) and is then encapsulated in a native container. This container acts as a bridge, enabling access to native features. On the other hand, cross-platform development entails creating the codebase using a common language such as JavaScript or C#. This codebase can be deployed across multiple platforms with minimal adjustments. This approach emerged as another solution to the demand for efficient and cost-effective app development across various operating systems. The advantages and disadvantages of hybrid and cross-platform development are shared, but since there is less overhead and no need for a web view, cross-platform applications often have better performance.

7.2.2.3.4 Chosen Methodology

After careful consideration, the best developmental approach for the mobile application is the native approach. Creating an application for a specific operating system will ensure the best user experience.

	Native	Hybrid	Cross-platform
User Experience (UX)	Excellent	Good - Very Good	Good - Very Good
Speed	Excellent	Good	Good
Debugging Tools	Excellent	Good	Good
Development Language	Platform-specific	HTML/JavaScript/ CSS	JavaScript

Table 29: Developmental Approaches

7.3 Software Design

As the technological world progresses, ordinary everyday devices are advancing in ways that enhance convenience, efficiency, and connectivity. This project is a manifestation of that ideal, and it aims to transform the way people play with their cats.

It is a well-known fact that cats are fascinated by lasers. The swift movement of the dot mimics lively prey worth chasing. Traditionally, when lasers are involved in playtime, it entails the owner drawing paths with the laser as the cat pursues the faux prey. While there is nothing inherently wrong with this tried-and-true approach, it is time for an upgrade. The relentless pace of modern life also means people have less time to devote to spending time with their cats. Not only does the bond between owner and cat suffer, but the mental and physical wellbeing of the cat may suffer as well. Domesticated cats get most of their exercise and mental stimulation through play. Incorporating a “smart” feature into a laser toy offers numerous advantages, with the most notable being that it ensures a cat never misses out on playtime, even when its owner is occupied or away.

7.3.1 Goals and Objectives

To ensure the best possible experience, the design of the mobile application will focus on four key elements: functionality, usability, reliability, and responsiveness.

Functionality can be considered the foundation of the application. It ensures the app has all the necessary functions to control the toy effectively. This includes interfacing with the device and controlling the pattern being played. With a well-built foundation, the application has the stability to support the development of additional features.

Usability is akin to the layout and design of a house. Just as a designer aims to create a space that is easy to navigate, a developer aims to create an application that is intuitive and user-friendly.

Reliability speaks to the soundness of the structure of a house. Just as one would not want their house to be blown away by the slightest breeze, a developer would not want users to experience frequent crashes and delays. The application should maintain a stable connection and ensure that commands sent from the app to the toy are executed reliably and promptly. This reliability is achieved through rigorous testing and quality assurance procedures. Any potential bugs, glitches, or vulnerabilities that could lead to crashes or delays will reveal themselves during this process, allowing them to be identified and rectified. Additionally, error-handling mechanisms will be implemented to gracefully manage unexpected situations, ensuring that the application remains robust and dependable.

Finally, responsiveness is analogous to the adaptability of a house. Just as houses are renovated, applications are constantly being updated to better suit the needs of their users. This application will have a quick response time, with real-time or near-real-time command execution. This will be achieved through the development of efficient code and ongoing enhancements to the communication between the application and device.

7.3.2 Overall System Architecture

Developing a high-quality application heavily relies on having an outstanding overall system architecture. The architecture functions as the blueprint that lays out the connections between various components of the application. Without a well-made architecture, even the smallest bug can devalue the overall quality of the entire application. Common system architectures include the monolithic, microservices, and client-server architectures.

7.3.2.1 Description of Different Architectures

A monolith refers to a massive and organized unified structure that acts as a single, unified force. Likewise, a monolithic architecture is a traditional system model built to house all software components, resulting in a freestanding and independent program. Although the architecture can build up to a large and complex framework, the applications it supports tend to be small and simple, housing one interconnected and interdependent code base. Even the smallest update will cause a ripple throughout the entire program.

For a more divide-and-conquer-like approach, the microservices architecture, often shortened to just microservices, offers solace. This approach divides a large application into smaller, more manageable, independent micro-components. When responding to a user’s request, these microservices may call on many other microservices to conquer the said request. Many large companies, like Netflix and Google, are drawn to this highly scalable approach.

In contrast to the self-contained nature of microservices, the client-server architecture presents a different paradigm of interaction and dependency. This architecture is used when there is a clear distinction between the needs of the client and the needs of the server. The server perpetually listens for a request from the client. When a request is received, it is processed and a response is sent back to the client. Client-server architecture is fundamental to many aspects of modern computing, including web browsing, email communication, and database management.

7.3.2.2 Choosing the Best Architecture

A plan is only as good as its execution. If the architecture chosen for the application is not the most suited blueprint for the program, the quality of the finished product will reflect a poorly chosen framework. There are certain key considerations when choosing an architecture for a project. First and foremost, it must satisfy the project's unique requirements. For example, projects that need to handle an increasing number of users should rely on an architecture that is scalable. In addition to scalability, factors such as reliability, maintainability, performance, and security are important to consider. Ultimately, the best architecture is the one that best aligns with the project’s goals and successfully addresses these key considerations.

7.3.2.3 Architecture Chosen for this Project

At its root, this project requires communication between a microcontroller and mobile application. In this case, the most classic and straightforward architecture to choose is the client-server architecture. The abstraction at the heart of this architecture is manifested with the mobile application as the client and the microcontroller as the server. The microcontroller (server) listens for requests from the mobile application (client), processes these commands, then controls the hardware accordingly.

7.3.3 Technical Specification

The foundation of any successful project lies in its technical specifications. These specifications are more than just a list of various tools and technologies; they represent the choices that underpin every aspect of the application's design and functionality. This section provides an in-depth overview of the technical components we will be using in this project.

7.3.3.1 Programming Languages

A programming language is a system of notation used for communication between humans and computers. It allows developers to write instructions that a computer can execute, translating complex human ideas into a format that a machine can understand. There are many different programming languages, but the core idea that defines them never changes. It is crucial to understand that formulating an idea and translating it into code is the cornerstone of software development; the programming language is generally a means to an end. The most popular programming languages today include Python, Java, C/C++, and JavaScript. Choosing the best programming language to use for development can come down to various considerations. First, the language should be compatible with the application that is being developed. Some programmers, especially beginners, tend to choose the programming languages for their projects based on popularity. However, as the complexity of the project increases, this decision may backfire. There is generally no wrong or right answer, but the best programming language to choose is the one most suited for the job.

The main components of software in the project include the mobile application and the embedded programming. During the research phase, a decision was made to use the Native application development approach. Consequently, we will be focusing on developing an application native to the Apple iOS operating system. Therefore, we will be using Swift, the programming language native to iOS apps. Developed by Apple, Swift is described as both powerful and intuitive. It was introduced in 2014 as a successor to Objective-C, with the primary goal of making app development for Apple's ecosystem more accessible and efficient.

7.3.3.2 Integrated Development Environments (IDE)

An Integrated Development Environment (IDE) is a computer application that encompasses all the tools a programmer needs to create software. This includes the ability to edit source code, build executables, and debug the application. There are also plugins that can be installed to further enhance the coding experience. Writing a program without an IDE would involve using a text editor for the source code and then building and running the program through the command line. In contrast, developing with an IDE offers a more efficient and productive experience.

The IDE that we will use to write the mobile application is Xcode 15, the latest version of Xcode. Released by Apple in 2003, Xcode remains the sole IDE encompassing the necessary tools, compilers, simulators, and libraries for creating, testing, and deploying iOS applications even after 20 years. Xcode 15 is equipped with enhanced code completion, interactive previews, and live animations, providing a fast and interactive experience for developers.

7.3.3.3 Frameworks

A framework is a structure that serves as the foundation for applications. Instead of building the entire application from scratch, frameworks provide a base that developers can build upon. This approach saves a considerable amount of time and effort, especially if the framework fulfills functions that are not central to the core logic of the application. To establish a robust base for our application, we will be utilizing the SwiftUI framework. SwiftUI offers a variety of essential components necessary for constructing the core infrastructure of the application, including animation, resource management, and a powerful event-handling system.

7.3.3.4 Development Tools

A Version Control System (VCS) is essential for tracking the history of changes made during the development process. As developers modify the application, a VCS allows for the recovery of previously committed versions at any time. The most popular VCS, and the one chosen for this project, is Git. Git is favored for its simplicity, speed, and efficiency. It enables developers to work on their local repository, committing changes as needed without compromising the system’s performance. This approach facilitates a streamlined and effective development process. In addition to Git, we will also be using Github. Github is a cloud-based hosting service used for managing Git repositories.

7.3.4 Class Diagram

Figure 23: Class Diagram

It is important to note that this diagram is tentative and will change as it's being implemented.

The `Application` class serves as the main entry point for the app.

- Attributes:
    - `deviceConnection` manages the bluetooth connection to the laser cat toy

    device.
    - `userSettings` stores default user preferences and settings.
- Methods:
    - `connectToDevice()` establishes a bluetooth connection with the laser cat toy. The status of the connection is then communicated with the `deviceConnection` attribute.
    - `disconnectDevice()` disconnects the bluetooth connection. The status of the connection is then communicated with the `deviceConnection` attribute.
    - `saveSettings()` saves the current user settings to the device or cloud storage.
    - `loadSettings()` loads user settings from device or cloud storage.

The `LaserToyDevice` class represents the physical laser device.

- Attributes:
    - `motorStatus` indicates whether the motor is on or off. During implementation, it may also be deemed useful for debugging any issues related to the motor.
    - `batteryLevel` stores the current battery level of the laser toy device.
- Methods:
    - `updateMotorStatus()` updates the `motorStatus` attribute.
    - `checkBatteryLevel()` retrieves the current battery level of the laser toy device and stores it in `batteryLevel` attribute.

The `BluetoothService` class handles the connection to the device.

- Attributes:
    - `connectionStatus` stores the current status of the bluetooth connection.
- Methods:
    - `searchDevices()` scans and lists all available bluetooth devices.
    - `pairDevice()` attempts to pair with the device user selected. Pairing will only succeed if the user selects the laser toy device.
    - `sendData()` sends commands to the laser toy device.
    - `receiveData()` receives data or status updates from the laser toy device.

`ControlPanel` is an abstract class that is extended by `ManualControl` and `AutoControl`, representing different modes of controlling the toy. Starting with `ControlPanel`,

- `Attributes:`
    - `currentMode` stores the current operating mode (manual or auto)
    - `speed` represents the speed setting for the laser movement.
- `Methods:`
    - `changeMode()` switches between the automatic and manual control modes.
    - `adjustSpeed()` sets the speed of the motor.
    - `start()` initiates the movement of the motor.
    - `stop()` stops the movement of the motor.

`ManualControl` represents the manual mode of the laser toy device,

- Methods:
    - `moveLeft()` commands the motor to move the laser to the left.
    - `moveRight()` commands the motor to move the laser to the right.

`AutoControl` represents the automatic mode of the laser toy device,

- Methods:
    - `runAlgorithm()` generates a pseudorandom algorithm for autonomous motor movement.

The initial class diagram we had planned, as shown above, did not come to fruition in the execution phase of the project. We opted to make the app more personal rather than just a controller for the toy by adding features like a profile page, gathering basic health information, introducing a favorites feature, and more. The completed app is over 50 classes, far exceeding the 7 originally pictured. We also phased out manual and auto controls in favor of more structured scanning patterns and removed the functionality where the app would receive settings feedback from the device.

7.3.5 Graphical User Interface (GUI)

In a mobile application, the Graphical User Interface (GUI) plays a pivotal role in defining user experience and usability. It serves as an intuitive bridge between the user and the software, providing a visual way of interacting through components like buttons, icons, and sliders. The images shown below display the important aspects we wish to execute in the application.

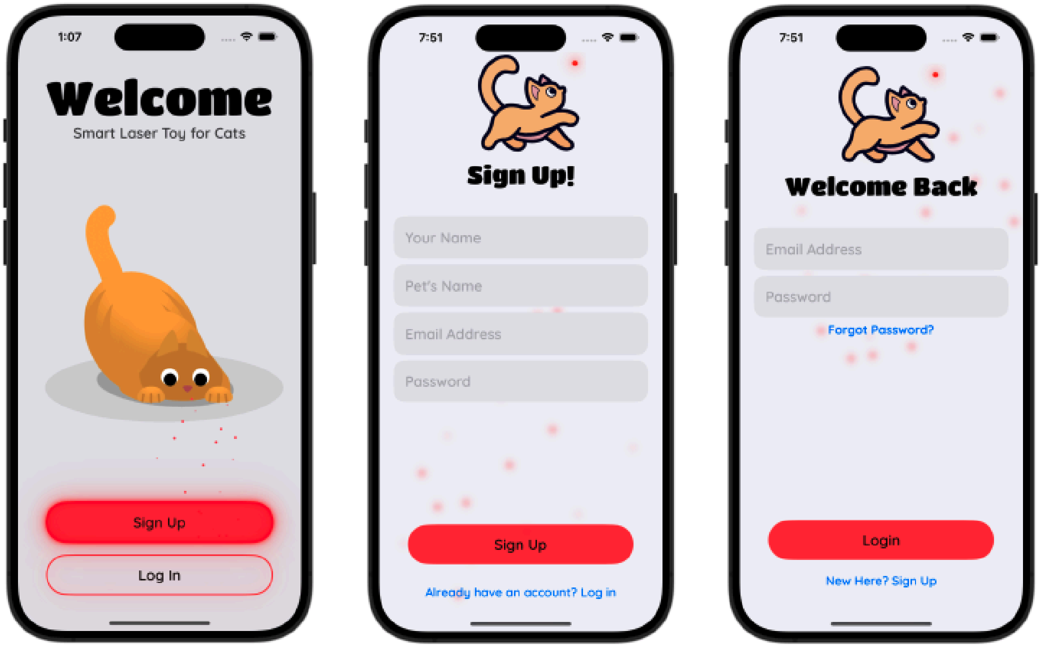


Figure 24: Welcome, Sign Up, and Log In Layouts

Considering this application is being developed with the sole purpose of providing a user with control of a cat toy, we are aiming to have the application evoke a feeling of playfulness. The welcome screen greets the user with an animation of a playful cat and features two buttons that allow users to sign up or log in.

Name
Xaria

Email
xaria@ucf.edu

Name
Walter Honey Bee 🐝

Age
2 years old

Weight
15.8 lbs

Collar Color
Red

Daily Quota
30 minutes

Figure 25: Dashboard, Patterns, Profile, and Settings Layouts

For users who have already logged in, opening the app will immediately take them to the dashboard. The dashboard presents a profile card with an image of the cat. Following this is an activity card that displays the cat's progress for the day based on a predefined daily quota. Finally, a list of the cat's favorite patterns is available for quick and easy access.

The patterns page is where the user finds all the available patterns. There is also a carousel of the favorited patterns for user convenience.

The profile page lists basic information about the cat, such as name, age, sex, breed, and weight. Below this, the activity card featuring the progress bar will serve as a visual representation of the total playtime achieved against the daily quota. Finally, any favorited algorithms for the toy’s movement will be listed for quick and easy access.

8 Hardware Development Process

The following sections describe the hardware development designs in detail.

8.1 Passive Infrared Sensor Design

The following section lists the design implementation of the IR LED and phototransistor for the passive infrared motion sensor.

8.1.1 IR LED Design

As a part of the Smart Laser Cat Toy passive infrared motion detection system, the infrared LED is located on the sides of the enclosure. The reason it is on the sides, rather than the top is because the device will need to be placed slightly above ground as a safety precaution to ensure the cat does not look directly into the beam of laser light exiting the cat toy. The IR LEDs emit light and function alongside the phototransistors to detect motion in a room and in turn, enable the camera detection system to determine if it is a cat, and then turn the laser system on as the final step.

The IR LEDs are not seen by the pets, nor the pet owners, because the IR LEDs are in the infrared spectrum, which is outside the range of visible light. The specific IR LEDs chosen for the Smart Laser Cat Toy are in the exact wavelength that the chosen phototransistors exhibit peak sensitivity to ensure that the motion sensor is at peak performance.

8.1.2 Phototransistor Design

The second component of the passive infrared sensor design for the Smart Laser Cat Toy is the phototransistor. There are four phototransistors placed around the device enclosure in a strategic manner to ensure that the maximum amount of light received from the IR LED is possible. This is also the reasoning behind selecting a phototransistor with the widest field of view available.

There will be one phototransistor placed next to the IR LED array to ensure that as much of the light from the IR LED is detected by the phototransistor and can enable the camera to turn on for the color detection portion of the system. When the reflected light is detected, the signal in the phototransistor produces an electrical signal between the emitter and collector, which will then send a signal to the microcontroller to enable the camera chosen for the system.

8.1.3 Sensor Schematic

To design the schematic of the passive infrared motion sensor, a phototransistor and IR LEDs are used in conjunction with a voltage source, resistors, and a regular LED. The regular LED in the visible light range is used to ensure that the motion sensor is detecting motion when turned on. Since the IR LED is not in the visible light spectrum, it is not visible to the human eye when powered. The original schematic, with on IR LED, is shown in the figure below.

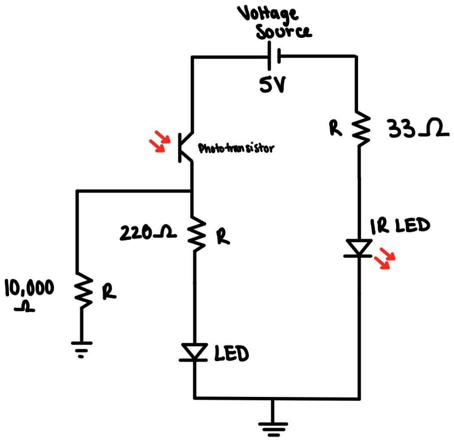


Figure 26: Passive Infrared Motion Schematic

Since the phototransistor is a “top view” phototransistor, the IR LED being placed next to the phototransistor does not affect its motion sensing capabilities, since the reflected IR light reaches the phototransistor from the top as the object, in this case, the cat, passes by. The visible light LED is placed below the phototransistor in the schematic because as the phototransistor receives light in the wavelength it operates at, it will “power on” allowing current to flow through. As this happens, current will flow to the visible light LED, allowing it to turn on and see the visible light. The 10 kΩ resistor acts as a “pull-down” resistor to direct the current to go towards that direction and through the phototransistor. The 220 Ω and 33 Ω resistors are then used to ensure the forward voltage of the LEDs are not exceeded so that it can operate properly. The resistance value of the IR LED was calculated through using the LED resistor calculation equation.

$$R_{IR} = \frac{V_s - V_{IR}}{I_{IR}} = \frac{5\,V - 1.7\,V}{100\,mA} = 33\ \Omega$$

The original testing of the schematic above showed that the sensor detection is only 4 centimeters on average, and it did not meet our design requirements. We then changed the schematic to the figure below, utilizing 100 ohm resistors to reduce current draw.

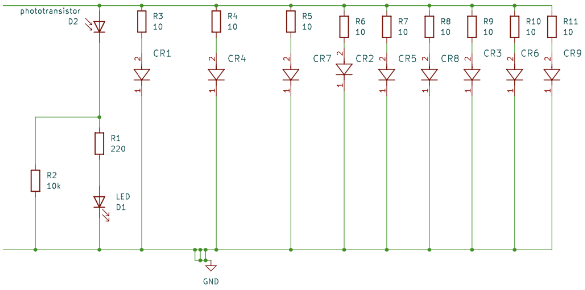


Figure 27: Modified Passive Infrared Circuit Diagram

Upon testing, the new circuit diagram enabled approximately 6 to 8 inches of detection, closer to our goal of 1.5 feet of detection. The way to mitigate this is to add a 50 mm plano convex lens with 50 mm of focal length, discussed in the next section.

8.1.3.1 Increased Sensor Distance Design

To increase the distance of the passive infrared motion sensor detection, the implementation of a lens will enable this. Where this would have given us greater detection range, the cost constraints of this project did not allow us to implement it into the final prototype of the Smart Laser Toy for Cats, but the design specs were calculated for future versions.

To calculate the focal length of the lens needed, the following equation was used with a 50 mm diameter lens because the three by three array of IR LEDs are 2 inches in height. The 50 mm lens diameter ensures it is capturing the majority of light.

$$tan(\theta) = \frac{h/2}{EFL}$$

Equation 14: Paraxial Ray Height Equation

The following diagram was used to implement values into the above equation.

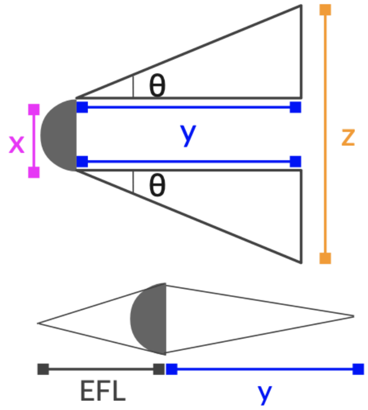


Figure 28: Diagrams for Lens Calculation

In the case of the diagram, the above graphical design is used to calculate the angle, θ. The variable x is the diameter of the lens, 50 mm, the variable y is the detection distance, 18 inches, and the variable z is the average length of a cat, 18 inches. We used these numbers to find the angle through trigonometry. Once the angle was calculated then the Paraxial Ray Height equation was used with that angle to find the focal length of the lens. We need a 50 mm lens diameter with 50 mm focal length to achieve collimated light up to 1.5 feet, and thus detection distance. The following table outlines the lens found.

Plano-Convex Lens	**#32-970**	**#48-795**
Material	N-SF11	N-SF11
Coating	Uncoated	NIR I
Refractive Index (n)	1.76182	1.76182
Reflectance	7.60%	1%
Transmission	92.40%	99%

EFL	50 mm	50 mm
Diameter	50 mm	50 mm
Cost	$47.50	$65.00

Table 30: Plano Convex Lens Comparison

The coated lens, #48-795, after calculating the transmission of a coated versus uncoated lens using the transmission equation.

$$T = 1 - \frac{(n-1)^2}{(n+1)^2}$$

Equation 15: Transmission Equation

The uncoated N-SF11 glass experiences a 7.6% transmission loss, whereas the NIR I coated lens only has 1% transmission loss. The lens was now simulated in CODE V to ensure collimation of light, seen below in Figure 29.

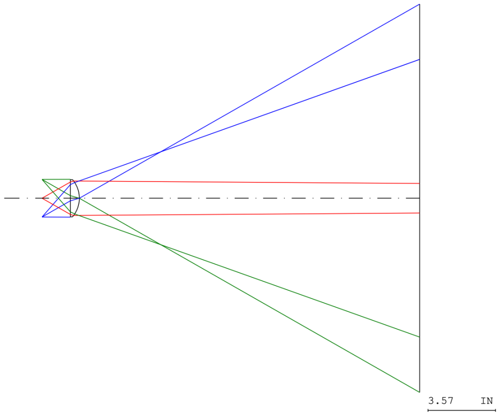


Figure 29: Simulated Plano Convex Lens

The simulation shows collimation of light 1.5 feet away with the lens placed 50 mm from the light source and the collimated spanning 20 inches of detection horizontally, which represents the length of the average cat. The implementation of this requires 4 lenses, increasing the cost $260.

8.1.4 Camera Detection Design

The following section describes the camera system, LED, and Fresnel lens design for the camera detection system.

8.1.5 Camera System Design

The chosen camera module was originally the Arducam IMX291 but we proceeded with the Pi Camera Module 2. Although it was found that the Arducam IMX291 would integrate best with the Smart Laser Cat Toy because of the 160 degree field of view, the Camera Module 2 served the same functions and did not increase the budget.

8.2 Cat Collar Tag Design

The cat collar is independent of the main hardware design of the design but still an integral system of the Smart Laser Toy for Cats. The following section describes the design details of the components integrated into the cat collar.

8.2.1 Color LED Design

The cat collar tag uses LEDs that only emit one color. This was chosen as the single color LEDs only have two leads, as opposed to an RGB LED that would have four leads. Since each color, red, green, and blue, LEDs have different forward voltages, 2.2 V, 3.4 V, and 3.2 V, respectively, Equation 6 was used to calculate the resistor value needed to supply the correct amount of voltage to the LED. The voltage source used is a 3 V CR1632 button cell battery because it is a light weight battery, 1.8 grams, which is useful for the design goal of a light collar tag. A waterproof switch was added to the circuit to be able to turn the LED on and off, and also implement the waterproof goal of the LED Cat Collar Tag.

Using Equation 6, the following calculations led to the resistance values: 40 ohms for the red LED, 130 ohms for the green LED, and 140 ohms for the blue LED.

$$R_{Red} = \frac{V_s - V_{Red}}{I_{Red}} = \frac{3\,V - 2.2\,V}{20\,mA} = 40\,\Omega$$

$$R_{Green} = \frac{V_s - V_{Green}}{I_{Green}} = \frac{6\,V - 3.4\,V}{20\,mA} = 130\,\Omega$$

$$R_{Blue} = \frac{V_s - V_{Blue}}{I_{Blue}} = \frac{6\,V - 3.2\,V}{20\,mA} = 140\,\Omega$$

Three separate circuits were created in Multisim Live to simulate and test the circuits before doing a live test to ensure the validity of the calculations and design.

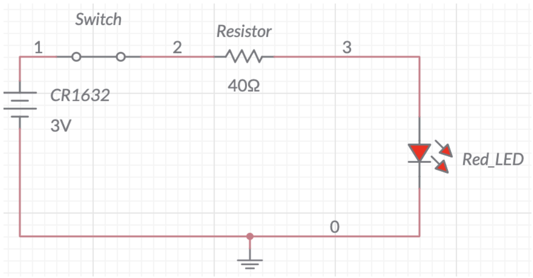


Figure 30: Circuit Schematic for Red LED

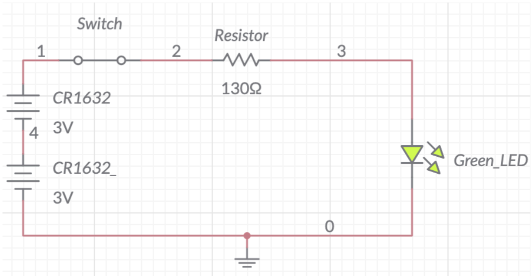


Figure 31: Circuit Schematic for Green LED

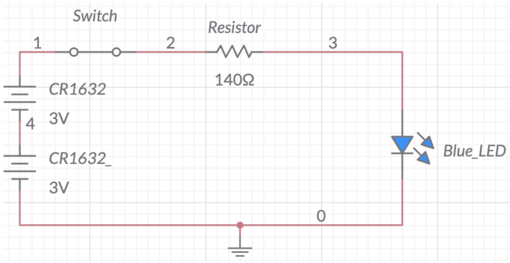


Figure 32: Circuit Schematic for Blue LED

It is important to note that the CR1632 button cell battery is 3 volts and the forward voltages of the green and blue LEDs are greater than that. Since the forward voltages are greater than a singular battery, two CR1632 batteries will be connected in series to increase the battery supply of the circuit to 6 V, and then the resistors to decrease the voltage to not damage the LED. To ensure that the schematic and calculations are accurate and will not damage the LEDs, the schematic was simulated to measure voltage and current entering the LED.

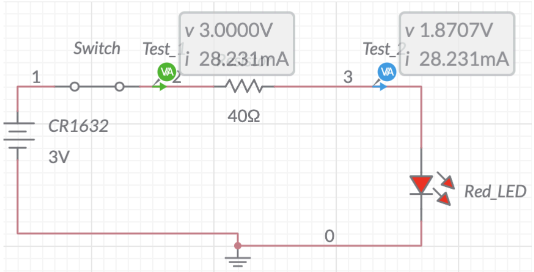


Figure 33: Circuit Simulation for Red LED

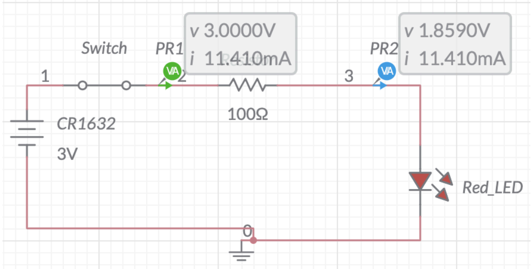


Figure 34: Circuit Simulation for Red LED - Test 2

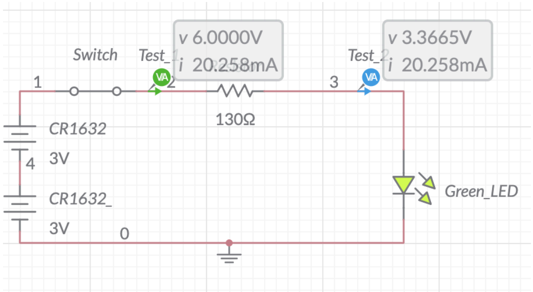


Figure 35: Circuit Simulation for Green LED

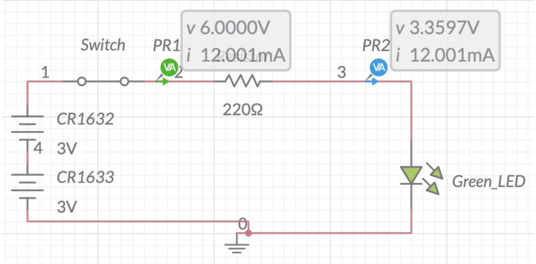


Figure 36: Circuit Simulation for Green LED - Test 2

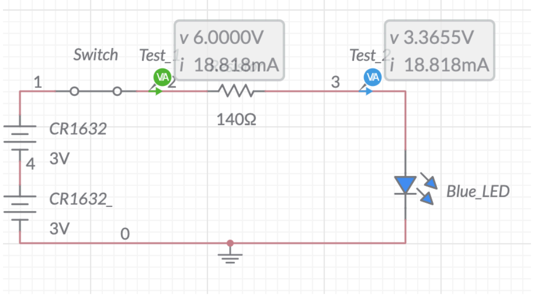


Figure 37: Circuit Simulation for Blue LED

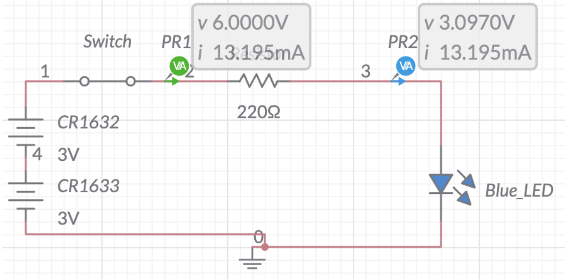


Figure 38: Circuit Simulation for Blue LED - Test 2

The circuit simulations show that the voltages entering the LEDs will not exceed the forward voltage listed on the data sheet for the respective component. The red LED's schematic shows the voltage entering the component to be 1.87 V, and although this is less than the forward voltage on the data sheet, this is acceptable because the LED will simply just not reach full brightness. However, a second test was simulated with higher limiting resistance across the voltage because the operating current was above 20 mA, it was 28 mA. By using a resistance of 100 ohms, the simulation lowered the operating current to 11.4 mA, below the 20 mA limit, and maintained it to 1.85 V. Since the selected red LED has a high luminosity, this is not a concern. The green LED schematic shows the voltage entering the component to be 3.37 V which is right under the 3.4 forward voltage of the LED on the data sheet. However, the same problem with current happened as well, so a resistance value of 220 ohms was implemented to reduce the current to 12 mA and maintain the voltage below 3.4 V. The blue LED schematic was tested twice because the first simulation showed the voltage entering the component to be 3.37 V, which is higher than the forward voltage of the blue LED, 3.2 V. To find a resistance value that would decrease the voltage supply of the battery to 3.2 V or below, extra simulations were conducted to determine the proper resistance value, which showed to be 220 ohms. The operating current for both simulations was below 20 mA. The following table lists all the major specifications of the LED components and how they compare to the circuit simulations. The current entering the LEDs were also measured to ensure it does not surpass the operating current of the LEDs, all of which are 20 mA.

	Red LED	Green LED	Blue LED
Voltage Source	3 V	6 V	6 V
Theoretical Forward Voltage	2.2 V	3.4 V	3.2 V
Resistance Calculated	40 Ω	130 Ω	140 Ω
Resistance Simulated	100 Ω	220 Ω	220 Ω
Simulated Forward Voltage	1.86 V	3.36 V	3.1 V
Operating Current	11.4 mA	12 mA	13.2 mA

Table 31: Simulated LED Schematic Calculations

8.2.2 Fresnel Lens Design

The Fresnel lens is an integral part of the cat collar design for the Smart Laser Toy for Cats. Although the luminosity for the chosen single color LEDs are very bright, the light dispersion is not very far, as with any LED. To compensate for this and ensure the light rays can reach the camera that detects color, the Fresnel lens is extremely important. The design of the Fresnel allows for a lightweight, as it is made of acrylic, and thinner than a typical glass lens, it is 2 mm thick. The lens is placed above the soldered single color LED circuit, as seen in the collar tag holder drawing detailed in the section below. The holder is designed specifically with a 2 mm thick indent at the top of the cylinder so that it does not fall down onto the LED or circuitry and disrupt the current flow or damage the LED itself. The figure below details how the light propagates through the fresnel lens, allowing further dispersion of the LED light rays as long as the Fresnel lens has the plano side facing the LED itself, with the curved side on top of the cylinder.

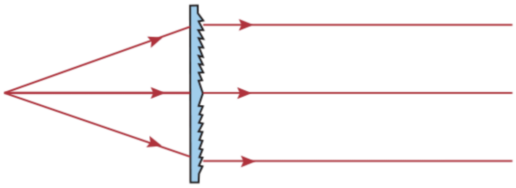


Figure 39: Light Rays Propagating through a Fresnel Lens (Courtesy of Edmund Optics)

To ensure that the calculations of 25 mm were sufficient for the purpose of this design, the lens was designed in Zemax OpticStudio to ensure a good spot diagram for all three LED wavelengths.

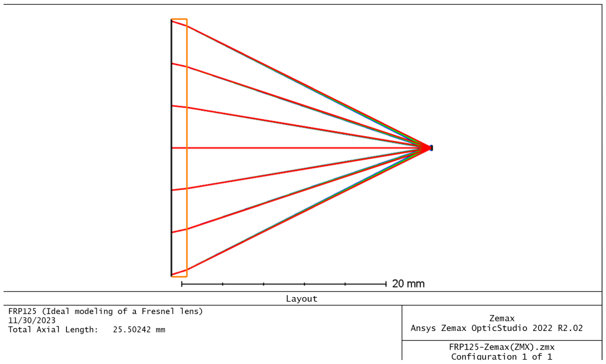


Figure 40: 25 mm Focal Length Fresnel Lens Cross-Section Layout

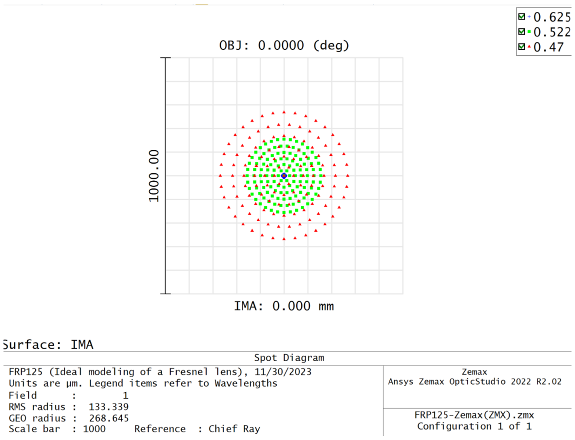
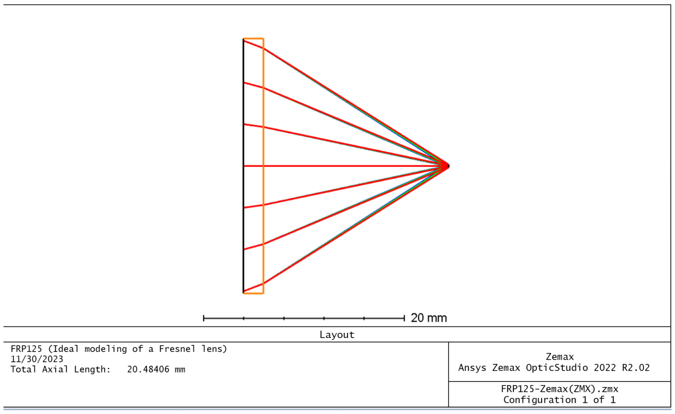


Figure 41: 25 mm Focal Length Fresnel Lens Spot Diagram

The spot diagram shows that the best focal point is for blue light, at 470 nm, then the green light at 522 has a larger spot size, but still pretty condensed, and the red light at 633 nm shows the greatest amount of dispersion. As previously stated in the part selection process, slight dispersion of the light is not something that causes too much concern because the main point of the Fresnel lens is to improve the propagation distance of the LED since it does not disperse very far. Because of this, a 20 mm Fresnel lens was purchased because it is made of acrylic, more resistant to destruction if the cat were to run into something and hit the lens, and more cost effective in the overall scope of the project.

To truly ensure that the Fresnel lens selected achieves the goals and objectives of the light dispersion portion of the color detection detection system and cat collar tag design, the Merit Function Editor in Zemax was used to change the focal length to 20 mm and account for the thickness of 2 mm of the Fresnel lens purchased. The layout and spot diagrams of the lens used in the system can be seen below.

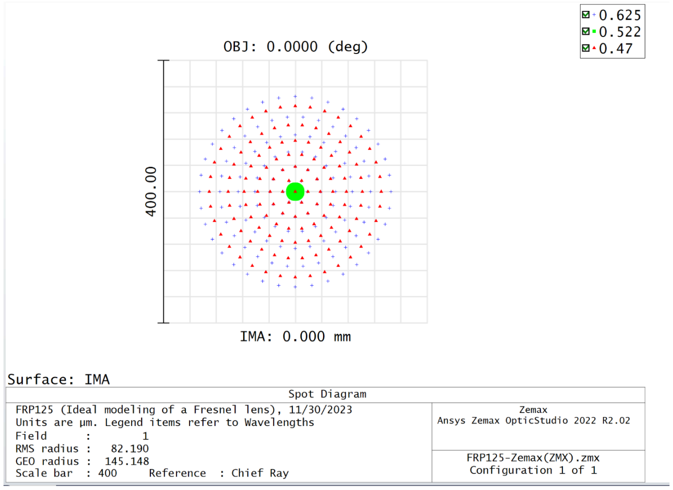


FRP125 (Ideal modeling of a Fresnel lens)
11/30/2023
Total Axial Length: 20.48406 mm

Zemax
Ansys Zemax OpticStudio 2022 R2.02

FRP125-Zemax(ZMX).zmx
Configuration 1 of 1

Figure 42: 20 mm Focal Length Fresnel Lens Cross-Section Layout



FRP125 (Ideal modeling of a Fresnel lens), 11/30/2023
Units are µm. Legend items refer to Wavelengths
Field : 1
RMS radius : 82.190
GEO radius : 145.148
Scale bar : 400 Reference : Chief Ray

Zemax
Ansys Zemax OpticStudio 2022 R2.02

FRP125-Zemax(ZMX).zmx
Configuration 1 of 1

Figure 43: 20 mm Focal Length Spot Diagram

Unlike the previous 25 mm lens,the 20 mm optimized lens has the smallest spot size for the 522 nm wavelength and disperses for the 625 nm and 470 nm wavelengths. However, the same concept applies where the spot size is not a huge concern because the purpose of the Fresnel lens is to disperse the light farther and brighter onto the camera rather than an LED on its own. The distance of detectable light propagation was tested during the hardware design testing of the project, denoted in further sections.

8.2.3 Collar Tag Holder

The collar tag holder design was drawn in SolidWorks with the purpose of holding the battery, resistor, LED, and switch. The holder was designed to ensure that the size dimensions of the collar were not bulky and heavy, as a goal of the Smart Laser Cat Toy for Cats is to have a lightweight collar to not disturb the cat's daily activities. An overall drawing of the design can be seen below, where the main cylindrical piece carries the battery, resistor, and LED. The lens is placed on top of the cylinder, where a small indent about 2 mm thick can be seen from the top to ensure that the Fresnel lens fits well and does not fall on the top of the LED. The hollow cuboid on the side of the cylinder is designed to hold the switch. It can be seen that there is a hole in between the cylinder and cuboid, and this is where the switch is placed to enable the turn on/turn off function of the LED light.

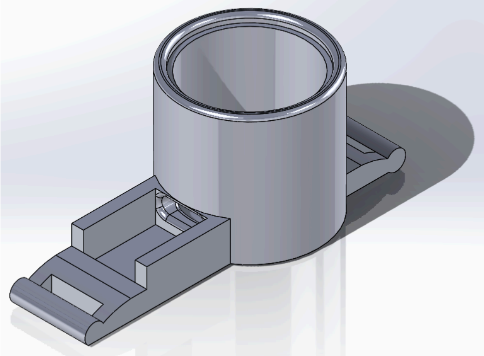


Figure 44: Collar Holder Design

As described previously, the figure above shows the overall schematic for the holder going on the cat collar. The figures below detail the exact measures of the holder. These measurements were decided based on the height of the components going inside the cylinder and the size of the push switch for the cuboid on the side. The cylinder height was decided based on the fact that the head of the LED is 8.6 mm, the batteries are 6.4 mm, the resistor is 4 mm, and the Fresnel lens is 2 mm. A total of 30.63 mm was decided for the height to account for the length of the wiring and to have room for soldering. The hole on the side of the cylinder is so that the switch wires can go through to reach the battery and resistor. The diameter of the inside of the cylinder is 30.25 mm because that is the diameter of the Fresnel lens. The outside diameter of the is 35 mm to provide some layer of protection to the components inside. It is important to note an extra 0.254 mm was added to all measurements as a tolerance for any deviations in 3D printing.

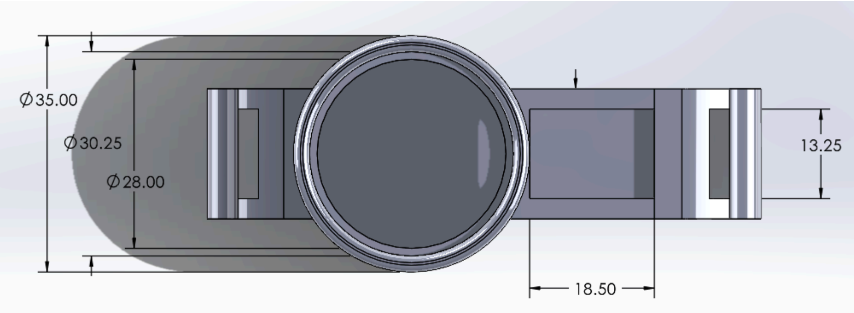


Figure 45: Collar Design Measurements - Top View (Note: measurements are in millimeters)

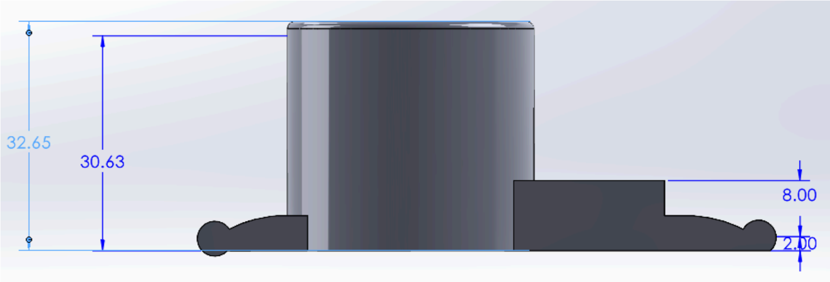


Figure 46: Collar Design Measurements - Side View (Note: measurements are in millimeters)

8.3 Laser System Design

For the cat toy to be designed, the group needed to both expand and steer a laser beam with optical elements all while having a small enough optical track to remain portable. From the lenses and prisms selected, it was known that the design would achieve 5x magnification if the lenses are separated a certain distance equal to the difference in focal length. For the beam steering components, it was decided to utilize the Risley prisms design as it would require less motors than the diffraction grating design. If the group attempted to rotate the diffraction grating, it would be difficult to select individual beams of light with motorized polarized film. Since the laser diode will emit light that can be considered afocal for the designated purposes and the beam expander will collimate light into an afocal system, the group needed a more comprehensive process to image the system than equation 10 can produce. For the purpose of the design, the group needed to utilize the paraxial ray tracing equations to image the system with the following equations.

$$y' = y + u't'$$

Equation 16: Paraxial Transfer Equation

$$n'u' = nu - y\phi$$

Equation 17: Paraxial Refraction Equation

Where y is the height of the light, u is the angle of propagations, ϕ is the surface power, t is the distance between surfaces, and the apostrophe determines if the variable is before or after the surface. These equations were used for paraxial ray tracing instead of using equation 1 or 9 to image the system because the small angles produced by the laser diode would result in trigonometric functions to equal the angle. To completely image a system with paraxial ray tracing, we utilized both equations 14 and 15 at each individual surface found in the optical axis. When this is done, the group is able to find the height of the traced ray of light at each surface, giving a clear value for the minimal height of the components.

8.3.1 Paraxial Ray Trace

As stated before, the beam emitted by the laser diode keeps coherency for great distances, allowing us to visualize it as an afocal system. Since the system is an afocal system, the distance between the laser diode and the first lens in the galilean beam expander can be considered arbitrary. Since it is still desired for the whole system to be portable, the laser diode was placed from 3 cm away from the initial lens to give enough space for the mounts the components were mounted on. It can also be stated that the height of the object (y_0) would be the same as the height of the beam spot size of the laser diode, 3 mm. With these initial values, equation 18 was utilized to find the height of the laser at surface 1 by tracing the ray that travels from the top of the object and is parallel to the optical axis. When the initial values are plugged into equation 18, it becomes clear that since the angle of refraction (u_0) is equal to 0, it causes the second half of the equation to cancel out and y_1 is equal to 3mm. The calculated height at surface 1 and equation 17 was used to find the angle of refraction through the material of the lens. Because the original angle of propagation was 0, the equation simplifies to be the product of the negative one, the height of the ray on surface 1 and the optical surface power, which can be described by the following equation.

$$\phi = \frac{n'-n}{R}$$

Equation 18: Surface Power

Where R equals the radius of curvature of the lens. It is known that the refractive index of N-BK7 optical grade glass is 1.51509 and the radius of curvature of the plano concave lens is -12.9 mm. The surface power 1 was then calculated using equation 18 and found it to be equal to -0.0388 mm^{-1}. The surface power and the height at surface 1 was then used to calculate u_1 and find it to be equal to 0.1163 radians. From equation 17, it can be seen that the value is technically equal to n_1u_1; and since we know the refractive index of the lens, u_1 is equal to 0.0775 radians.

The calculated values of y_1 and u_1 from surface 1 were used to solve for the values of y_2 and u_2 at surface 2 using the same process. To solve equation 18, the distance the light traveled between surface 1 and 2 must be known, and can find it to be equal to the thickness of the plano concave lens which is 3 mm. The value of y_2 was then calculated, finding it to be equal to 3.233 mm. As we can see from figure 44, the height from surface 1 to surface increased by 0.233 mm, which is a good indication that our lens is oriented in the correct direction to expand light. Because this lens is a plano concave lens, the radius of curvature of the second surface is ∞, which results in a surface power of 0. With this in mind it can be seen from equation 18 that if ϕ is equal to 0, then $n_2u_2=n_1u_1=0.1163$ radians. Because the medium that light will be traveling through after surface 2 is air, the refractive index is 1 resulting in u_2 to be equal to 0.1163 radians.

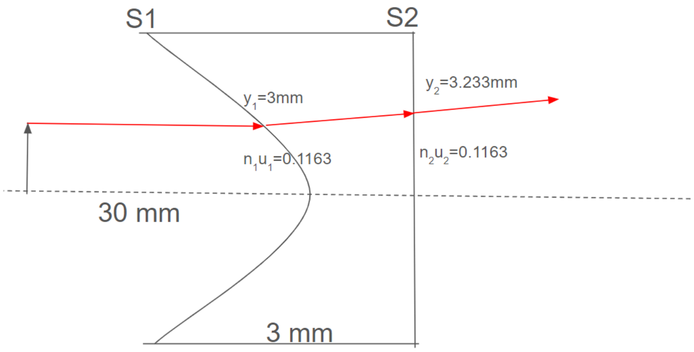


Figure 47: Paraxial Ray Tracing Through Lens 1

The light then travels from surface 2 through open space for 10 cm to enable the light to expand to 5x the original magnification until it reaches surface 3. Once again we used the height at surface 2, the angle of refraction through surface 2, and the distance between surfaces to calculate the value of y_3, finding it to be equal to 14.86 mm. As it can be seen from figure 43, surface 3 corresponds with the plane surface of the plano convex lens, the surface power is equal to 0 and therefore n_3u_3 is equal to 0.1163 radians. The value of u_3 alone is 0.0775 radians, and this is calculated by dividing n_3u_3 by the refractive index of N-BK7 optical grade glass.

The light would then travel a distance of 2 mm as it goes from surface 3 to surface 4. The distance traveled as well as y_3 and n_3u_3 were used to solve equation 16 for the height at surface 4, finding the value of y_4 to be 15.016 mm. To find the angle of refraction at surface 4 the value of the radius of curvature of the plano convex lens must be known, and from the specification sheet we knew it was equal to -64.4 mm. The radius of curvature is negative in this instance due to the curved surface of the plano convex lens is bent away from the center of the lens and is the second surface light is incident on. Equation 17 was then used to find the angle of refraction as light exits the galilean beam expander, finding n_4u_4 to be equal to -3.009×10^{-4} radians.

The values that were calculated throughout the paraxial ray trace were used to confirm the parameters of the galilean beam expander. This was done by solving equation 16 for the value of t when the variable y_5 is equal to 0, and for this lens system we found that light will travel 50 m before it crosses the optical axis. This can also confirm the magnification is correct by taking the height y_4 and divide it by the height of the original object, finding it to be roughly 5.0052 magnification. Through testing of physical components, we confirmed the calculation obtained through paraxial ray tracing.

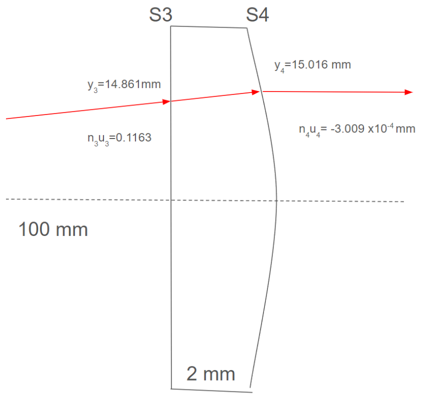


Figure 48: Paraxial Ray Trace through Lens 2

8.3.2 Snell's Law Calculations

Once the laser light has been expanded by passing through our galilean lens design, the angle of refraction was calculated as it passes through the wedge prisms. Similar to paraxial ray tracing, equation 4 is repeated for each surface of the prism. Risley prism pairs are oriented in a way so that plane surfaces are facing each other, with the angled surface facing away from each other. Usually the angle of incidence of light would be equal to 90° in reference to the surface normal; however, since the first surface of the wedge prism is slanted by the wedge angle, the light is incident slightly off the axis of the surface normal. To do this it is important to take advantage of geometrical and trigonometric principals to find the relevant angles needed to solve equation 4. From the specification sheet of the wedge prisms that were selected that both have a wedge angle of 18°; therefore, it is known that the angle of incidence at the first surface (θ_1) is equal to 18°. Equation 1 can now be manipulated to solve for the angle θ_2, finding the result to be equal to 11.81°. Because the light is traveling from air with a refractive index of 1 to N-BK7 glass with refractive index, it is known that the light will bend toward the surface normal. To solve for the θ_2, the angle of incidence must once again be found in reference to the surface normal as the back half of the prism is a plane surface and would have a different orientation in reference to the first surface. To find the angle θ_3, the angle between the optical axis and the refracted light (θ_a) must be calculated, as they are congruent angles through the opposite interior angle theorem. It can be seen that θ_a and θ_1 are congruent angles, resulting in θ_a being equal to 18°. Now it can be seen that the angle θ_a is bisected by the ray of light, which indicates that to find θ_3 the group must find the difference in angle between angles θ_a and angle θ_2. When this is done, the value of θ_3 is equal to 1.02°, which can now be used along with the refractive index of N-BK7 glass to solve equation 1 for θ_4, finding it to be refracting at an angle equal to 9.39° away from the surface normal.

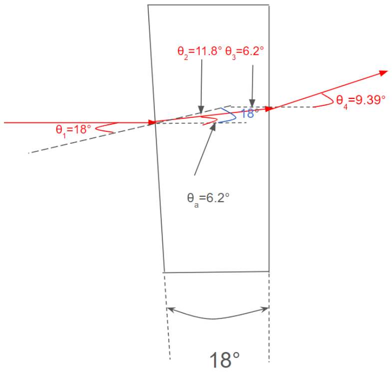


Figure 49: Snell's Law Through Prism 1

The second prism in the Risley pair is placed roughly 5 mm away from the back surface of the first prism. This distance was chosen because the wedge prism must be a short distance apart to achieve the correct angle of deviation listed on the specification sheet. The front surface of the second prism is the plane surface meaning the angle of incident in relation to the surface normal (θ_5) is equal to the angle θ_4 that was calculated from the back surface of the initial prism. With this, equation 1 was used to solve for the θ_6 finding it to be equal to 6.2° and is refracting toward the surface normal. The back surface of the prism is slanted at an angle of 18° and because of this the angle of incidence must be calculated in reference to the surface normal (θ_7). To do this the smaller interior triangle is created as the ray of light travels from surface 1 to 2 and the wedge angle is utilized. This is done by taking the sum of θ_6, 90°, and the wedge angle and subtracting the sum by 180° to find the final angle on surface 2. Once this process is done, the value of that the angle is equal to 65.99°, and we can see from figure 47 that the difference between the surface normal of 90° and 65.99° getting an angle of 24.01°. θ_7 and equation 4 can now be used to solve for the final angle of deviation, finding it to be equal to 32.85° in reference to the surface normal. Since the final surface is slanted by 18°, the angle is shifted by that angle in relation to the optical axis. When the angle was calculated in relation to the optical axis, the angle of deviation is 20°

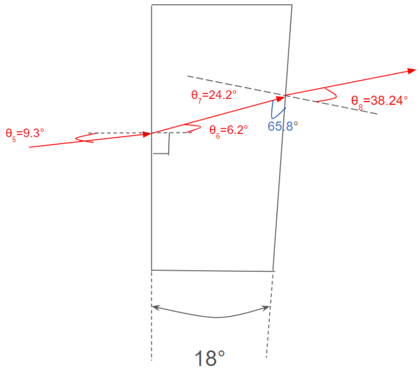


Figure 50: Snell's Law Through Prism 2

8.3.3 Optical Axis Design

By utilizing equation 4, the angle of deviation listed on the specification sheet was found to be consistent with calculated angle of deviation. Although equation 4 does not give the distance to space the Risley pair, the combination of prisms will function as intended so long as all of the light is incident within the diameter of the prism. The final angle of deviation of the Risley pair was used to calculate the size of the opening needed for our device. Before this was done, the group must determine on the optical axis where all the components in both the galilean beam expander would be placed. The Risley pair was placed within the housing of the device. The group will place the laser diode that was selected at the beginning of the optical axis and will take up 2 cm of space. The plano concave lens with a thickness of 4.7 mm would then be placed on the optical axis 3 cm away from the laser diode, as this distance is arbitrarily chosen for portability. The plano convex lens was placed 10 cm away from the initial lens of the beam expander and has a thickness of 2 mm. Once the light passed through the galilean beam expander and was collimated, the laser beam would eventually converge to the optical axis at a distance of 50 m; therefore, the Risley pair must be placed before this distance. Since the distance that it would take light to converge to the optical axis is far greater than either the entrance of the device or the intended operating distance, the space after the second lens can be considered as arbitrary and we chose to space the wedge prisms 3 cm away. Both of the wedge prisms are identical, and have a thickness of 3 mm each. The spacing of between the prisms was decided to be 5 mm, as Risley prisms are designed to have minimal spacing. The sum of all of these distances was used to see how much space within our device, finding it would require a minimum of 19.8 cm. The distance of the optical axis was subtracted from the total length of our device (30.5 cm) to find the distance between the final prism and the entrance to the device, with us finding it is equal to 10.7 cm. The 20° angle of deviation along with the distance that was just calculated to find the radius needed for the opening of our device. This was done by taking the product of 10.7 cm and tan(20°) to find the radius of the entrance is equal to 3.89 cm.

The play area of the device was calculated by utilizing the angle of deviation from the wedge prisms and the distance of the device to the intended play area. As the device is meant to be portable, the play area was calculated at several different distances to simulate this. The play area was calculated at the operating distances of 1 m, 5 m, and 10 m to have a range of play area sizes. This was done by finding the product of tan(20°) and the operating distances; calculating the play areas to be a circle with a radius of 6.993 cm, 34.963 cm, and 69.927 cm for the operating distances of 1 m, 5 m, and 10 m respectively.

8.4 Printed Circuit Board Hardware Design

Below is the process for designing the group’s electrical hardware system. The parts of the electrical hardware are the microcontroller, the bluetooth shield, the motor driver, and the interface for each of them.

8.4.1 Hardware Design Process

Overall, the general process of designing electrical hardware is called the waterfall methodology. This methodology uses a step by step process where each part of the system is designed in order. This is in contrast to agile methodology that builds all the parts of the system at the same time and uses continuous integration and testing methods to build and test the system at the same time.

The steps to use the waterfall methodology are first begin with system requirements, research the best solution to implement those requirements, create a system block diagram, create sub-system block diagrams if required, then do analysis on the sub-systems to ensure the requirements are met, next create an individual version of each subsystem, then test each subsystem individually. After subsystem testing then the team will do system integration testing.

8.4.2 Printed Circuit Board System Design

The process of printed circuit circuit board system design is similar to overall system design with some caveats. There are several steps: the first step is to define requirements, the second step is to meet those requirements, using a block diagram, then the third step is to find components that meet the system requirements of the printed circuit board.

The system requirements were defined previously under the section labeled ‘Engineering requirements’. Next the group made a block diagram that detailed each sub system, and each subsystem's responsibilities. However, the printed circuit board houses several of his sub systems. Below is a diagram of the subsystems within the printed circuit board. Since the printed circuit board holds several systems the description of the design of these systems shall be broken up section by section.

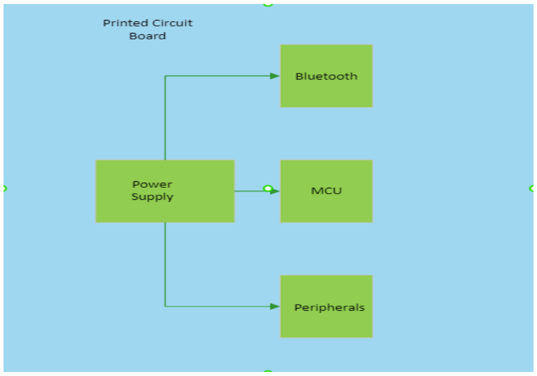


Figure 51: PCB Distribution

Version 1:

The reference design chosen for this project is the Arduino mega. The reasons for choosing the Arduino manga are detailed in the report above in the section labeled “Parts Selection”. Below is a screenshot from the reference design provided by the Arduino standard for an Arduino mega.

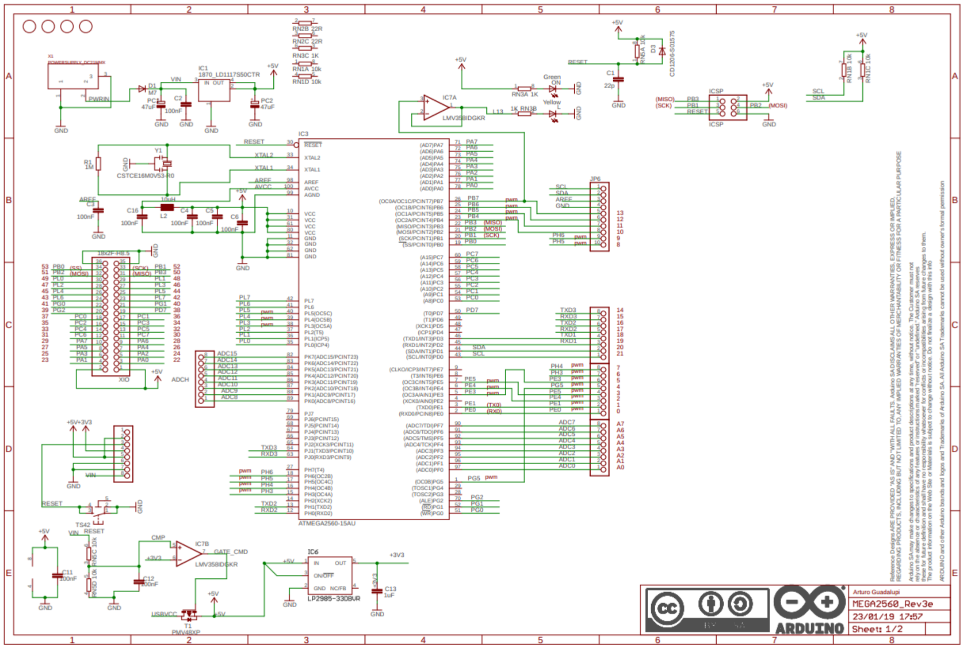


Figure 52: Schematic of Printed Circuit Board Version 1 (Courtesy of Arduino Foundation)

Depending on the needs of the project, there shall be two or three versions of the printed circuit board. The first version shall be a copy of a traditional Arduino mega. The second version shall be a modified version of the Arduino Maga that suits the needs of the project. The purpose of the first version is to find any inadequacies in the printed circuit board design process. The purpose of the second version is to provide the project with a more suitable printed circuit board. The first version of the board is solely based on a traditional Arduino mega. The second version will have the following changes; the linear dropout regulators will be different, the Arduino 16 U2 integrated circuit that is traditionally used on an Arduino. The Arduino 16U2 will not be present, and will be replaced by FTDI which is a USB to serial peripheral interface converter. The schematic for the finalized version is in the section labeled hardware schematics. This shows the schematic of the printed circuit board that is intended to be the finished product.

After testing version 1 the group decided to quickly move on to version 2 of the board. Version 1 of the board had a short and overheated. Furthermore the batch of ATMEGA 2560's the group received were very susceptible to electrostatic discharge and it is likely that the MCU burnt due to electrostatic discharge. The group determined this under Dr. Art Weeks' guidance.

Version 2:

As said previously there shall be at least two versions of this board. This first printed circuit board is shown and was discussed above. The second board shall be discussed below.

The main purpose of the secondary board is to make a board that is built for the team's purposes. The rationale behind making two boards is to be able to quickly design software and test integration of the various systems. The second board shall be more power efficient, will need fewer connectors, and will use less power due to the changes that the team has made for the purpose board.

Below is a screenshot of the second version board and is the microcontroller section of the board. There were several reference designs used by the team to construct the board. The first reference design is the ATMega 2560 datasheet, since the ATMega 2560 datasheet has similar requirements as the Arduino Mega this design is largely the same as version one of the team's board. The second is the EVK-NINA-W1 and EVK-NINA-B3 users guide. The third reference design is from the manufacturer of the FT220XS.

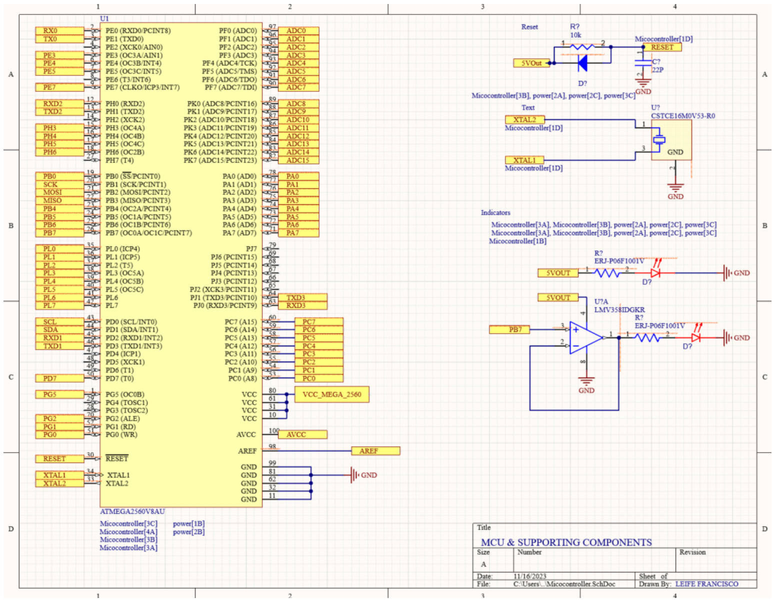


Figure 53: Microcontroller and Supporting Components Schematic

The overall description of the schematic diagram above is on the left is the microcontroller and on the right is the crystal oscillator, two light emitting diode power indicators, and the reset button system.

The microcontroller on the right is connected according to the datasheet to its appropriate and respective parts. The respective parts are off page because it makes the schematic cleaner and easier to read. The purpose of each of these systems will be discussed briefly.

The reset button is a button connected to the reset pin, a resistor, a capacitor, and a diode. The purpose of the resistor capacitor network is to act as a low pass filter. The reason a low pass filter must exist on the entrance of the button is to make sure that high frequency changes in voltage, that occur when the reset button is pushed, are not forced into the microcontroller which is sensitive to these effects. The diode functions as a way of preventing back electromotive force from traveling from the capacitor to the power system labeled 5VOUT.

The crystal oscillator provides the clock input for the microcontroller and controls the way that the microcontroller functions and the processing speed.

The two light emitting diode indicators are used to ensure that the proper voltage signal is present. One of the indicator circuits is the input of an op amp

Furthermore each of the pins on the microcontroller have a purpose. The pins on the microcontroller that will be used by the project are the serial peripheral interface pins and the general purpose input output pins. The reason the project will use the serial peripheral interface pins is that the serial peripheral interface can act as a bus. This purpose is able to process data quickly and can have many peripherals connected to it at once. The purpose and reasoning to use a bus is to enable the user or future hobbyists to add more functionality to the design. The purpose of using the general purpose input output pins is to allow the software design team to have the flexibility to use whatever pins the software design personnel or team needs to use. Another benefit of using GPIO pins is to allow the hardware design to use short traces which as a general design principle is a good rule of thumb to make sure that miscellaneous problems do not arise in the printed circuit board. For example using shorter signal traces reduces the resistance and inductance of each trace. Another benefit of using shorter signal traces reduces the complexity of design and can reduce the need to 'design out' effects like crosstalk (magnetic coupling between two traces that results in lower signal integrity).

Version 3:

Version 3 of the printed circuit board was made to reduce complexity, reduce cost, and make a functional system to fulfill the group requirements. The reason for choosing the ESP32 is that the ESP32 has a cheap development board, is easy to integrate with arduino code, and has an integrated antenna.

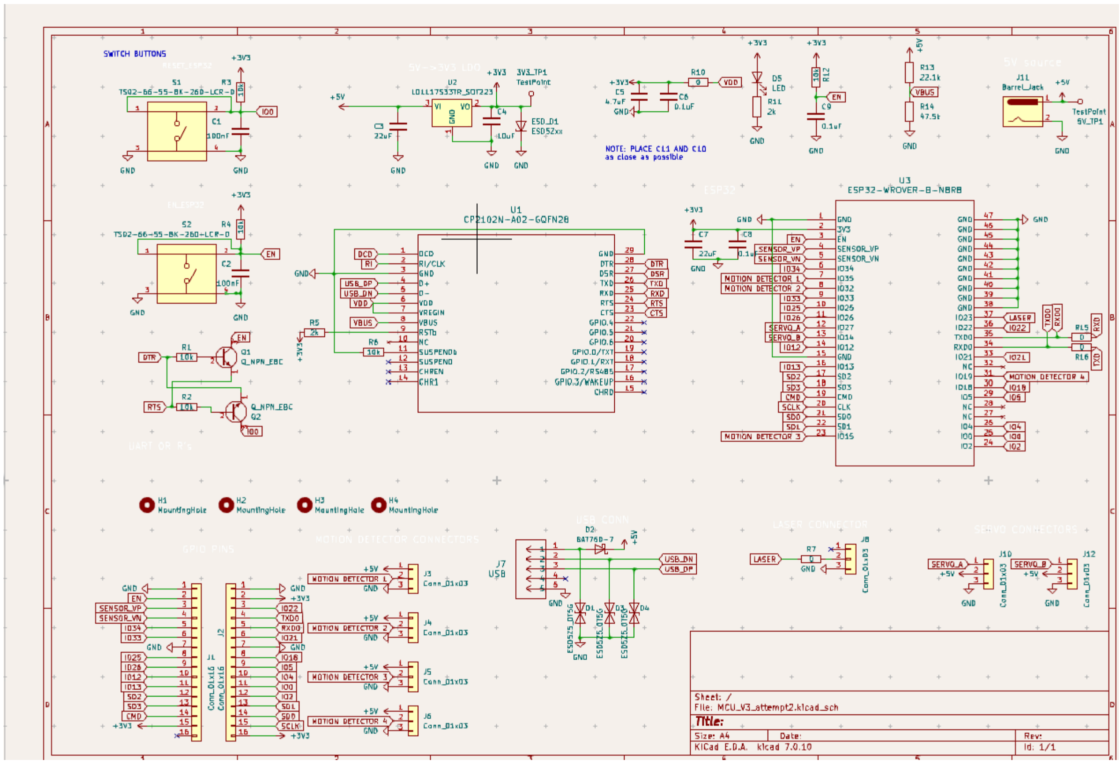


Figure 54: third version of the printed circuit board and schematic

8.4.3 Bluetooth Module System Design

The following steps were used to design the bluetooth subsystem; first research was done using the standards written by the Bluetooth Core v.40 standard, second link budget analysis was used to establish the signal power and noise power, third using these parameters a bluetooth module was chosen, fourth the schematic was made using an application note and reference designs to ensure proper layout.

This paragraph describes the link budget analysis done to find the signal power and noise power. First the group used the Friis transmission formula to find the signal power. The Friis Transmission formula finds the signal power at a specific frequency and distance. However, it assumes the path loss is the free space path loss. This assumption provides a simple first order approximation method to find the signal power. However, since the Friis Transmission formula relies on this assumption a margin of ten decibels was subtracted from the minimum receiver sensitivity to account for losses and unknown effects like multipath, fading, atmospheric attenuation, etc. Below is a picture that shows the formula and the values used for the formula.

There are two types or forms of freeze transmission formula. There is the contemporary type, and the original form for the purposes of this project. The contemporary formula shall be used and it shall be used in decimal form. $P_R = P_t + G_t + G_R + 20log_{10}(\frac{\lambda}{4\pi d})^2$. Each of the variables in this formula have a specific meaning. The first value, P_t, is the power transmitted by the antenna. The second value is the gain of the transmitting antenna. The third value is the gain of the receiving antenna. The fourth value is the path loss.Extensive background knowledge of this formula is not applicable to the application that the group will use it for however this formula provides a quick and simple way to ensure that the values given by manufacturer and the values used by the board designer that produces the reference designs used by the team are logical.

To review the Bluetooth Core Standard says that the module must be able to do several things; first it must be able to receive from 2400 - 2483 MHz, second the sensitivity must be -90dBM, third the module must be selective, fourth it must be able to block interference. This criteria gives a baseline for the group to ensure that the provided reference designs are adequate.

Version 1:

The first version of the printed circuit board will be separate boards that are connected via their individual pin heads. Or more simply explained version one will be a series of evaluation boards that are connected via their pins. As stated previously the purpose of doing this in version one is to make sure that the design process used by the team is the correct way of creating a board. And then the second version will be purpose built, have a small form factor, and fit the design criteria of the group's project.

Below is a screenshot of the bluetooth module on its own printed circuit board. This is version one. The reference design used to make this board is the EVK-NINA-W1 user's guide.

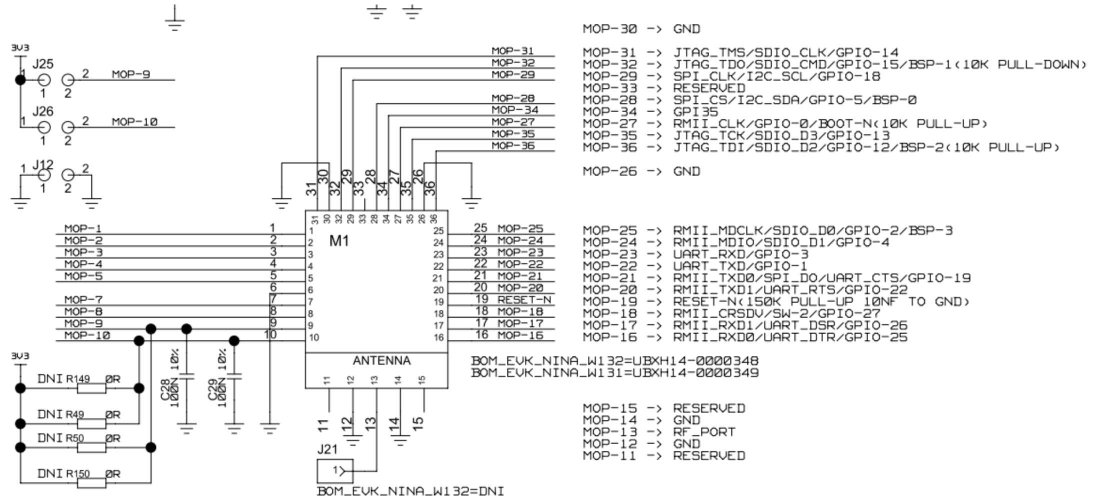


Figure 55: Bluetooth Module Reference Design (Courtesy of EVK-NINA-W1 and EVK-NINA-B3 user guide)

Version 2 of the bluetooth module:

Below is a screenshot of the bluetooth module as a part of the finalized printed circuit board. This is version two. It is integrated in the same package as the microcontroller, the

FTDI chipset, and the power electronics. The reference design used to make this board is again the EVK-NINA-W1 user's guide.

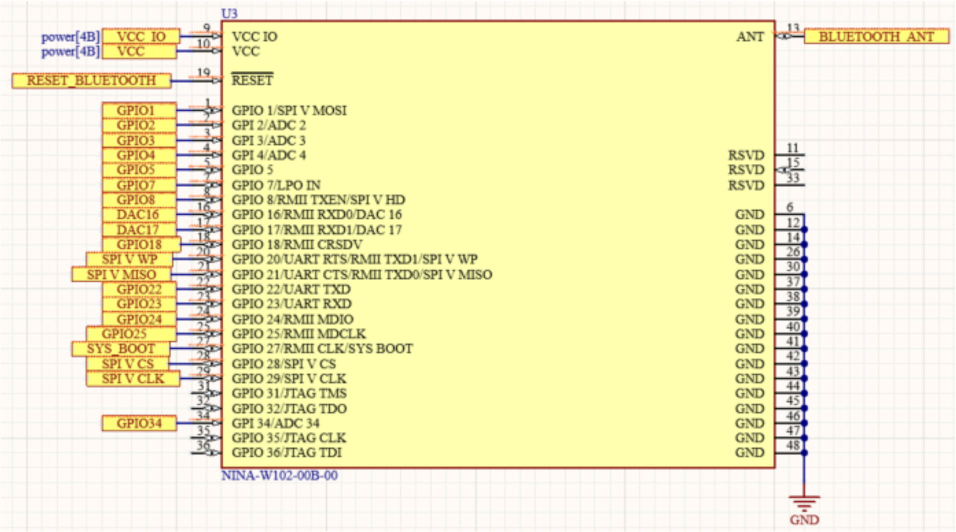


Figure 56: PCB Schematic (Courtesy of EVK-NINA-W1 user guide)

There are forty eight pins on the NINA-W102-00B-00. The pins that this project shall use are the SPI pins, the power pins, and the BOOT pins. The rest of the pins are either not connected, reserved, or grounded.

First the SPI pins are the following; SPI MOSI, SPI V MISO, SPI V CS, SPI V CLK. The purpose of the SPI V MOSI is that it functions as the controller output. The SPI V MOSI sends data from the controller to the receiver. The SPI V MISO stands for serial peripheral interface 5 master in slave out. The SPI V MISO functions as a way for the NINA-W102-00B-00 to receive data from a peripheral or receiver. The SPI V CS stands for the serial peripheral interface V chip select pin. The purpose of this pin is to essentially turn on the system so that data transfer can begin. The final serial peripheral interface pin is the SPI V CLK pin. This stands for serial peripheral interface V clock pin. The purpose of this pin is to act as a clock that tells each system, the main and the sub, when data transfer occurs.

The second set of pins that will be used are the VCC_IO and the VCC pin. The VCC and VCC_IO pins are the pins that provide power to the chip.

The third pin that is used is the RESET pin. The RESET pin resets the system without turning off the enable of the linear dropout regulators that power the system.

The remaining pins will not be connected since they are not needed. The pins and their purpose will be summarized at the end of the discussion in order to provide a neat representation of their purpose and connections. Specifically it should be mentioned that the ANT pin, the antenna connection pin, is not connected as well. The reason this pin is not connected is that the NINA-W102-00B-00 has an onboard chip antenna that meets all the requirements for bluetooth connections and therefore does not need to be connected.

Version 2 shall have an FTDI chip. The FTDI chipset is shown below and the reference design used for this chipset is the reference design from the manufacturer of the FT220XS.

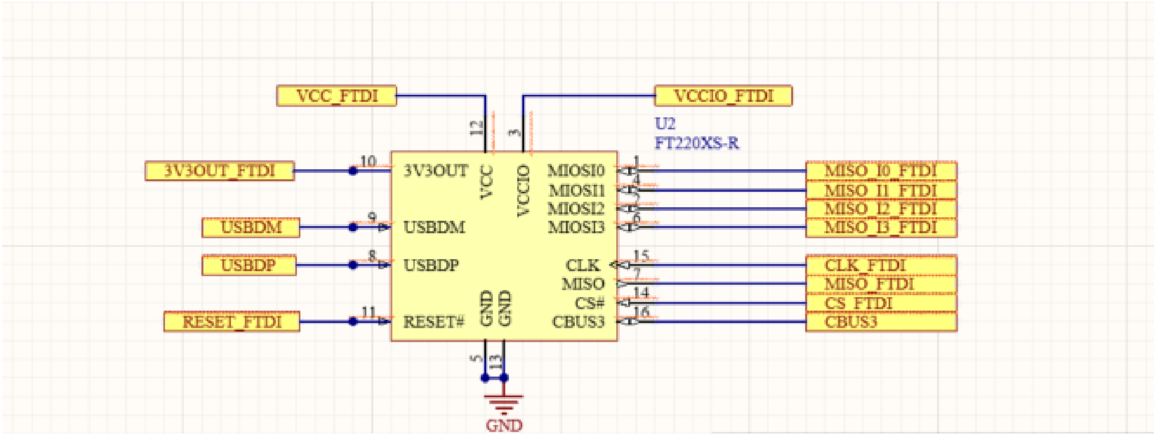


Figure 57: FTDI USB to Serial Converter Schematic

The FT220XS is a chipset that converts data from universal serial bus to serial peripheral interface. The reason the group chose to make this change is that on the previous board the ATMEGA 16 is used to convert from universal serial bus to serial peripheral interface. This is a simple system design that does not use the full potential of the ATMEGA 16. This chipset, the ATMEGA 16, is power intensive and adds several auxiliary components that the FTDI components do not need.

The pins for the FTDI chip that are connected are the power pins, the serial peripheral interface pins, and the universal serial base pins.

Pins 1,2,4,6 are MIOS pins. These pins are not necessary for the design that are used in the board. Since these pins are not necessary they are not connected.

The 3V3_Out pin is an output voltage pin that provides 3.3 volts to the universal serial base connector. This pin provides power for that system. The USBDM and USBDP pins are connected to the universal serial base connector. And the FTDI_RESET pin will be connected to a push button. The purpose of this pin is to reset the FTDI chip. This pin is for troubleshooting purposes. The next set of pins are serial peripheral interface pins. The purpose of these pins is to convert universal serial base data from the universal serial base drive that can be connected to the board to SPI which can then be transmitted to the microcontroller.

The last part of the system that was designed is the power system. The power system is shown below. This power system used all three reference designs to make the power supplies for each of the systems.

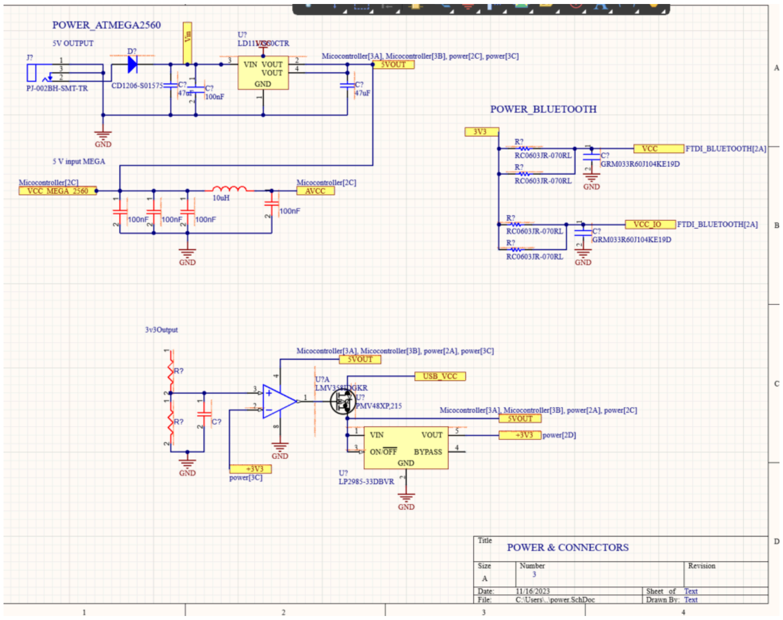


Figure 58: Power And Connectors Schematic Version 2

The purpose of this paragraph is to discuss each part of the power system in the entire PCB. There is an alternate power system that provides stable voltage and current that features a charge controller. However, that section will be featured later in the paper.

First is the power for the ATMEGA_2560 itself. This system is featured in the top left hand corner of the schematic shown above. There are many components and each has an individual purpose in the design. First is the connector in the top left. The purpose of this connector is to allow the entire printed circuit board to be powered by a standard connector used to power most hobbyist boards. This connector attaches to the pin of the connector labeled PJ-002BH-SMT-TR.

The next component is a power diode. The purpose of using this power diode is to prevent back electromotive force that will be stored in the two decoupling capacitors that are used in the pin labeled ‘VIN’ to the linear dropout regulator. The two decoupling capacitors are forty-seven and one hundred nanofarads. The forty-seven nanofarad capacitor is meant to prevent low frequency spikes or signals that can occur. The one hundred nanofarad capacitor is meant to prevent high frequency signals from passing to the input of the linear dropout regulators. The way capacitors do this is they provide a lower impedance path to ground relative to the input of the linear dropout regulator to their respective high frequency signals. The output of this network feeds several pins on the microcontroller that have been discussed above.

The next network is labeled ‘5 V input MEGA’. This network is a simple ‘PI’ filter that has three one hundred nanofarad capacitors, one ten microhenry inductor, and another one hundred nanofarad capacitor on the output. This ‘PI’ filter is an extremely effective method of filtering transients that may come from the output of the dropout regulator in certain specific cases.

The next network is labeled ‘POWER_BLUETOOTH’. This has two outputs each to the FTDI chip. Each of these networks have two zero ohm resistors and a one hundred nanofarad decoupling capacitor. What is the purpose of a zero ohm resistor? The purpose of a zero ohm resistor is to provide a testing point into the input of a circuit. As stated above in the power module section decoupling capacitors provide a low impedance path to ground for high frequency signals.

The next network is the three point three volt network. The purpose of this network of components is to provide 3.3 volts. There are two resistors, a capacitor, an op amp, a mosfet drive, and a linear regulator. First the purpose of the two resistors is to reduce the voltage by one half. The purpose of the capacitor is to act as a low impedance path for high frequency signals (it is a decoupling capacitor). Next the purpose of the metal oxide semiconductor field effect transistor is to act as a switch for the output of the operational amplifier; essentially it switches on and off the voltage from the universal serial base connector, and to the linear regulator. Next is a linear regulator. This regulator switches 5 volts from the universal serial base supply to three point three volts for the components that need three point three volts. Next the output of the linear regulator is connected from the linear regulator to the inverting terminal of the operational amplifier. Finally, the operational amplifier acts as a comparator. The purpose of this comparator is to compare the input voltage and the linear regulator volt and drive the gate of the metal oxide semiconductor field effect transistor. The purpose of doing this is to make sure that if the input voltage equals or drops below three point three volts the switch (the MOSFET) driver will turn off which will in turn disable the linear regulator and safely turn off all the components that depend on it.

Pin Number	Pin Name	Description
20	SCK/PCINT1	Serial Clock
21	MOSI/PCINT2	Data Transfer for the MCU
22	MISO/PCINT3	Data transfer for the Peripheral
30	RESET	Resets the MCU
33	XTAL2	Oscillator 2
34	XTAL1	Oscillator 1
0,1,4,5,53-60	Digital I/O (GPIO)	General purpose pins for the software team.

Table 32: Microcontroller Pin Mapping

Pin Number	Pin Name	Description
9	VCC_IO	Input output pins power

10	VCC	Bluetooth module power
19	RESET	Reset pin
20	SPI V WP	SPI pin
21	SPI MISO	MISO pin
28	SPI V CS	Select SPIN pin
29	SPI V CLK	SPI Clock Pin

Table 33: Bluetooth Module Pin Mapping

Printed Circuit Board Layout

Below is the layout of the boards that the group will use to make the finalized project.

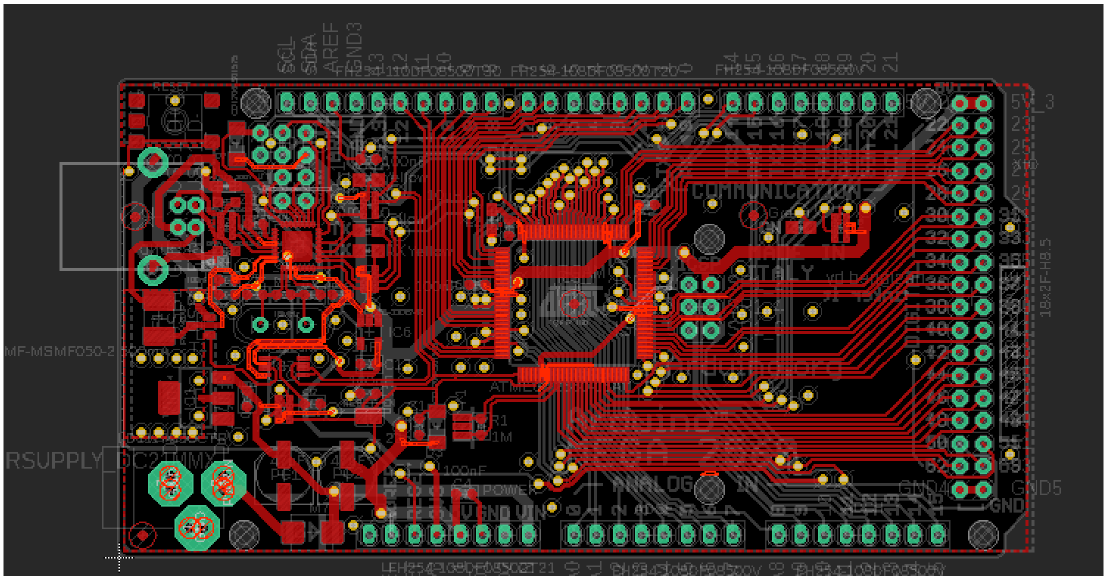


Figure 59: Layout of Printed Circuit Board Top Layer

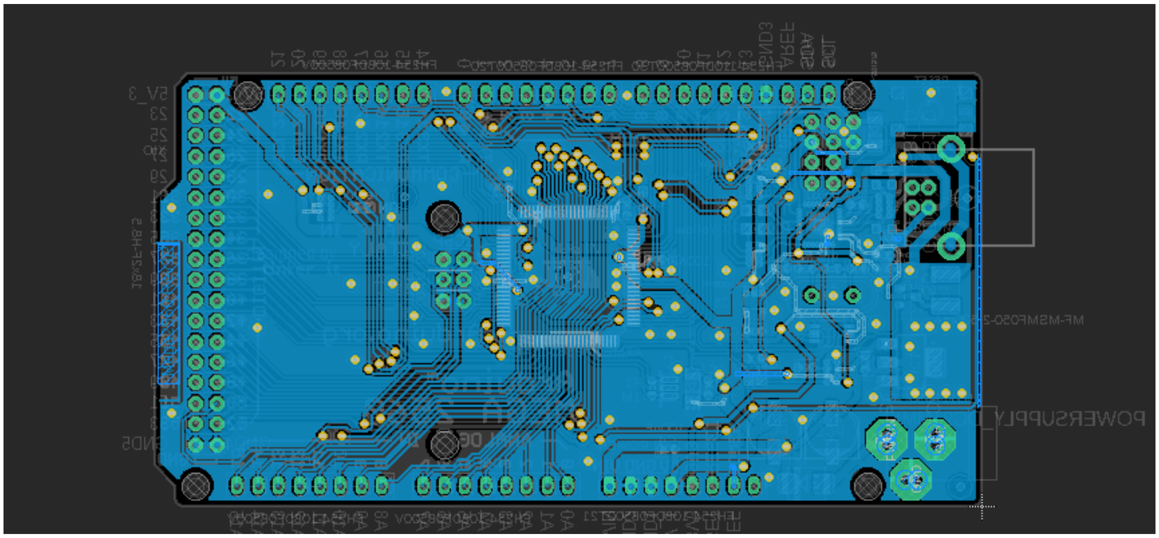


Figure 60: Layout of Printed Circuit Board Bottom Layer

The final and third version of the printed circuit board required a new layout since the group switched to the ESP32. Below is a figure of the layout of the third version.

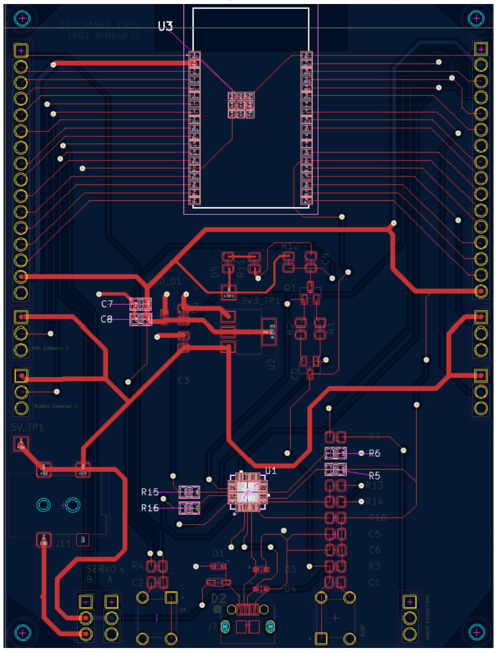


Figure 61: layout of the third version of the printed circuit board top layer.

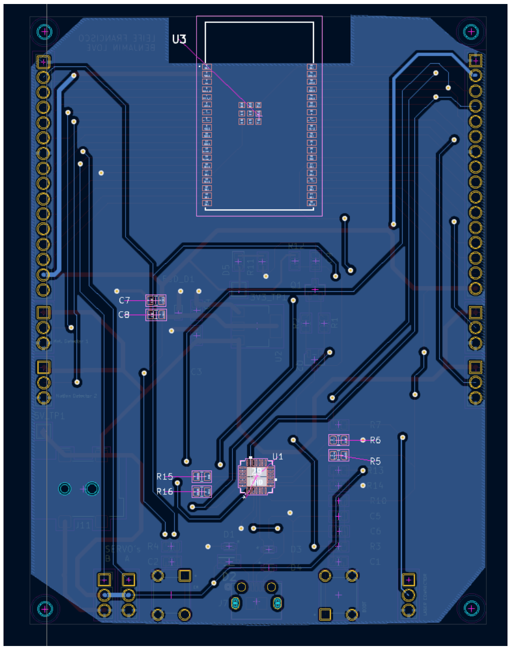


Figure 62: layout of the third version of the printed circuit board bottom layer.

8.4.4 Analysis

8.4.4.1 Link Budget Analysis

Link budget analysis is the process of analyzing signal power and noise power. The formula for signal power usually is the Friis transmission formula. That formula was shown in the previous paragraphs. An important part of the link budget is also the noise power. The noise power formula was not discussed or explained above.

The general recommendation from the Bluetooth Core Standard V4.0 document is to design for a noise power of 100 dBM. Converted to watts this is zero watts. The general recommendation for the signal to noise ratio of ten decibels. This means that the noise power should be ten times less than the signal power. Since the recommended signal power is seventy decibels the noise power must be one watt. Below is a table showing the link budget analysis. A margin of negative ten decibel milliwatts was added in the link budget analysis to ensure that the system is manageable.

Parameter	Formula	Value
Signal Power to Noise Ratio (SNR)(Given)	$SNR = 10log_{10}(\frac{P_s}{P_N})$	10 dB
Signal Power (Given)	$S = 10log_{10}(P_s)$	20 dBM

Noise Power	$N = 10^{\frac{SNR}{10}} * S(dB)$	$N = 10^{\frac{10}{10}} * 0.1 = 1$ Watt
Path Loss	$L_p = \frac{4*\pi*D}{(\frac{f}{c})^2}$	$L_p = \frac{4*\pi*3.08}{(\frac{2400*10^9}{3*10^8})^2}$ =0.61
Received Power	$P_R = P_t + G_T + G_R - L_p$	$P_R = - 44.59\, dBM$

Table 34: Link Budget Analysis Table

*calculated using a calculator from Pasternack Friis Transmission Formula Calculator.

Since the receiver of a bluetooth module is capable of adequate coverage at negative eighty decibel milliwatts. This system design is very robust and it is very unlikely the system will experience problems due to weak signal strength.

8.4.4.2 Power Analysis

The power analysis was done in the open source and free program named LTspice, made by linear technologies. Below are the diagrams of each of these systems. The power analysis stage of the design is usually one of the final stages of design. The purpose of the power analysis stage is to simulate the power circuitry and answer several questions; Does the design output the correct voltage and current? What is the robustness of the design? How does a constant noise signal affect the power stages? How does a transient noise signal affect the power supply? The purpose of the following simulations is to answer those questions.

First, a spice model of the LD1117S50CTR does not exist. Therefore a similar model will be used and tested for the purpose of making sure the design is not catastrophically compromised by the power supply. The component that is similar to a LD1117S50CTR that is available in linear technologies spice models is the LT117. Below is a circuit schematic that was used for the circuit similiation.

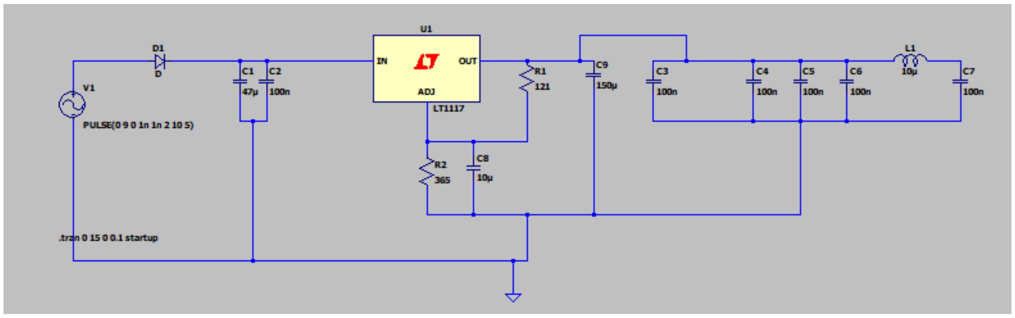
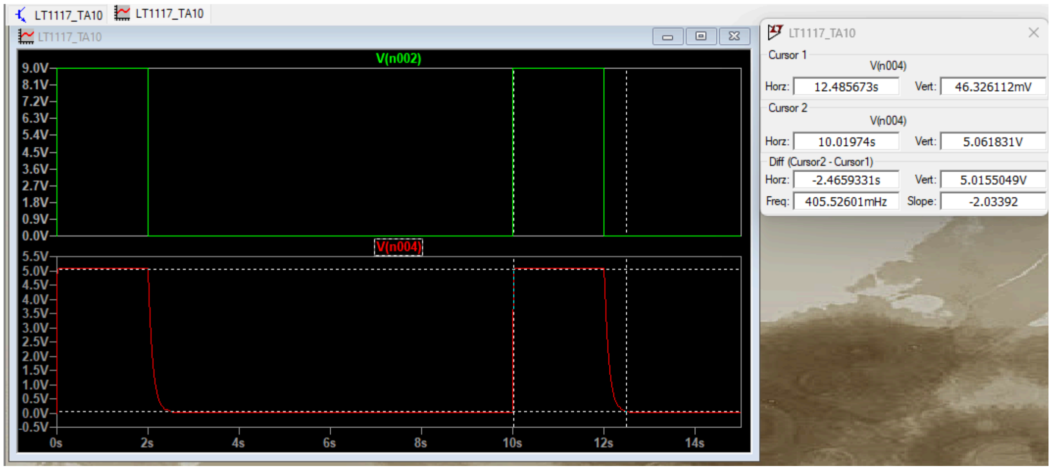


Figure 63: 5.5 Volt Output Analysis Schematic

It is important to notice that the LT117 has a few extra components. It has a bypass capacitor, and two resistors. The purpose of these components is to ensure the output voltage can be adjusted to the proper setting. The results of the first simulation are below.



Cursor 1
V(n004)
Horz: 12.485673s Vert: 46.326112mV
Cursor 2
V(n004)
Horz: 10.01974s Vert: 5.061831V
Diff (Cursor2 - Cursor1)
Horz: -2.4659331s Vert: 5.0155049V
Freq: 405.52601mHz Slope: -2.03392

Figure 64: 5.5 Volt Output Time Domain Analysis

This simulation shows a few things. First the linear regulator is stable to transients; second the linear regulator outputs the correct voltage of 5.06 volts; third if a shutoff or reset event happens then the linear regulator will maintain its proper output voltage for a significant period of time. The next the main power supply was tested for noise stability. Below is a circuit schematic that shows the difference between the original schematic and the new schematic. The only difference is the addition of a noise source labeled ‘B1 V=white(noise)’. This simulates the addition of white noise in the source to the linear regulator.

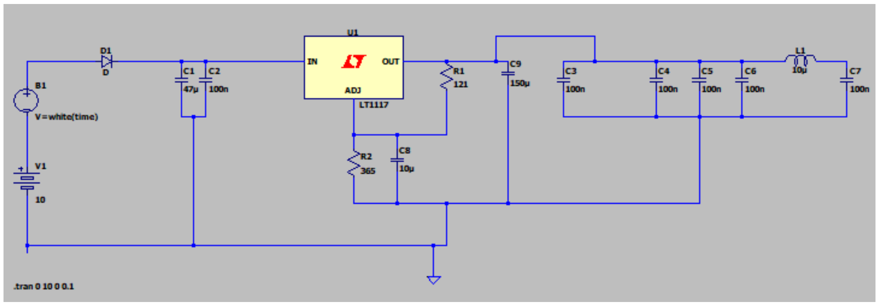


Figure 65: 5.5 Volt Output Schematic with White Noise

Below is a figure of the output voltage and the input voltage. The input voltage is green and the output voltage is red. To summarize the linear regulator’s ability to reject or filter noise meets the design criteria needed by the team.

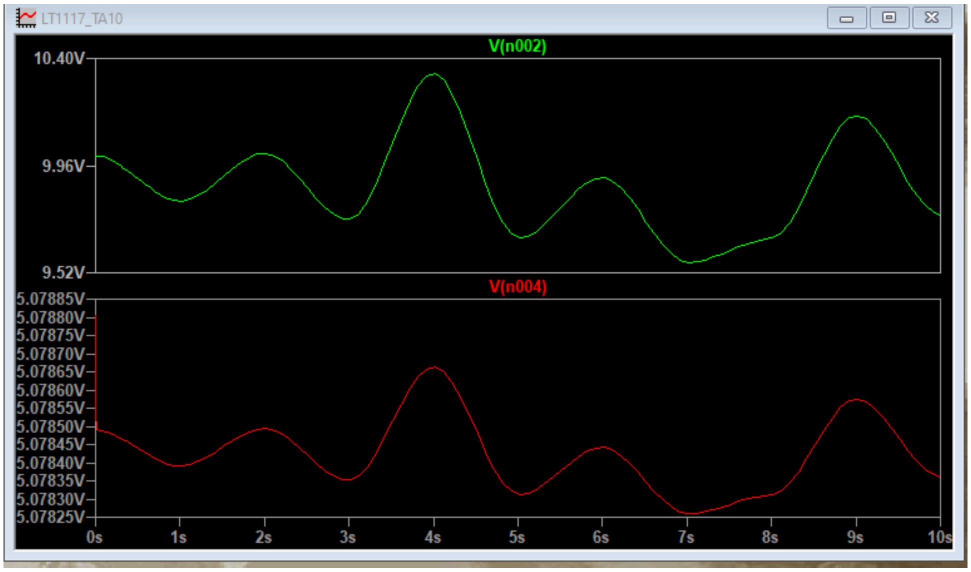


Figure 66: 5.5 Volt Output Schematic with White Noise Time Domain Analysis

Even though the linear regulator is able to reject noise well it is important to discuss the results. First the noise fluctuates from 9.52 volts to 10.40 volts. This is a fluctuation of 0.88 volts. Next the output voltage fluctuates by 0.09 percent. This is less than 1 percent ripple due to noise. This meets the criteria for extremely precise systems and is over designed for the purposes of a cat toy.

The next power system that needs to be analyzed in a similar fashion is the three point three voltage supply. Since the three point three voltage power supply is provided by an onboard FTDI chip or the ATMEGA16 in version 1 or version 2 there is another set of components that ensures there are no voltage spikes. In both versions the purpose of the next circuit in the schematic below is to ensure that the output voltage for the output voltage is resilient to noise and stable. The schematic below shows the second linear regulator that is simulated.

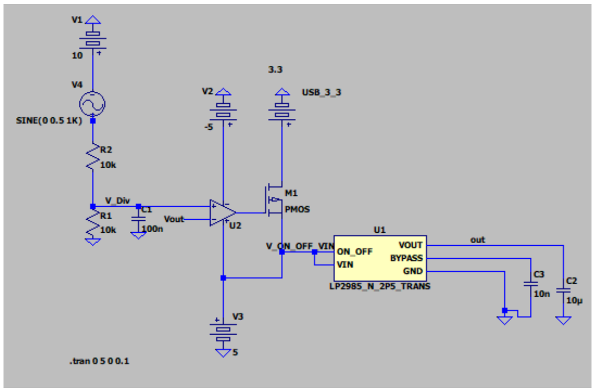


Figure 67: 3.3 Volt Output Schematic

The next screenshot below is one of the results. To summarize, the linear regulator is able to operate at an extremely stable voltage even with a one kilohertz signal that represents noise.

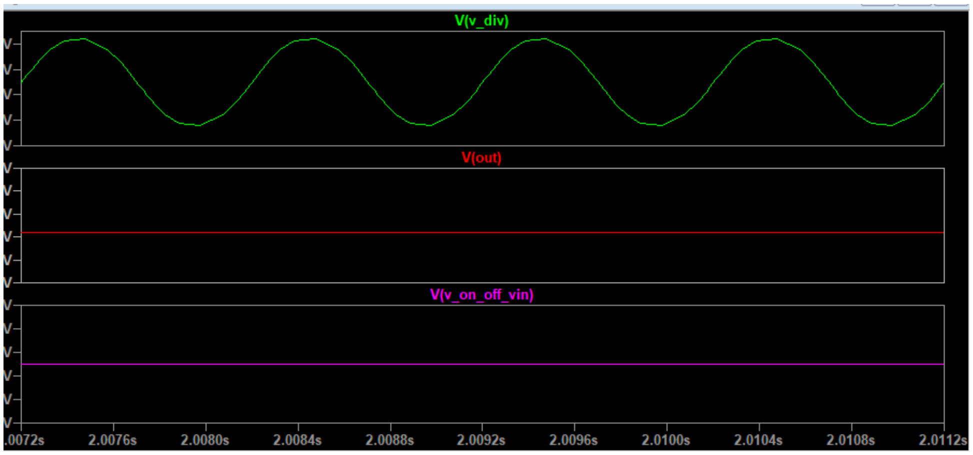


Figure 68: 3.3 Volt Time Domain Analysis with Noise

8.4.5 Power System Design

The power system for this project is deliberately as simple as possible by design. A smaller number of components handling many tasks is desirable for a power system because it improves reliability by removing points of failure, particularly for a battery system. To this end, the majority of tasks for power management were meant to be handled by a charge controller, consisting of only one IC. This component handles nearly all of the basic tasks such as charging the battery, regulating current, and thermal protection, and even user interface tasks such as pushbutton power control and an LED charge gauge. The only other major component is a 3.3 volt low-dropout voltage regulator to power the ESP32 module. All other components are capable of drawing 5 volts. The final design has these components drawing power directly from an AC adapter, but the charge controller contains an integrated switching regulator that would’ve accomplished this same task. Although the battery and charge controller were not integrated into the final project, the discussion on design and integration of the controller has been included here.

8.4.5.1 Development Board Discussion

As previously discussed, a development board for the charge controller was procured for testing. This was deemed necessary for multiple reasons. The first is that the IC features an unusual pin arrangement, which makes the chip incompatible with the majority of breadboard adapters for the package type. (See Appendix Section 8.2: Datasheets for an illustration of the pin layout). The second was that the controller has a very large amount of ancillary components that are adjustable, but require a tremendous amount of initial design if being built up from scratch. These issues were juxtaposed with the necessity of testing the controller immediately.

The development board has a datasheet published by the manufacturer, complete with a schematic. The design and schematic of the board served as a good example circuit, but they contain some missing or underdeveloped features as well as containing application-specific features that are irrelevant to this project. For example, the board contains two USB ports for charging and discharging, with the assumption being that this will be a useful feature for examining the controller for use in a battery bank.

The ancillary circuitry for the charge controller for this project is expected to undergo more than one revision as testing continues this semester as well as throughout Senior Design 2. Key points of consideration for further design work include perfection of an automated charge/discharge mode selection when the AC adapter is inserted, improved tuning of voltage compensation for PCB line loss, and additional thermal management testing.

The following image is the first prototype schematic for the charge controller. Some design considerations and recommendations were taken from the development board schematic for this design. These will be further discussed in detail, but the most noteworthy items include space allocated for optional extra filtering capacitors on the load voltage output. Although the schematic bears a similarity to the development board, many design changes were required to be made to better suit this project.

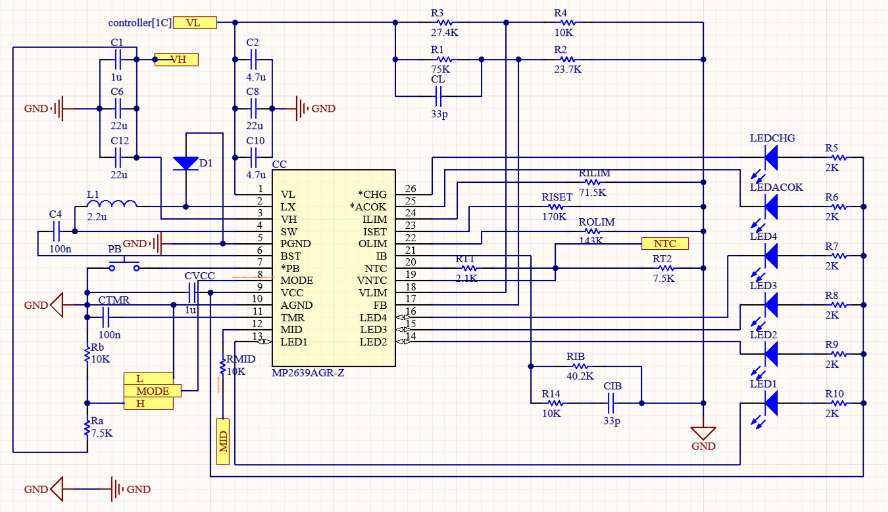


Figure 69: Prototype charge controller circuit schematic

8.4.5.2 Charge Controller Design

The charge controller of choice, the MP2639A, was an all-encompassing chip meant to be used for power management in mobile devices, where consolidation of all of the relevant tasks on one chip is an obvious benefit. Not only does this save on space and complexity, but also improves safety and reliability by ensuring the systems are tightly integrated with each other. It is capable of overseeing many crucial functions, but requires many external components to accomplish these tasks. Additionally, it is what is known as a “standalone” controller, meaning that settings for values such as current limits are set via hardware components such as resistors.

Fortunately, the datasheet lays out very clear instructions on how to specify these components for a given project. Some of the functions are less relevant than others to this project, however. For example, the controller supports loop compensation for output voltage drop. This is a useful feature for a portable battery bank where a long USB cable may see voltage drop, but this will be less likely within this project's printed circuit board.

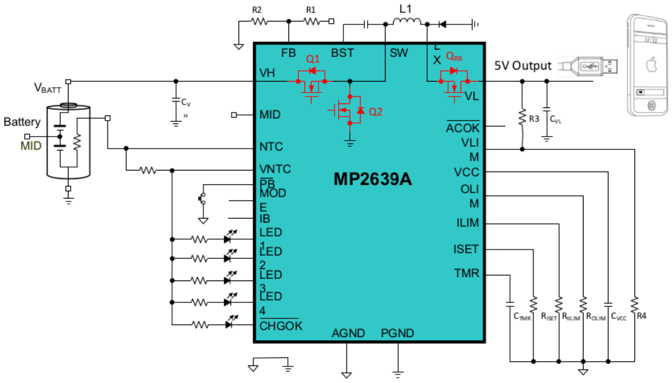


Figure 70: Typical application schematic courtesy of Monolithic Power

Pin Number	Pin Name	Function
1	VL	Low-voltage terminal for 5v input/output
2	LX	Connecting node between inductor and switching node
3	VH	High-voltage connection for positive battery terminal
4	SW	Connection for switching node
5	PGND	Power ground for battery, input/output power
6	BST	Bootstrap. 100nF capacitor connects between here and SW for internal IC use.
7	PB	Push button input for cycling power, checking SoC
8	MODE	Mode selection for charging/discharging. Pulling low enables charge mode, pulling high enables discharge mode.
9	VCC	Internal power supply for IC. Must be bypassed to ground with 1μF capacitor.
10	AGND	Analog ground. Used as ground for resistive parameter settings.

11	TMR	Oscillator period timer. Capacitor of value or shorting to AGND controls charging timeout function.
12	MID	Midpoint tap for 2-cell battery. Used for optional cell balancing, can be grounded to AGND if not being used.
13	LED1	State of charge “fuel gauge”’ indication, 0%-25%
14	LED2	State of charge “fuel gauge”’ indication, 26%-50%
15	LED3	State of charge “fuel gauge”’ indication, 51%-75%
16	LED4	State of charge “fuel gauge”’ indication, 76%-100%
17	FB	Feedback input for voltage compensation in discharge mode
18	VLIM	Input setting for voltage limit in charge mode
19	VNTC	Pull-up bias voltage for NTC voltage divider
20	NTC	NTC thermistor input
21	IB	Output for battery current monitor
22	OLIM	Current limit setting for system output in discharge mode
23	ISET	Current limit setting for battery in charge mode
24	ILIM	Current limit setting for entire system in charge mode
25	ACOK	Charging input supply verification indicator. Pulled low when input source is identified as usable.
26	CHG	Charging indicator. Pulled low when charging is active.

Table 35: Table of Pin Assignments for MP2639A

8.4.5.2.1 Input Current Limit

The controller is capable of routing input power through itself separately from the charge current of the battery. A limit of up to 3 amps can be set for overcurrent protection. This is selected using a single resistor tied to analog ground, which is set with the following equation:

$$I_{ILIM} = \frac{640(k\Omega)}{3 \times R_{ILIM}}(A)$$

Equation 19: Input Current Limit Setting

For this project, an AC adapter capable of 3 amps has already been specified not only for charging the battery, but also potentially for charge-and-play functionality. Specifying a full 3 amps for input current ILIM gives a resistance R_{ILIM} of no less than 71.5kΩ.

8.4.5.2.2 Charge Current

As previously implied, cells have a rated charge current for maximum cell life and safety. This current is set separately from input current in order to allow the controller to know how much "overhead" is available between input current capacity and charging current. This setting can be adjusted to up to 2.5 amps. This is selected using a single resistor tied to analog ground, which is set with the following equation:

$$I_{CHG} = \frac{640(k\Omega)}{3 \times R_{ISET}}(A)$$

Equation 20: Charge Current Limit Setting

The selected Samsung cells have a recommended nominal charge current of at most 1.25 amps. This gives a resistance R_{ISET} of no less than 170kΩ. However, this value may change to better match total current requirements of the final project should current requirements be higher than anticipated.

As is standard practice with charging lithium-ion cells, the controller charges the battery in three phases: trickle charging, constant current charging, and constant voltage charging. During all three phases, the voltage output of the charger is designed to be equal to or slightly greater than the battery voltage. During constant current charging, which this specification dictates, the current is fed to the battery at a constant current as the battery voltage rises. When the battery reaches full voltage at around 80 percent state of charge, the charger enters constant voltage mode, which tapers the current off until it reaches the cutoff threshold.

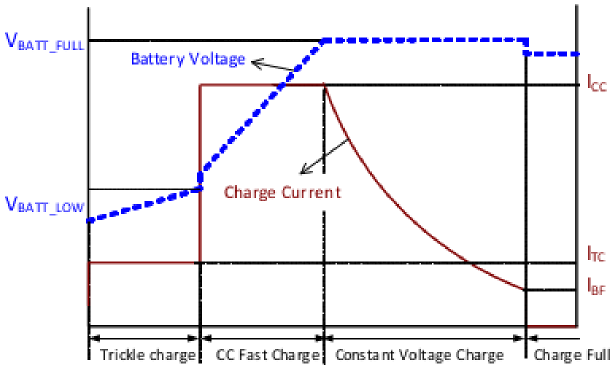


Figure 71: Charging phase graph of controller courtesy of Monolithic Power

8.4.5.2.3 Input Voltage Regulation in Charge Mode

When the controller is operating in charge mode, a resistor voltage divider can be used to stabilize the voltage for charging. The V_{LIM} pin of the controller uses this fraction of the voltage input to adjust the switching voltage for charging accordingly.

$$V_{INLMT} = 1.2V \times \frac{R3 + R4}{R4} (V)$$

Equation 21: Input Voltage Regulation Setting

For the nominal input of approximately 5 volts, the datasheet recommends R3 and R4 values of 27.4kΩ and 10kΩ, respectively. This is basically a requirement given that the controller is already designed to charge the battery at this nominal voltage, so the recommendations will be adhered to.

8.4.5.2.4 Output Current

The controller powers the connected load via a built-in 5 volt switching regulator. The regulator is rated for up to 5 amps of output current, but the current threshold for treating the load as overcurrent or short circuit can be limited below this with the following equation:

$$I_{OLIM} = \frac{640(k\Omega)}{3 \times R_{OLIM}} (A)$$

Equation 22: Output Current Limit Setting

Although the final current requirements of the project are still subject of debate, the total current required will absolutely fall below the 5 amp maximum. The selection at this time is under 1.5 amps, which would complement the present battery charging current. This gives I_{OLIM} a resistance of no less than 143kΩ, but this setting is subject to further review.

8.4.5.2.5 Output Voltage Regulation in Discharge Mode

Similar to the voltage regulation setting in charging mode, the output voltage can also be stabilized in discharge mode. This is done by effectively adjusting the voltage over the nominal value in anticipation of voltage drop. The main recommended purpose of this setting is to compensate for line loss in USB cables, or to compensate for PCB trace resistance in particularly voltage-sensitive applications. In the equations shown, R_{TRACE} is the line resistance from the IC's 5 volt output to the system load, K_{SNS} is a fixed value of 0.3, and R_X is a value of 150kΩ.

$$V_{LOAD} = 1.2V \times \frac{R1 + R2}{R2} (V)$$

Equation 23: Load Voltage Regulation Setting

$$R1 = \frac{R_{TRACE} \times R_x}{K_{SNS}}$$

Equation 24: Trace Resistance Tuning Equation

The selection is fairly simple, but the issue is that it is based on measured resistive values of the PCB, which are not fully known at this time. The development board uses resistors R1 and R2 with values of 76.8kΩ and 24.3kΩ, respectively. Looking at an example selection table in the datasheet implies a line resistance of slightly over 150mΩ for the development board's traces. However, it could also be just as likely that this would be necessary for the voltage drop in a USB cable connected to the board. For the time being, the values from this table will be utilized, giving values of R1 = 75kΩ and R2 = 23.7kΩ. Note that it is possible that these will need to be adjusted for a greater voltage correction due to the fact that the final PCB for the project will be larger than the development board.

8.4.5.2.6 NTC Thermistor

The controller accepts input from a negative temperature coefficient (NTC) thermistor for thermal management of the battery. Thermistors are resistors whose resistance changes with temperature. They are used as a simple, cost-effective means to sense temperature. The "negative temperature coefficient" designation denotes that as the temperature of the thermistor is negatively correlated to its resistance; As its temperature increases, its resistance value decreases. The selected thermistor for this project was manufactured by Vishay, part no. NTCLE100E3103JB0. This thermistor has a base resistance of 10kΩ, which means that the resistance is nominally this value at 25°C, which is approximately room temperature. The equation for the resistance and temperature correlation is shown below, which is used to calculate values besides that of the base. The resistance $R_{(T)}$ is the value for which to be solved at a desired temperature, and R_{ref} is the resistance at a reference temperature, in this case the base value of 10kΩ at 25°C above. The temperature T is the temperature in degrees Kelvin. To reiterate, this is Kelvin, not Celsius, so attention must be paid when cross-examining with the reference value. The remaining variables are constants that are taken from a lookup table in the datasheet. This table contains a large number of values for thermistors of various specifications; The values necessary for the selected component are shown in the table below.

$$R_{(T)} = R_{ref} \times e^{(A + B/T + C/T^2 + D/T^3)}$$

$$T_{(R)} = \left(A_1 + B_1 \ln\frac{R}{R_{ref}} + C_1 \ln^2\frac{R}{R_{ref}} + D_1 \ln^3\frac{R}{R_{ref}}\right)^{-1}$$

Equation 25: NTC Thermistor Resistance at Temperature Equation

Thermistor Parameter	Specific Component Value
A	-14.6337

B	4791.842
C	-115334
D	-3.730535e-06
Nominal Resistance at 0°C	32.54kΩ
Nominal Resistance at 50°C	2.49kΩ

Table 36: Table of parameters for determining nominal resistance values

The controller monitors reference voltages at four temperatures for safety purposes: V_{COLD}, V_{COOL}, V_{WARM}, and V_{HOT}. These correspond to thresholds of 0°C, 10°C, 45°C, and 60°C, respectively. However, a separate area of the design suggests that the controller should be designed so that V_{HOT} should represent no more than 50°C. This was opted for instead. Inserting these values into the above equation gives nominal resistances of 32.54kΩ when cold and 2.49kΩ when hot, respectively. These values will be used for calculating values needed in the voltage divider.

8.4.5.2.7 NTC Resistive Voltage Divider

With the thermistor parameters specified, it can now be integrated into the project. Thermal management is an important feature to have, but requires additional design. The thermistor has its own range of resistance for temperatures, which likely don't correspond with the resistances for appropriate limits of the controller itself. The solution to this problem is to use a voltage divider to scale the resistive range into one which is intelligible to the controller. The layout of this circuit is shown below.

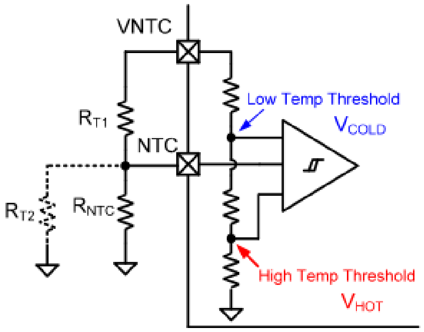


Figure 72: NTC Circuit Schematic

$$\frac{\frac{R_{T2}\times R_{NTC\_COLD}}{R_{T2}+R_{NTC\_COLD}}}{R_{T1}+\frac{R_{T2}\times R_{NTC\_COLD}}{R_{T2}+R_{NTC\_COLD}}}=V_{COLD} \qquad \frac{\frac{R_{T2}\times R_{NTC\_HOT}}{R_{T2}+R_{NTC\_HOT}}}{R_{T1}+\frac{R_{T2}\times R_{NTC\_HOT}}{R_{T2}+R_{NTC\_HOT}}}=V_{HOT}$$

Equation 26: NTC Thermistor Voltage Divider Equation

Also shown is the system of equations for finding appropriate values. In these equations, V_{HOT} and V_{COLD} correspond to predefined values in the controller for temperature. These values are the voltages as percentages of the voltage V_{NTC} (around 47.4% for V_{HOT} and 69.9% for V_{COLD}). V_{NTC} is internally pulled up to VCC. R_{NTC} is the thermistor pulling the NTC pin to signal ground, and R_{T1} and R_{T2} are the divider values to specify. Combining these equations gives values of around $R_{T1} = 2.1\text{k}\Omega$ and $R_{T2} = 7.5\text{k}\Omega$.

8.4.5.2.8 Internal Switching Regulator Components

The controller has two internal field-effect transistors (MOSFETs) employed for switching voltage regulation. This is to use a 5 volt input to charge the battery, as well as to output a regulated 5 volts using the battery as a supply. Although the transistors are integrated, some external components are required. These include an inductor and two capacitors, each with their own design criteria and constraints. It is interesting to note that unlike most of the previous criteria, the datasheet gives explicit recommendations for component values for best results. These will be noted and some of them adhered to, but equations to calculate these component values will still be discussed.

8.4.5.2.9 Inductor

The inductor is responsible for reducing ripple current of voltage switching in either direction. Generally, a higher inductance value lowers the ripple current and allows for smaller filtering capacitors, which are two highly desirable benefits. However, this also increases the DC resistance (DCR) losses. The following equations are used to decide an appropriate inductor value based on expected maximum current requirements:

$$L = \frac{V_{VL} \times (V_{VH} - V_{VL})}{V_{VH} \times f_{SW} \times \Delta I_{L\_MAX}}$$

$$\Delta I_{L\_MAX} = 30\% \times I_{VL(MAX)}$$

$$I_{VL(MAX)} = \frac{V_{VH} \times I_{VH(MAX)}}{V_{VL} \times \eta}$$

Equation 27: Inductor Selection Equation System

$$L = \frac{V_{VH} - V_{VL}}{\Delta I_{L\_MAX}} \times \frac{V_{VL}}{V_{VH} \times f_{SW}}$$

Equation 28: Inductor Selection Equation, derived

The recommended inductance value is 2.2μH with a sufficiently high current rating (no less than that of the MOSFET), although lower values are possible. For this project, ripple current must be kept to a minimum, so the high recommended value will be chosen.

8.4.5.2.10 VL capacitor

The load voltage capacitor C_{VL} is selected directly as a result of the current ripple, which is determined by the inductor, switching frequency, and maximum battery voltage. The current ripple and the capacitor value are obtained from:

$$\Delta r_{VL} = \frac{\Delta V_{VL}}{V_{VL}} = \frac{1 - V_{VL} / V_{VH}}{8 \times C_{VL} \times f_{SW}{}^{2} \times L}$$

$$C_{VL} = \frac{1 - V_{VL} / V_{VH\_MAX}}{8 \times \Delta r_{VL\_MAX} \times f_{SW}{}^{2} \times L}$$

Equation 29: Load Capacitor Tuning based on Current Ripple

The datasheet of the controller describes a 4.7µF ceramic capacitor with X7R dielectrics as "sufficient." Computing the capacitance based on the expected battery and load voltages, a ripple of 0.5%, and 1200kHz gives a value of 3.194µF, which is acceptably within this range. However, the datasheet for the development board shows a more robust option. The development board features three capacitors in parallel to increase the capacitance, with space on the board for an optional fourth.

For the board design, this technique of allocating space for additional capacitors in parallel will be used, but it is not likely that these additional components will be warranted.

8.4.5.2.11 VH capacitor

The battery voltage capacitor C_{VH} is used for stabilizing the "VH" node, which is the positive battery terminal. The capacitor or capacitors must be selected based on current ripple, much like that or those of the load:

$$I_{RMS\_MAX} = I_{VH\_MAX} \times \frac{\sqrt{V_{VL} \times (V_{VH\_MAX} - V_{VL})}}{V_{VH\_MAX}}$$

Equation 30: Battery Voltage Capacitor Tuning

Out of all the recommendations for the switching components, this capacitance value was the most specific. According to the guidelines, the average application will have "two 22uF capacitors and one 1µF capacitor as close to the IC as possible."

8.4.5.2.12 Table of Selected Values

Shown in the table below are the selected values for all of the application-specific charge controller settings. Note that some settings have no recommended value (denoted with N/A) such as limits on current, and others have "example" recommendations that must absolutely be changed based on external criteria (denoted with an asterisk) such as resistors for thermistor tuning.

Component	Desired Outcome	Recommended	Selected
R_{ILIM}	Input current no more than 3A	N/A	71.5kΩ
R_{ISET}	Charge Current no more than 1.25A	N/A	170kΩ
R1	Stabilize output voltage at 5v	76.8kΩ*	75kΩ
R2	Stabilize output voltage at 5v	24.3kΩ*	23.7kΩ
R3	Stabilize/reference input voltage	27.4kΩ	27.4kΩ
R4	Stabilize/reference input voltage	10kΩ	10kΩ
R_{OLIM}	Output current no more than 1.5A	N/A	143kΩ
R_{T1}	Used to tune safe temperature range	2.27kΩ*	2.1kΩ
R_{T2}	Used to tune safe temperature range	6.86kΩ*	7.5kΩ
L	Minimize current ripple	2.2μH	2.2μH
C_{VL}	Keep VL ripple <1%	4.7μF	>4.7μF
C_{VH}	Keep VH ripple <1%	45μF	45μF

Table 37: Table of recommended and/or selected charge controller component values

8.4.5.3 Voltage Regulator Design

The majority of the other systems of this project require a voltage input of 5 volts, which can be supplied directly from the charge controller. However, there is one exception; The project calls for a Bluetooth module for communication with a smartphone. The selected module, an ESP32, has a nominal voltage requirement of 3.3 volts, so a dedicated voltage regulator was selected for the task.

One of the regulator options acquired for testing, the TLV1117LV33DCYR low-dropout voltage regulator from Texas Instruments, has many features that complement the requirements for this role. It features a very low quiescent current as well as no minimum current requirement, which allows the module to operate in standby mode with little to no risk of destabilization of the output voltage. Additionally, this component features a higher than average power supply rejection ratio (PSRR), which allows it to operate from a switching voltage source while maintaining very little noise on the output. Ultimately, an alternative regulator, the LM1117LD, was requested during PCB design, but the operating principles discussed here are still applicable. An example schematic is shown below.

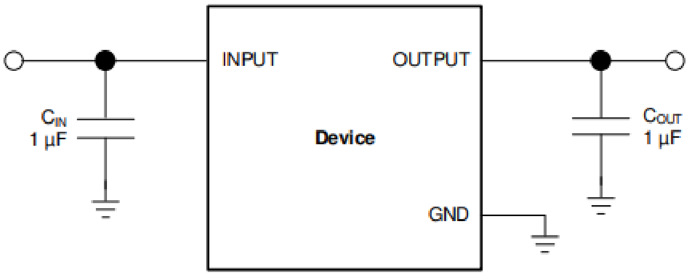


Figure 73: Example TLV1117LV33DCYR regulator schematic

As is the case with all LDOs, this component's operation relies on the difference between input and output voltages being less than the specified dropout voltage. That being said, the component has two operating modes: Normal mode and dropout mode. In normal mode, the LDO is able to regulate voltage to the nominal rating as designed. However, this requires three conditions to be true:

1. The input voltage is greater than the sum of the output voltage and dropout voltage
2. The output current is less than the current limit
3. The device is operating at a temperature below that of thermal shutdown (145°C)

If the first condition is not met but the other two conditions are, the component operates in dropout mode. In dropout mode, the input voltage is effectively passed straight through to the output. This can keep a system powered in such a condition, but is highly undesirable. The transient performance is greatly reduced due to a lack of current regulation in this mode. This results in any transients in the input voltage or current being passed to the output, which is precisely the problem we are seeking to avoid. Fortunately, the V_{IN} from the charge controller is a regulated 5 volts. With a dropout voltage of no more than 455 millivolts at maximum current and a nominal V_{OUT} of 3.3 volts, it is highly unlikely that dropout mode will ever be seen in the final project.

Operating Mode	V_{IN}	I_{OUT}
Normal Mode	$V_{IN} > V_{OUT} + V_{DO}$	$I < I_{CL}$ guaranteed
Dropout Mode	$V_{IN} < V_{OUT} + V_{DO}$	$I < I_{CL}$ not guaranteed

Table 38: Table of selected low-dropout regulator operating modes

The recommended design procedure is fairly simple, with the only major requirement being that a ceramic capacitor should be placed at the output. An additional capacitor at the input as shown above is optional but recommended. Values of the capacitors are specified to be a minimum of 1µF. This value may need to be increased if there is a significant physical distance between the regulator and the input voltage source. A capacitance of 1µF for each capacitor will be opted for. This is because the potential for significant physical separation is not anticipated to be an issue in this project, but this can be altered if problems arise.

The following image is the schematic that was to be used in a PCB design in a previous stage of the project. The final design is the same, save for a different component. The only item of note is that owing to the component's SOT-223 package, two pins are connected to the output as opposed to one in the example schematic.

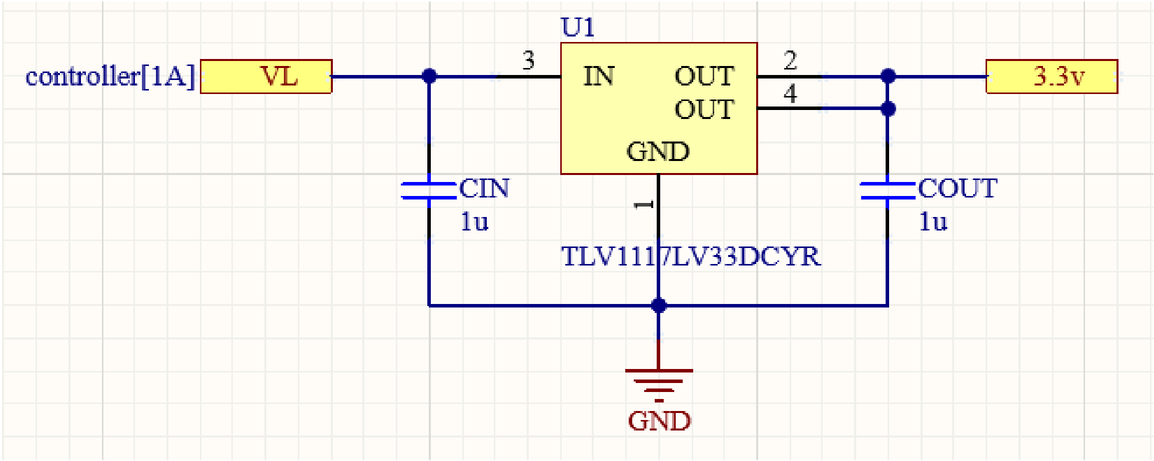


Figure 74: Example TLV1117LV33DCYR regulator design

8.5 Laser Movement System Design

The laser movement system is responsible for movement and mounting of the wedge prisms and ancillary components of the laser system. These precise movements were made with hobby servos manufactured by DFRobot, a reputable brand for such motors. The following is a discussion on the power and control requirements for these motors.

8.5.1 Power and Control

The first design requirement for the servos is the connection to the printed circuit board or microcontroller. Virtually all hobby servos on the market use a three-pin connector with a 0.1" pitch for this task. The order of the pins is fairly consistent among different manufacturers, but the connector is not polarized, which means that special attention must be paid to the color coding of the wires when inserting the connector to ensure it is not being connected backwards. Additionally, the color coding of the wires can vary between manufacturers, so this coding must be observed as well.

Pin Number	Signal	Hitec Color Scheme	JR Color Scheme	Futaba Color Scheme
1	Ground	Black	Brown	Black

2	Supply Voltage	Red or brown	Red	Red
3	Control Signal	Yellow or white	Orange	White

Table 39: Table of de facto standards for hobby servo wire colors

DFRobot, the manufacturer of the motor of choice, opts for the color scheme used by JR, which assigns the colors of brown to ground, red to supply voltage, and orange to the pulsed-width modulation (PWM) control signal.

The second design requirement is the voltage supply to the servo motor. The motor has very basic power and control requirements. The supply voltage is simply a nominal 5 volts, which can be supplied directly from the charge controller. The motor's integrated PCB is responsible for directing power to the motor as needed.

The third design requirement is the pulsed-width modulation (PWM) control signal for positional control of the motor. For hobby servo motors, this is a PWM high signal between 1 and 2 milliseconds on a 20 millisecond cycle. It is important to understand that the range of 1 to 2 milliseconds accounts for the entire range of velocity for a continuous servo, controlling both speed and direction. A duty cycle of 1.5 ms sets the servo to a "stop" setting with velocity of zero, and the "full throttle" velocities in either direction correspond to 1 and 2 ms. A specific velocity can be commanded by setting the duty cycle, but attention must be paid to the code and/or selected software library. Most libraries are set up to parse the duty cycle in terms of degrees of rotation, typically from 0 to 180. For example, the standard Arduino servo library anticipates 180 degrees of freedom for a fixed-rotation servo, as is the case with the fixed-rotation motor option for this project. This is a holdover from fixed-rotation control, which is more common. This is still compatible with any hobby servo regardless of range of movement, but can be a point of misunderstanding for new engineers and developers.

8.5.2 Structure

The laser, motors, wedge prisms, and plano lenses all require a mounting system to precisely align them. All of these components have very tight tolerances that must be adhered to. Commercial solutions for this task exist. However, during the planning stages, these options were quickly ruled out as they tend to have a cost of up to several thousand US dollars, which is far too cost prohibitive for this project. Instead, an optical rail system was designed and 3D printed from scratch. All design was performed in TinkerCad, a free-to-use noncommercial cloud software product from AutoDesk.

The most challenging part of the design was the mounting of the wedge prisms. All of the optical components need to be fastened to the rail, but many of these utilize simple static brackets, which components press-fit into. The wedge prisms, on the other hand, must be capable of rotating. The solution was to design a cylindrical holder with an integrated gear, which itself loosely fits into a separate bracket holding a servo and matching gear.

The optical rail itself is a single 10mm wide by 5mm tall rail with an I-beam cross section. All components are aligned with a center of focus of 30 millimeters above the rail. This height was chosen in order to provide adequate clearance for the motor brackets and associated gearing. The final toy raises the laser system 47 millimeters higher, so additional riser brackets have been designed to raise the rail, and the entire laser system with it. This has the added benefit of opening up space below the rail for other components.

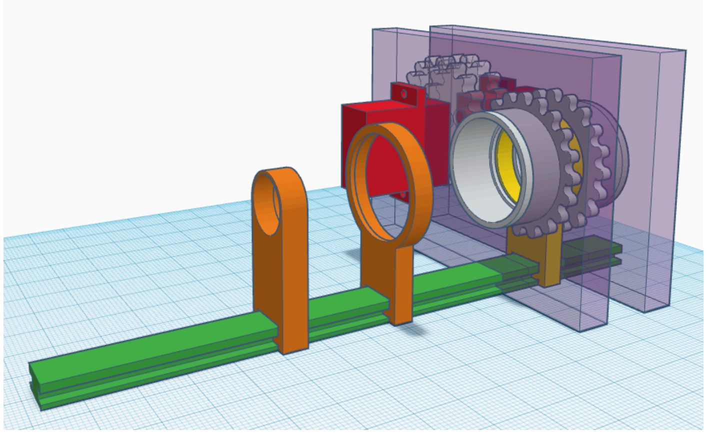


Figure 75: First prototype of laser movement system

During final integration, it was discovered that the system would not fit into the enclosure as-is. The problem was that with the wedge prisms positioned last (see above), the total system length was over 162 millimeters, which was slightly too long. The culprit was not the prisms themselves but rather the motor of the second stage prism. (rightmost in both images) After some experimenting, it was discovered that the wedge prisms could be relocated directly in front of the plano lenses without affecting the appearance of the laser. This change was integrated into the final design, shown below.

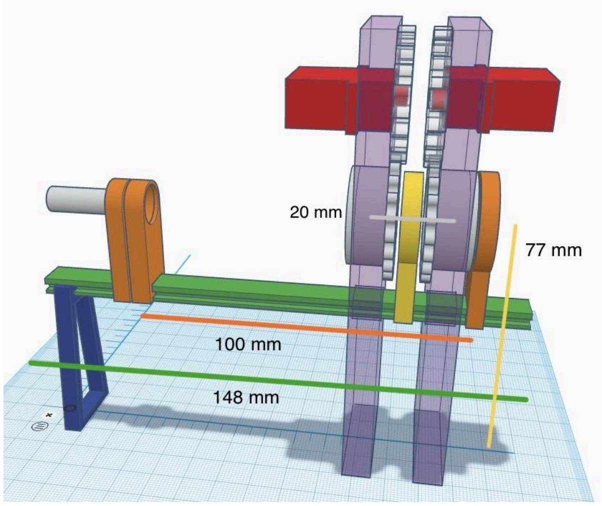


Figure 76: Final design of laser movement system

8.6 Enclosure Design

The purpose of the following sections is to describe the enclosure that contains the printed circuit board, the power system, passive infrared sensor, laser system, and camera system. The following screenshot below shows a picture of the housing and the paragraphs below describe the function of each part.

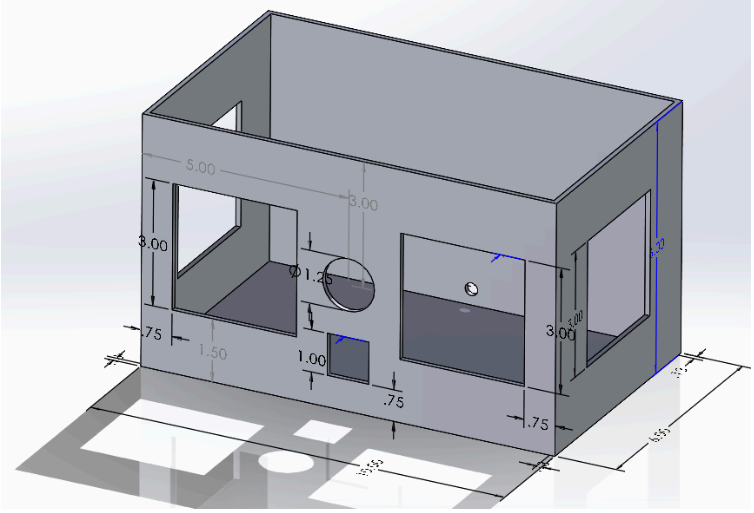


Figure 77: Enclosure Design

The enclosure itself is a 10 inch by 10 6 inch by 6 inch box. There will be a 1.25 inch diameter circle in the center where the laser will exit out of. On each side of the circle are 3 inch by 3 inch squares that house the passive infrared sensors. Under the laser exit circle is a one inch square for the camera to sit on. On the side of the enclosure is one single 3 inch square on both sides to house another passive infrared sensor. The back of the box will have drilled holes where the cables of the power supply exit. The lid opens with hinges to allow easy access inside.

Overall the purpose of this system is to house the printed circuit board in a portable and lightweight design, and provide outward connections where neccessary. The final design on the box can be seen in the figure below.

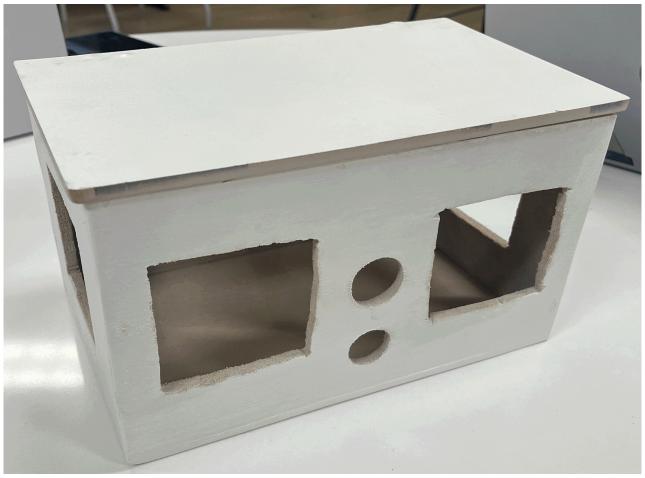


Figure 78: Final Enclosure

9 Test Design

The following section details the hardware and software testing.

9.1 Test Design Environment

The environment of the design testing was not one that required a lot of preparation nor a lot of intensive foreign object debris (FOD) mitigation. Since the objective of the device is to be a cat toy that can operate indoors and in a regular household, the hardware testing was conducted in similar environments. By testing components in a regular household environment, it ensured sustainability of the final end product in its true desired use.

9.2 Cat Collar Tag Testing

The cat collar has several components that required testing to ensure optimal working of the color detection. The parts that contribute to the cat collar color detection are highlighted in the sections below.

9.2.1 LED Testing

To ensure the schematic of the single color LEDs and simulations work, a working prototype of the LED was created using electrical tape, a switch, a resistor, battery cells, and the LED chosen for the design of the device. The figure below shows how these components were connected in series to test.

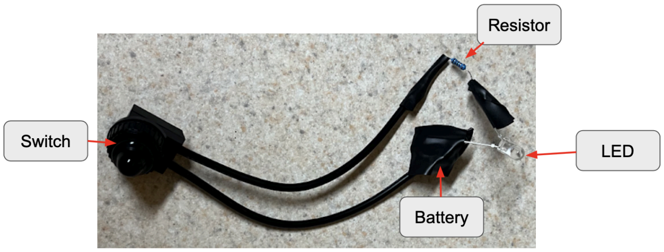


Figure 79: Single Color LED Circuit Components

Three circuits of the LEDs were tested, one for each color, since they all have different forward voltages. This was also used to test initial luminosity visually, to ensure the bright LEDs chosen for the device do in fact have high brightness. The brightness, without a lens, can be seen in the figure below.

Figure 80: Working LED Circuits - Initial Test

9.2.2 Color Detection Testing

To test the color detection portion of the Cat Collar Tag design goals, a Raspberry Pi was used in conjunction with OpenCV to determine if the color testing was being done well.

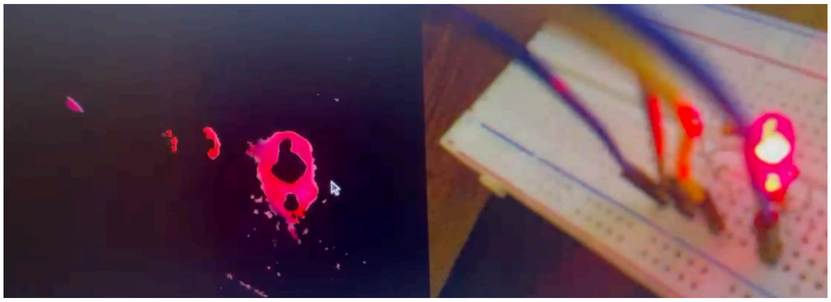


Figure 81: Red Color Detection Testing

Unlike the midterm demonstration for students in the College of Optics and Photonics, this color detection tracking system is more consistent with the actual functionalities of the end device design. The mobile application will determine the color of the cat collar tag through user input. To explain further, the app will allow the user to input whether the color of the cat collar is red, blue, or green and then the chosen color will determine which code the application will run on the device. The chosen code will then run as the figure above shows. When the red, blue, or green color is detected, it enables the laser system to turn on as the desired color that determines a cat is present has been found.

As part of the hardware testing, a small experiment was conducted and repeated three times to detect the farthest distance the camera could detect the colors using the LED. The results can be seen in the table below.

		Detectable Distance		
		Trial 1	**Trial 2**	**Trial 3**
LED Color	**Red**	45 inches	42 inches	46 inches
	Green	50 inches	44 inches	45 inches
	Blue	43 inches	48 inches	43 inches

Table 40: Color Detection Distance

Through testing the color detection detectable distance, the design goals and objectives are in line to be achieved. The original specifications list a detection range of 0.5 feet to 3 feet. Approximately four feet of detection was achieved.

9.3 Passive Infrared Motion Sensor Testing

Another large hardware component that must be tested before being integrated into the final design is the passive infrared motion sensor. As denoted in previous sections, the two main optoelectronic components that are integrated into the motion sensor are the phototransistor and IR LED. A visible light LED is not necessary but used as a checkpoint to ensure that the phototransistor is being turned on when motion is detected and current is flowing through it. The figure below shows how the passive infrared motion sensor is created.

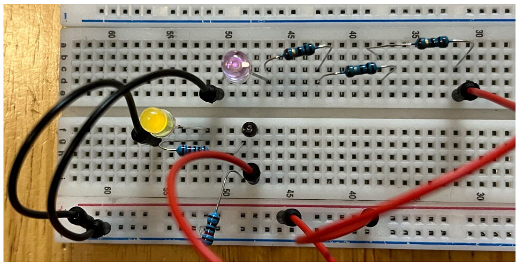


Figure 82: Passive Infrared Motion Sensor Circuit Board

After creating the circuit for the passive infrared motion sensor, its functionality was tested through experimentation of the farthest distance that motion can be detected throughout three different trials. The results are presented in the table below.

	Detectable Distance
Trial 1	4 cm
Trial 2	5 cm
Trial 3	4.5 cm

Table 41: Motion Sensing Detectable Distance

Upon testing of the initial circuit, there were implementations of lower resistance to the IR LEDs and creating a multi-LED grid array. The three-by-three grid of IR LEDs increased the detection distance to eight inches. While this was not sufficient yet per our engineering specifications, the earlier sections detailed the path moving forward for a further version of the Smart Laser Toy for Cats. A 50 mm diameter plano convex lens with 50 mm focal length to collimate the IR light 1.5 feet with 1% reflection loss during transmission.

9.4 Power System Testing

The power system had nearly all of its components procured and tested with each other for the sake of examining for compatibility. The following tests were conducted with a development board and breadboards in the fall prior to integration with printed circuit board revision 2. Although the battery and charge controller were not integrated into the final project, testing of the development board has been included here.

9.4.1 Cells

The two cells selected for this project were two examples of the Samsung INR18650-25S. This is an 18650 cell with a rated capacity of 2500 milliamps hours (mAh). Upon delivery, the cells were immediately tested for their current state of charge (SoC). It is important to always do this with cells that are newly procured or about to be implemented. The reason is that a cell can be permanently damaged if it falls below its rated maximum discharge voltage. This damage increases the likelihood that the cell will internally short circuit if charging is then attempted, which can and often does result in thermal runaway. The rated cutoff voltage for this particular cell is 2.5 volts, which is comparable with other cells of similar chemistry.

This cell has a rated range of 2.5 to 4.2 volts. With most variations of lithium ion chemistry, the voltage across the cell terminals correlates directly to the state of charge, with the voltage dropping in a nearly linear fashion as the state of charge decreases. Testing the cells involved simply using a multimeter to measure the voltage across the terminals, which revealed it to be around 3.5 volts per cell. This equates to less than 50% state of charge. This is well within a safe range, so the cells were deemed safe and ready to use.

Additionally, the development board does not require or implement the balancing feature by default, so measurements of each individual cell were made after each test. Measurements showed that state of charge was identical between cells with no balancing, which is consistent with expectations of brand-new cells.

9.4.2 Charge Controller Development Board

The charge controller was of the utmost importance to the battery system in this project. This is because it is not only responsible for safely charging and discharging the battery, but also overcurrent protection of the systems receiving power and managing the power path of the AC adapter input to charging and external power. Therefore, testing this component was given top priority. The first choice of charge controller for this project was the MP2639A from Monolithic Power Systems. To briefly review, the standout features of this controller are:

- Total control over charging discharging, and overcurrent protection
- Bidirectional 5 volt switching regulation with very low noise
- Support for on/off/visual SoC check with a pushbutton input
- Support for four LEDs that allow for a “fuel gauge” effect for showing SoC

When the project moved into the breadboard testing stage, a problem arose. The MP2639A integrated circuit is of a commonly-used QFN package, but it has an unusual, possibly non-standard arrangement of its pins. One side possesses only five pins, while the others possess seven. The reason for this is that the five pins in question are responsible for connections with high current requirements, such as to and from the battery and the 5 volt input/output line. The problem with this is that although the chip can be procured, an off-the-shelf QFN adapter with an appropriate pin layout cannot. Fortunately, a development board was available at a reasonable price, so one of these boards was procured for testing.

The development board, the EV2639A-R-00A, is a board that has the MP2639A chip as well as the following hardware features:

- Built-in USB-A and micro-USB-B ports for simplified charging and discharging tests
- Built-in four-LED “fuel gauge,” as well as charge and status LEDs
- Integrated power button
- Jumper-selectable charge and discharge modes

9.4.3 Servo Motors

The original motor selection for this project was the SER0006, a 180 degree 9 gram hobby servo from DFRobot. These servo motors have a rotational travel of up to 180 degrees nominally, plus some extra movement in the extremes to allow for some overextension without damage. It was determined in the final design that continuous servos were needed, so replacement servos from the same product family were procured from the same manufacturer, in the same enclosure and motor format, but with 360 degrees of motion and no endpoints.

The old motors are closed-loop positional control, owing to a positional sensor to set an angle for the output shaft. This means that the sensor provides feedback to the integrated motor driver, which makes this positional control more accurate. By contrast, the new motors are velocity-controlled to better suit their continuous movement. They lack the positional sensor as part of their design, so they are open-loop control in which the motor velocity is effectively “running blind.” This could’ve been an issue in theory with setting motor velocities accurately, but in practice this was not observed to be of any concern worth addressing.

9.4.4 Discharge Testing

The first step of testing the battery system was ensuring that the charge controller could safely discharge the two cells. The main purpose of this test was to check that the controller’s overdischarge protection was functional. Ideally, the controller is supposed to automatically cease current flow from the battery when it falls below a cutoff voltage of around 6 volts. It should be noted that this amounts to a per-cell voltage greater than 2.5 volts, which is the rated cutoff of the selected Samsung cells.

The controller was discharge tested by powering and/or charging various devices using the various outputs of the development board. These included mobile devices using the USB-A port and microcontroller test boards for other project systems via the VL and PGND terminal posts. A more comprehensive list of mobile devices tested via USB, as well as the test results, are explained and shown below. For noise testing of microcontrollers and their results, see the section labeled “Microcontroller Testing.”

The devices used for USB discharge testing were the case for a pair of Jabra brand wireless earbuds, an Apple iPhone 13, a Nintendo Game Boy Micro mobile gaming device, and a Nintendo Wii U gamepad input device. All of these devices were charged from the development board's USB-A connector using known good USB cables, with mating device connectors of various types. Whether or not any of these devices could be charged appears to be a USB communication issue in which a charging session must be negotiated for current requirements, which is not relevant to the final project as the controller will be integrated into the final board. Nevertheless, issues were noted as they arose.

Device	Jabra Earbud Case	Apple iPhone 13	Nintendo Game Boy Micro	Nintendo Wii U Gamepad
Cable Connector Standard	Micro-USB-B	Apple "Lightning"	Proprietary	Proprietary
Current Negotiation?	Unknown	Yes	No	No
Charged?	Yes	No	Yes	Yes*
Problem	N/A	Refused to charge	N/A	Behavior erratic near full SoC
Suspected Cause	N/A	Inability to negotiate current	N/A	Known device issue

Table 42: Test criteria and results of charging mobile devices via USB

The controller automatically shut off somewhat unexpectedly in the middle of a test. Closer inspection revealed the first LED of the state of charge gauge had changed from a static "on" state to a slow blink. According to the controller datasheet, this indicates a measured battery voltage of below 6 volts. Further measurement revealed that there was some voltage drop (around 0.2 volts) between the cell terminals and the controller development board input, meaning the battery had a slightly higher state of charge than anticipated. This has been deemed to be somewhat good news as it still ensured that the state of charge was at or above the minimum at the time of cutoff. Although the voltage drop should be addressed in the final project, this result confirms that the controller shuts off as anticipated for over discharge protection.

9.4.5 Charge Testing

The next test was to ensure that the charge controller could safely charge the cells. The controller accepts a 5 volt input at a current which is up to the decision of the engineer, which the controller uses to charge the cells using an integrated boost converter. This was facilitated in this test by the development board's built-in micro-USB-B port. It is also possible to use a bench power supply by connecting it to the board's "VL" post, but this route was not pursued due to the added inconvenience compared to testing via USB. The only change to be made was to move a jumper's position on the development board to pull the "mode" pin low, which switches the controller mode from discharging to charging.

With this done, virtually any USB adapter or port on a computer can be used to charge the battery. The controller measures a selected resistance to ground to set the input current limit, and the development board is pre-designed to draw current from the USB input at no more than 500 mA. Charging was tested with two power sources. The first was a generic USB AC adapter manufactured by Samsung intended for charging mobile devices, and the second was a USB port on a desktop computer. Both sources were recognized by the controller as indicated by the controller's integrated status LEDs. The "ACOK" LED illuminated indicates that the connected power source has been declared usable, and the "CHG" LED indicates charging in progress. Additionally, the four state of charge LEDs blink and illuminate to indicate the state of charge in increments of 25 percent per LED.

Device	Battery (both cells)	Cells (individual)	Charge Controller
Voltage as-delivered	7.0v	3.5v	N/A
Low voltage cutoff	6.2v	3.1v	6.0v
High voltage cutoff	8.13v	4.06v	8.38v

Table 43: Test criteria and results of battery state of charge

The voltage at both the cell terminals and the charge controller terminals were measured at random during charging. Measurements showed that similar to discharge testing, there was a discrepancy of about 0.2 volts between the charge controller terminals and the battery terminals. This time the controller terminals showed a higher voltage than that of the battery, owing to the controller being the voltage source during charging.

After the controller reached 8.38 volts during charging, it suddenly ceased raising the voltage for the next 30 minutes of charging, which was noticeable as previous measurements showed an increase in voltage by nearly 0.5 volts per 15 minutes of charging. This is consistent with the nominal cutoff voltage of the charge controller, and indicates that the charge controller attempted to enter the final stage of charging, in which the voltage is held constant as current is tapered off. This could potentially lead to an issue in the final design if the connection to the battery has a similar voltage drop. The reason for this is that if the voltage is perfectly equalized and current ceases to flow as a result, the controller and battery could find themselves in a "stalemate." That being said, the controller has a charging "timeout" function should an event like this occur.

9.4.6 Servo Motor Testing

The two servos were first tested as-delivered. The purpose of this test was to check for basic functionality of the motors, specifically over positional control and movement. To accomplish this, the following components were employed:

- One Arduino Uno rev.3 microcontroller development board
- The project's selected 5v AC adapter (see part selection)
- One barrel jack connector with dimensions matching that of the AC adapter
- One breadboard and jumper wires
- The Arduino IDE

The sketch, or code, for this test was a basic "sweep" operation. The code simply steps the servo from zero degrees to 180 degrees and back to zero degrees at a defined rate. The underlying function of this code is the Arduino servo library, which predefines the required pulsed-width modulation signals to drive hobby servos and greatly simplifies the programming process by allowing the angle to be defined and set as an integer variable.

After flashing the sketch to the Uno and assembling the circuit, each servo was tested individually. Both servos seamlessly ran through their full range of motion as desired.

9.5 Laser System Testing

The laser system has several components that were used to achieve both beam expansion and beam steering that required testing to ensure optimal performance. The components that would affect the performance of the laser system the most are highlighted in the testing procedures below.

9.5.1 Galilean Beam Expander Testing

Once the initial design and calculations of the laser system were completed, the next step was testing the physical components to confirm that the theoretical results were consistent with the experimental results. The testing process begins by mounting the VLM-650-03 LPT laser diode to the beginning of the optical axis. A distance of 3 cm was measured with the LC1054 plano concave lens placed there, with the curved surface facing toward the laser diode. The LA1986 plano convex lens was then placed 10 cm away with the plane surface facing the plane surface of the previous lens. When the galilean beam expander was completely set up on the optical axis, all of the heights of the components were aligned so that the laser beam is incident on the center of the plano concave lens. The lights in the room where the testing was conducted were turned off in order to see where on the lenses the laser light makes contact. From the test it was observed that the light that was incident on the plano concave lens was expanded from the original size, while still fitting within the face of the plano convex lens. The beam blocker was then placed at the end of the optical axis 1 cm away from the plano convex lens and the spot size was measured, finding the spot size was expanded from 3 mm to 15 mm. The ratio of the spotsize was taken at the original spot size to find that the system magnifies light by a factor 5x just as we calculated. The beam stopper was then moved back from 1 cm away from the plano convex lens a distance of 5 cm, then again at 10 cm, measuring the spot size at each distance and checking that the magnification stays consistent. Once this was done it was observed that the magnification remains consistent, indicating that the laser is expanded and collimated into an afocal beam of light.

9.5.2 Wedge Prism Testing

Once the testing of the galilean beam expander in our system was completed, the laser was turned off so that the Risley prism can be added to the optical axis and tested. The distance from the beam expander was measured to be 3 cm to remain consistent with the calculation done in the optical design. Both of the prisms were then separated by a distance of 5 mm and oriented with the thickest part at the top of the prism. A beam stopper was then placed 1 cm away from the back surface of the second prism, so we can calculate the angle of deviation using trigonometric relationships. When this was done the laser beam was displaced from the optical axis 3.6 mm which was difficult to measure since it is a small value. The beam stopper was then moved back 3 cm away from the back surface of the second prism so the beam would deviate further away from the optical axis in order to accurately measure the distance of deviation. When the beam stopper was moved back, the new distance of deviation from the optical axis is 1.2 cm. When the angle of deviation was calculated by solving the arctan of 1.2 cm/3 cm, calculating the angle of the laser beam in reference to the optical axis to be equal to 22.9°.

Once all of the testing is complete, the experimental results can be compared with the theoretical results. It was seen that the galilean beam expander and the Risley pair both function as indented, getting 5x magnification and an angle of deviation of 20°. Originally this process was conducted for two 2° wedge prisms before it was discovered through testing that 4° of deviation is insufficient for our project. In an effort to optimize the empty space in the optical rail, the wedge prisms were moved in between the 10 cm that separated the lenses. Through testing we observed that the laser was able to replicate the effects of beam expansion and steering that were observed when the prisms were in their original location.

9.6 Printed Circuit Board Hardware Testing Process

Testing the printed circuit board requires several rounds of extensive testing. Below is a summary of the steps required to test each subsystem and perform integration testing.

9.6.1 Printed Circuit Board Hardware Subsystem Testing

First, each subsystem must be tested. In order to do that prototypes were built of each individual subsystem that were tested for their individual performance. Second, each subsystem must be tested for integration. Essentially each of the subsystems have a communication protocol that must be tested as well to ensure that all of the systems can communicate their respective data accurately and precisely.

There are three main subsystems; the first one that should be tested is the power system. There are two reasons this should be tested first and not last. The first reason is that the rest of the systems depend on the power system to send out a clean power signal. If that power signal has too much switching noise, is over or under voltage, or does not provide enough current for all the peripherals then the system will not function.

To actually test the power system. First the charge controller has to be tested. Once that is tested each of the power rails for the FTDI, MCU, and bluetooth module must be tested as well. Since each of these have their own power requirements they must have adequate power in order to function properly. Testing the voltage and current of the power system is simple on a printed circuit board. In the layout there are test points that can be used to measure the voltage relative to ground and will allow a multimeter to be inserted in the current loop to check the current.

The second of the main subsystems that must be tested is the bluetooth module. Since the NINA-W102 series has drivers and the necessary software to turn it on. The only test that must be done is to make sure that it can transmit. The way this is performed is to turn on the provided application by the manufacturer and transmit data from a telephone to the module and make sure it is receiving a signal.

The next system that must be tested is the microcontroller. Thankfully this system is fairly robust and based on previous designs. However, the microcontroller has one hundred individual pins. ANd each of these pins must be tested to make sure that they individually work. Fortunately the easiest way to do that is to have a breadboard setup with individual resistors and make sure that the software when it sends a command each of the pins responds with an appropriate voltage.

After building the project as initially intended the group could not get positive results due to various consequences. So the group switched to an ESP32 WROVER. This greatly simplified the design. However, the three essential subsystems are essentially the same. The three subsystems the group tested were the power system, the USB to UART system, microcontroller, and the bluetooth module.

The power system was tested by soldering on components and using the two voltage test points testing that each voltage line has the appropriate voltage. The group initially did not have 3.3 volts and five volts where it was needed however after replacing the linear dropout regulator the voltage testing was concluded and successful.

The next systems that were tested were the bluetooth module and the microcontroller. Since the ESP32 is a system on chip and combines a wireless bluetooth link controller and a microcontroller the testing on the printed circuit board is to make sure the system on chip is sending and receiving commands. The group tested this by using an LED and breadboard, and then measured the voltage outputs using an oscilloscope, and then by integrating the printed circuit with the other parts of the system; this was discussed above and below.

9.6.2 Printed Circuit Board Hardware Integration Testing

To integrate all the hardware, the main concern there is power, and communications protocol. Most of the peripherals by design use a serial peripheral interface and our method of testing the systems will be to use a bus and select the individual peripheral to make sure that the serial peripheral bus is functioning properly.

The printed circuit board was tested first for 'bring up', then heat dissipation, then for functionality.

The first problem the group ran into with version 1 is that the board had an open circuit. The group believes this open circuit is caused by electrostatic discharge and that the ATMEGA 2560 is sensitive too. Many other groups had this same issue; the figure below shows the shot on a power supply.

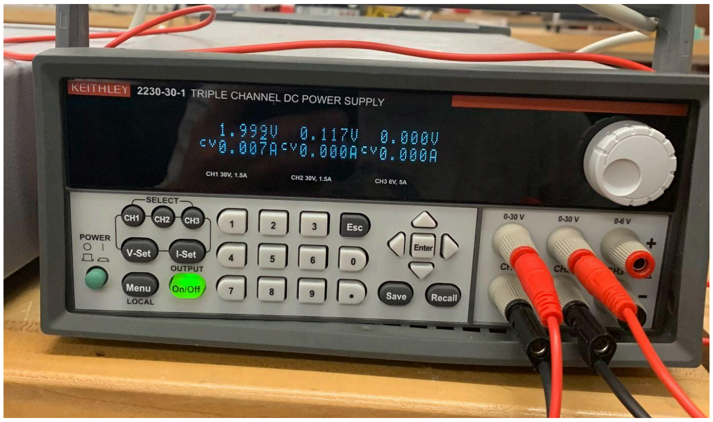


Figure 83: First Version PCB Open on Power Supply

The second printed circuit board had heat dissipation issues, and a short in the board, and finally the charge controller was unstable.

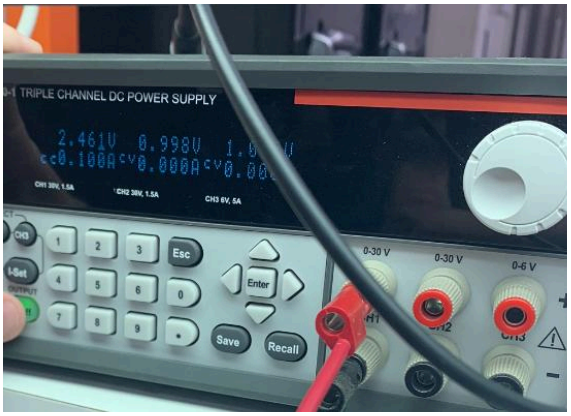


Figure 84: Second Version of PCB Short

Figure 85: Second Version of PCB Heat Issues

10 Comparison of ChatGPT or Similar Platform

The following sections lists the potential use of ChatGPT or similar platforms in the design and documentation of the Smart Laser Toy for Cats.

10.1 Introduction

As the world continues to advance technologically, artificial intelligence (AI) is significantly reshaping the way we approach creativity and problem-solving. One of the most recent manifestations of this creativity is ChatGPT, a chatbot characterized by its ability to simulate human-like text-based conversations. According to ChatGPT's GPT-4 "Chatbot GPT (Generative Pre-trained Transformer) refers to a series of AI models developed by OpenAI used for various natural language processing tasks, such as text completion, translation, summarization, and more. These systems, particularly the later versions like GPT-3 and the most recent at my last update, GPT-4, are sophisticated deep learning models based on the transformer network architecture." This section aims to critically examine ChatGPT, delineating its utility and potential drawbacks, particularly focusing on its application in Senior Design projects.

ChatGPT launched in November 2022 and quickly garnered a following of active users, reaching 100 million by January 2023 and setting the record for the fastest growing platform in history. Currently, ChatGPT sits at 180.5 million active users, seeing an 80.5% increase over an eight-month period. It was trained on a corpus of 300 billion words, consisting of text across the web, including books and Wikipedia. GPT-4, the latest underlying architecture, boasts a context memory of 25,000 words.

Beyond its commercial success, ChatGPT's influence extends to profound societal impacts. GPT-4 predicts that GPT models will directly impact 300 million jobs. A 2023 survey revealed that 25% of US companies have already saved $50,000-$70,000 using ChatGPT, and 11% have saved over $100,000.

ChatGPT is also being used in the realm of education and academia. It has demonstrated its capabilities by passing the US medical licensing exam, law school exams, and Wharton's MBA exam. India's government is actively developing an educational tool built on ChatGPT to help its students. Notably, educational technology companies, like Khan Academy and Duolingo, have already started using GPT to enhance their students' learning experience.

Although ChatGPT is thriving and increasingly beneficial to us, concerns over its ethical use have become increasingly palpable. There are individuals who have been using ChatGPT with malicious intent. This involves generating hacking scripts, academic dishonesty, writing phishing emails, and more. It has already been used to create an information stealer, encryption tool, and dark web malware scripts. There is a serious cybersecurity threat while the ethics surrounding AI are being assessed and debated. Considering it passed the medical and law exams, users with malicious intent can use ChatGPT to write realistic medical advice articles and legal documents. This also extends to academia, as students can submit assignments written by ChatGPT. Correspondingly, tools like plagiarism detectors are being created to mitigate the ethical issues surrounding ChatGPT.

In the context of Senior Design, ChatGPT is a useful tool that can be used to help get ideas and edit our final reports, without committing academic dishonesty. It also serves as a convenient code snippet generator for menial development tasks, like writing a sorting algorithm or recursive fibonacci function.

In the ensuing sections, we aim to explore the definition and architecture behind ChatGPT, the architecture behind the technology, the pros and cons of using it in the context of senior design, and more. To further highlight the purpose, this section will be written with the help of ChatGPT but limited to examples and certain quotes to maintain academic integrity. Ultimately, we aim to develop and explain our informed opinion on whether ChatGPT or similar platforms are helpful when creating a senior design project.

10.2 Understanding ChatGPT and similar platforms

10.2.1 Definition of ChatGPT

ChatGPT, or “Chat Generative Pre-trained Transformer,” is a cutting-edge development in the field of artificial intelligence (AI), specifically, machine learning. This complex natural language processing (NLP) machine learning model is characterized by its ability to mimic human speech and hold text-based conversations. The ChatGPT journey began with OpenAI’s release of GPT-1. At the time of its release in February 2018, GPT-1 was a groundbreaking piece of technology. Its predictive text capabilities, although nonsensical at times, stood unrivaled. Unfortunately, GPT-1 was still a novel idea and was limited to smaller training datasets, restricting its true predictive text capabilities. Remarkably, most of the outputs produced by GPT-1 were more-story like than conversational. For example, when GPT-1 is prompted with “Once upon a time,” it produces “the village had suffered many winters, the cold nights sometimes catching him in the chest and paralyzing it with fever, yet a season seemed like a lifetime to us. from time to time, a family would cross the city to visit her, and while they were gone...” The real breakthrough for ChatGPT occurred with the release of GPT-3. This iteration is what realized its definition, as it was truly able to hold a coherent conversation with a human.

Although the training datasets of the three GPT models also are in size as the technology advanced, so did the models. At its release in 2018, GPT-1 held an already impressive 117 million parameters. Fast forward one year later in 2019, GPT-2 held an immense 1.5 billion parameters. At the release of the most pivotal model in 2020, GPT-3 reached a total of 175 billion parameters. The chart below shows a comparative breakdown of the different GPT-models.

	GPT-1	GPT-2	GPT-3	GPT-4
Parameters	117 Million	1.5 Billion	175 Billion	1.8 Trillion
Decoder Layers	12	48	96	120

Context Token Size	512	1024	2048	8000 - 32000
Hidden Layer	768	1600	12288	12000 - 20000
Batch Size	64	512	3.2M	16M

Table 44: GPT Model Comparison

Following GPT-3's astounding success, OpenAI further refined their approach producing GPT-4, the most powerful NLP model to date. This model makes use of the largest training dataset of all the GPT models, resulting in an even larger model. At its release in March 2023, GPT-4 featured a total of 170 trillion parameters, solidifying itself as the most versatile model yet. Not only can GPT-4 generate an impressively wide range of natural language text, it can also be used to generate images, video, audio, and even art. GPT-4 has proved itself as the most impressive GPT model to date.

The progression from GPT-1 to GPT-4 highlights the importance of a solid underlying architecture. At the center of GPT, is the transformer architecture, a neural network design that replaces traditional sequential processing with parallel processing. This departure from conventional methodologies has allowed for the revolutionary advancements seen in the GPT models.

10.2.2 Architecture

The "brain" behind ChatGPT is an innovative neural network architecture introduced in 2017 called the Transformer. This architecture was proposed in a revolutionary paper titled "Attention is All You Need" which forever changed the way NLP tasks are approached. In the paper, the authors introduced the Transformer as an alternative to recurrent neural networks (RNNs) and convolutional neural networks (CNNs), which were heavily used in NLP tasks at the time. The Transformer outperformed the existing approaches, whilst proving easier to train and increasing parallelizability. Both RNNs and CNNs rely on sequential processing, making them subpar to transform when capturing dependencies between words efficiently. The key concept behind the Transformer is a mechanism known as "attention." Attention allows for the model to weigh the relevance of different words in a sentence and determine how much importance should be given to each word to determine the next one. This is what allows ChatGPT to generate coherent and contextually relevant sentences. Platforms similar to ChatGPT, like Google Bard and Meta AI's Llama, also use the transformer architecture. Below is a detailed diagram of the Transformer Architecture:

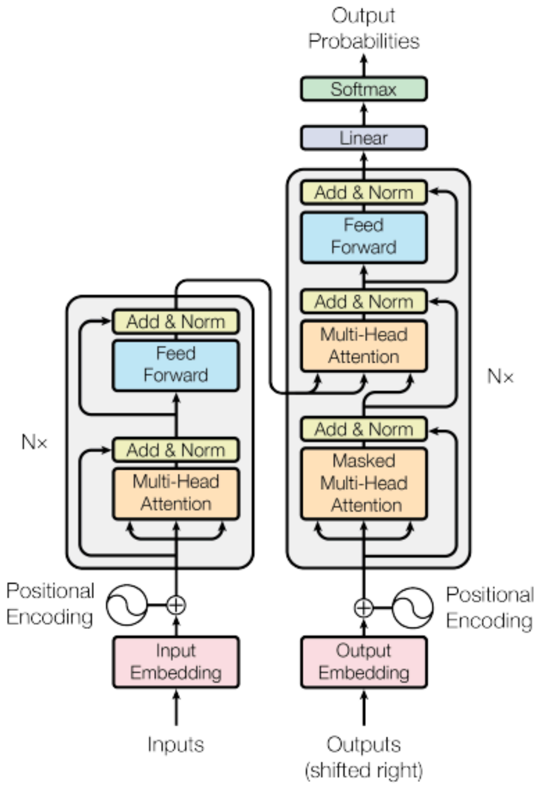


Figure 86: Transformer Architecture

First, the neural network receives an input sentence, then converts it into a sequence of word vectors and a sequence of positional encodings. This conversion outputs a numeric representation of the sentence, which is necessary for it to be properly processed by the network. Then, the transformer adds the word vector and positional encoding together before passing all the vectors through a series of encoders, followed by a series of decoders. Each encoder and decoder contains the "attention" mechanism, allowing for each input word to include relevant information pertaining to the surrounding words. As mentioned earlier, the transformer will process these vectors in parallel, rather than sequentially. The encoders convert the inputs into a sequence of vectors called encodings, while the decoders convert the encodings into a sequence of probabilities for output words. The output probabilities can then be converted into another sentence using the softmax function. Since this calculation may be performed multiple times, it is known as the multi-head attention mechanism. In other words, instead of one "self-attention head," the input is being passed through multiple independent "self-attention heads," each with a unique set of learned weights that may pay more attention to different aspects of the input. This allows for a deeper understanding of the context and more complex features of the input.

When asked to give a concise conceptual example of the self-attention mechanism, ChatGPT responded, "In a simplified analogy, imagine each word in a sentence as a student in a classroom discussion. During a conversation, not every student's information is equally important at all times. Similarly, the self-attention mechanism in a transformer model calculates "attention scores," which are similar to levels of importance that each word (student) contributes based on the current discussion topic (sentence context). These scores determine how much focus each word receives. The words then use this adjusted focus, gathering insights from the entire class (all words in the sentence) to develop a richer understanding of the discussion. This process allows each word to carry a comprehensive sense of the larger context, contributing to a more informed and coherent group response, much like students in a productive discussion."

10.3 Pros of Using ChatGPT in Senior Design Projects

ChatGPT's pervasiveness in society is undeniable. It has become more important than ever to explore the best ways to use it, especially in education. Some educators fear that students will mainly use ChatGPT for academic dishonesty. Unfortunately, this concern is not baseless, as 1 in 4 educators have caught students cheating using ChatGPT. However, some educators believe that the benefits of using ChatGPT as an educational tool outweigh the risks and have already started implementing it in their classrooms. These teachers claim over time the education system will not see an increase in cheating, but a "revitalization of lesson plans and classroom instruction". When prompted to generate some examples of ways ChatGPT may help with Senior Design projects, it produced a list highlighting its uses in "innovation, resource optimization, and educational depth." Below are some of the examples generated by ChatGPT:

- Innovation and Creativity: ChatGPT can be used to brainstorm, offering creative solutions or ideas that students might not have considered. Its ability to generate human-like text based on the input it receives can inspire new directions for research or application design.
- Efficient Information Gathering: Students can interact with ChatGPT to quickly gather information on a wide range of topics, helping to streamline the research process. Although it shouldn't replace traditional research methods, it can certainly speed up the initial stages or fill in gaps where information is scarce.
- Coding and Development Assistance: For projects involving programming, ChatGPT can assist in code development by suggesting pieces of code, providing documentation assistance, or helping debug issues by offering potential solutions found in its training data.
- Educational Reinforcement: ChatGPT can supplement learning by providing explanations of complex concepts, translating information into simpler terms, or offering additional context. This aspect is crucial for reinforcing knowledge acquired through lectures, readings, and discussions.
- Stress Relief and Support: The journey through a capstone project can be stressful. Having a tool like ChatGPT to ask questions without judgment or to offload ideas can be a subtle yet effective form of support.

Interestingly enough, these examples are not without human support. Some main points for why students should use ChatGPT when completing coursework include ChatGPT's ability to answer specific questions about a concept, increase problem-solving through guidance, reinforce concepts, and improve writing skills.

Group 3 has already utilized ChatGPT in various ways during the planning phase of Senior Design. ChatGPT was used to generate the foundational code for the website. It was also used to help non-programmers break down the programming concepts they encountered while completing their portion of the project. There may even be a chance that ChatGPT could streamline the circuit design and component selection for the power system. Above all, ChatGPT allows for a smoother process while working with an interdisciplinary team, because it is able to explain the complex ideas of members of a different discipline in a simple fashion. As Senior Design progresses, it is foreseeable that ChatGPT will be used in all the examples generated above.

10.4 Cons and Limitations of Using ChatGPT in Senior Design Projects

When considering the cons and limitations of using ChatGPT in education, the most popular is using ChatGPT for academic dishonesty. 1 in 4 teachers have caught students cheating using the chatbot. This has resulted in many teachers taking an overwhelming amount of time checking students' work for plagiarism and "revamping their lesson plans to be 'AI proof'". Another con of including ChatGPT in academic environments is its potential for over-reliance. Although ChatGPT is not necessarily a search engine, it is easy to use it to get the answer for something. This encourages students to eliminate the middleman and forgo doing the research themselves. In effect, the students' ability to figure out the solution on their own will suffer. If students start relying on the content generated by ChatGPT, the nuance and uniqueness of the human voice will be absent from their work, limiting their creativity. When prompted to generate some cons and limitations of using ChatGPT in Senior Design projects, it produced a list focusing on academic integrity and dependency. Below are some of the examples generated by ChatGPT:

- Dependence on Existing Information: ChatGPT can only provide information and generate responses based on the data it was trained on, up to its last training cut-off in 2021. It doesn't "know" anything post-training and isn't capable of original research or insight, potentially limiting innovation and the freshness of the content in capstone projects.
- Academic Integrity Concerns: There's a thin line between getting assistance and outsourcing entire tasks to ChatGPT. Relying heavily on the tool for generating content could raise issues regarding the authenticity of the work and the student's personal contribution, potentially leading to academic dishonesty if not properly cited or if used against school policies.
- Loss of Learning Opportunity: Over-reliance on ChatGPT might hinder students from the in-depth research process, critical thinking, problem-solving, and the learning experience that comes with tackling challenges independently.

- Creativity Constraints: While ChatGPT can aid in idea generation, excessive dependence might limit a student's creative process, as the responses generated are based on pre-existing information and not on novel, creative thought.

Group 3 has not experienced any of the listed cons or limitations. We aim to use ChatGPT as a tool, not as another group member or mentor. How we use ChatGPT is contained in the examples listed in the preceding "Pros of Using ChatGPT…" section and the following "Real-World Examples…" section.

Although there are many advantages to implementing ChatGPT in education, specifically Senior Design Projects, it is imperative to acknowledge the downfalls that may come with it. For example, while writing a lengthy senior design report, a student may rush to tell ChatGPT to generate the content for a section. While the student may change some things, more so to avoid potential academic integrity consequences, they miss out on the opportunity to explore and learn about the topic themselves. In this way, ChatGPT is treated more like another group member instead of a tool. In the future, when it is time for implementation, ChatGPT may not be able to help as much, but the student did not learn as much as they should have during the research phase, leading to potential conflict and project stalls. Instead of asking ChatGPT to generate the content for the section, the student should ask it to write an example outline. In this way, ChatGPT is used as a tool. The student now has an example path to follow, but they are responsible for exploring and researching the topic.

10.5 Real-World Examples of Using ChatGPT and Similar Platforms in Senior Design Projects

The goal of this section was to assess the pros and cons of ChatGPT or a similar platform, then determine whether it is beneficial when working on a Senior Design project. Our preferred AI text-generating chatbot platform is ChatGPT, and after thorough evaluation, we've determined that it is beneficial to our project. However, it is important to note that the answer to whether these platforms are beneficial when working on Senior Design projects is dependent on the group and the nature of the project. To corroborate our claim, we have chosen three of our listed pros and illustrated how ChatGPT helped advance our project in that regard. Furthermore, we have chosen to compare the responses given by ChatGPT to the ones given by Google Bard or ZenoChat's Sophos-2 to demonstrate why ChatGPT is our preferred platform. Google Bard and ZenoChat's Sophos-2 are excellent candidates for comparison because, unlike other chatbots, they are run by proprietary models and not OpenAI's GPT, which already powers ChatGPT.

10.5.1 Innovation and Creativity

Prompt: Can you brainstorm some ideas to make a website featuring a laser cat toy more interesting and interactive?

ChatGPT's Response: Certainly! Making a website featuring a laser cat toy more interesting and interactive can engage visitors and encourage them to explore your products. Here are some ideas:

1. Interactive Laser Pointer Simulator: Create an interactive laser pointer simulator on the website. Users can move their cursor (which simulates the laser pointer) around the screen, and virtual cats on the page will chase the laser dot, providing an entertaining experience.
2. User-Generated Content: Allow customers to submit videos or photos of their cats playing with the laser toy. Feature a gallery of these user-generated content pieces on the website to showcase happy customers and their furry friends.
3. Virtual Cat Playground: Design a virtual cat playground on the site where users can click on different elements to make them interactive. For example, clicking on a toy might make it move, and virtual cats can chase after it.
4. Laser Toy Challenge: Host an interactive laser toy challenge or game on the website. Users can control the laser pointer's movement to guide virtual cats through a maze or obstacle course.
5. Cat-Related Quizzes: Create engaging quizzes related to cats and their behavior. For instance, "What Type of Laser Toy Is Ideal for Your Cat?" or "Test Your Cat Trivia Knowledge." Offer prizes or discounts for participating.
6. Live Cat Cams: Set up live webcams in a cat playroom with laser toys. Users can watch real cats play with the toys in real-time, providing entertainment and product demonstration.
7. Cat Toy Reviews and Ratings: Implement a user review and rating system for your laser toys. Encourage customers to share their experiences and rate the products, building trust and credibility.
8. Cat Toy Customization: Offer an interactive tool that allows users to customize their laser cat toys. They can choose colors, patterns, or even add their cat's name to the toy.
9. Educational Content: Create a blog or resource section featuring educational content about cat behavior, play, and exercise. Include interactive quizzes and guides on how to use laser toys safely.
10. Cat Photo Contests: Host regular cat photo contests on the website. Users can submit photos of their cats playing with the laser toy for a chance to win prizes or get featured on the site.
11. Virtual Cat Adoption: Partner with local animal shelters to feature virtual cat adoption events on the website. Users can virtually "adopt" a cat, and a portion of the proceeds can go to the shelter.
12. Chatbot Assistant: Implement a chatbot that provides personalized product recommendations based on users' cat breeds and preferences. Make it interactive and playful, with cat-themed responses.

Remember to make the website mobile-friendly, as many users might access it on their smartphones. The goal is to create an enjoyable and interactive online experience that cat owners and enthusiasts will love while showcasing your laser cat toys.

Google Bard's Response: Here are some ideas to make a website featuring a laser cat toy more interesting and interactive:

1. Add a live demo of the laser cat toy. This would allow potential customers to see how the toy works and how much fun their cats will have with it. You could also use the live demo to showcase different features of the toy, such as its different laser patterns and speeds.
2. Create a community forum where cat owners can share their experiences with the laser cat toy. This would be a great way to build brand loyalty and generate customer-created content. You could also use the forum to collect feedback from customers and identify areas where you can improve the product.
3. Offer a variety of interactive content on your website, such as quizzes, polls, and games. This would help to keep visitors engaged and coming back for more. For example, you could have a quiz that helps cat owners determine the best laser cat toy for their cat's needs. Or, you could have a game where visitors can race their cats to catch the laser.
4. Partner with other pet-related businesses to offer exclusive discounts and promotions to your website visitors. This would be a great way to attract new customers and cross-promote your products and services. For example, you could partner with a pet food company to offer a discount on laser cat toys to customers who purchase a certain amount of pet food.
5. Use social media to engage with your audience and promote your website. You could share photos and videos of cats playing with the laser cat toy, as well as tips and tricks for using the toy. You could also run social media contests and giveaways to generate excitement and interest in your product.

Analysis: We are responsible for creating a website to showcase our project. Since we all have minimal to no experience in web development, we decided to ask ChatGPT for some creative ideas to make the website engaging. For a starter website, we decided on the first idea given since it is simple to implement but still eye-catching. The responses given by both ChatGPT and Google Bard are both relevant and well-written. Nonetheless, ChatGPT's ideas more closely adhere to the current state of our project. Bard's ideas are more feasible in the context of commerce, not Senior Design.

10.5.2 Efficient Information Gathering

Prompt: Can you use OpenCV and a camera to detect color in real-time?

ChatGPT's Response [Code Omitted]: Yes, you can use OpenCV and a camera to detect color in real-time. OpenCV (Open Source Computer Vision Library) is a very powerful tool used in real-time image processing and computer vision applications. Here's a simplified explanation of how you might set up a basic system for real-time color detection using OpenCV:

1. Setup and Requirements:

    a. First, you need to have a working camera connected to your computer.
    b. You'll need to install OpenCV on your system. You can do this using pip (Python's package installer).
2. Capture Video:
    a. You start by capturing live stream video from the camera. OpenCV does this through the `cv2.VideoCapture` method.
3. Real-Time Processing:
    a. Once you have the video stream, you can process it in real-time to detect specific colors. You do this by capturing individual frames from the video and processing them.
4. Color Detection:
    a. Color detection is generally done in the HSV (Hue, Saturation, Value) color space, which is more consistent than the RGB color space under varying lighting conditions.
    b. First, you convert the frame from RGB to HSV. Then, you set the lower and upper bounds of the color you want to detect and create a mask.
5. Display Video:
    a. Now, you can show the original video and the processed video stream in real-time.

This script will continuously capture video frames, process them to highlight your specified color, and display the original and processed video streams in real-time until you decide to stop the process by pressing 'q'. The exact hue, saturation, and value bounds will depend on the color you want to detect, and you may need to experiment to determine these values.

ZenoChat's Response [Code Omitted]: Yes, OpenCV can be used with a camera to detect color in real-time. OpenCV is a popular computer vision library that provides many image and video processing functions. One of the functions provided by OpenCV is color detection. By using a camera, you can capture video frames in real-time and then use OpenCV to detect the color of objects in the frames.

To do this, you can use the cv2 library in Python to capture the video stream, and then use OpenCV functions to process each frame of the video by converting it to a color space such as HSV or RGB, thresholding the image to isolate the colors of interest, and then detecting the contours of those colored objects.

Here is some sample code that demonstrates color detection using OpenCV and a camera:

Analysis: The optical systems in this project require a preliminary demonstration while still in the research stage. Unfortunately, without all the components, a working demonstration requires improvisation. Based on prior knowledge, we believed using OpenCV was sufficient to illustrate the concept behind the color detection system. For a quick answer and subsequent explanation, we decided to ask ChatGPT. Surprisingly, along with its response, it gave detailed steps and code for an example implementation. This gave us a good outline for how to proceed with the demonstration. While ZenoChat's responses were similar, and there was an example implementation given, it was not as explanatory and descriptive as ChatGPT's.

10.5.3 Educational Reinforcement

ChatGPT Prompt: I'm reading Bluetooth Core Specification V4.0. I'm reading the section of baseband modulation and I don't understand why in the enhanced data rate baseband modulation there is a trailer field after the payload in the data packet. Can you explain this to me?

> **ChatGPT's Response:** Certainly! The Bluetooth Enhanced Data Rate (EDR) was introduced in Bluetooth 2.0+EDR and was further continued in the Bluetooth 4.0 specification. The main reason for introducing EDR was to provide higher data rates compared to the basic rate (BR) by using a different modulation scheme.
>
> Now, when it comes to the data packet format for EDR, it includes several fields: preamble, access code, packet header, payload, and a trailer. The trailer is specifically there for EDR packets and serves a distinct purpose.
>
> The trailer, which is typically 2 bits, serves as a guard time to allow the transceiver circuitry to stabilize when switching from transmission (TX) to reception (RX) or vice versa. This is crucial because during communication, devices may frequently alternate between sending and receiving packets. When a device switches its mode of operation, there's an inherent transient period where the transceiver circuits might not yet be stable, potentially leading to errors in the subsequent packet's preamble or sync word detection. By introducing a small gap or guard time (the trailer), devices can ensure that they're ready and stable for the next operation, thus reducing the chance of errors.
>
> In summary, the trailer in the EDR packet helps ensure reliable communication by providing a buffer or guard time for circuit stabilization during transitions between transmit and receive modes.
>
> **Google Bard's Response:** The trailer field in Bluetooth EDR baseband modulation serves two purposes: To provide a known sequence for frame synchronization at the receiver. The trailer field consists of a CRC (cyclic redundancy check) of the payload and some padding bits. The receiver can use the known CRC value to align the incoming bitstream with the frame boundaries. This is especially important in the presence of noise or interference, which can cause bit errors. To ensure that the payload length is a multiple of 8 bits. The Bluetooth EDR baseband modulation scheme uses differential phase-shift keying (DPSK), which requires the payload length to be a multiple of 8 bits. The padding bits in the trailer field are used to ensure that this requirement is met.
>
> In summary, the trailer field in Bluetooth EDR baseband modulation helps to ensure reliable communication by providing a known sequence for frame synchronization and ensuring that the payload length is a multiple of 8 bits.

Analysis: Senior Design projects demand extensive research. Some of the concepts we need to delve into are highly technical and may not be easy to understand. In addition, the lack of prior knowledge could potentially lead to more questions than answers. Using ChatGPT to help break down these complex concepts and answer unforeseen questions is a key reason why it is a beneficial resource in Senior Design projects. In this example, both ChatGPT and Bard answered with well-written and concise responses. However, we feel that the readability of ChatGPT's answer is much better than Bard's. Bard's response was still fairly technical and led to more questions. ChatGPT's response was understandable and consisted of relevant background information that deepened our understanding.

11 Administrative Content

The following sections list the bill of materials, scheduling and division of labor that was a part of designing and building the Smart Laser Toy for Cats.

11.1 Bill of Materials

	Item Purchased	Unit Cost	Quantity	Total
1	Camera Module	$25.00	1	$25.00
2	Raspberry Pi 4 Model B	$87.96	1	$87.96
3	Fresnel Lens	$7.24	5	$36.21
4	Bluetooth Module/Microcontroller	$5.00	1	$5.00
5	Laser Diode	$14.04	1	$14.04
6	Switches	$2.13	3	$6.38
7	Printed Circuit Board	$8.48	1	$8.48
8	PCB Components	$20.00	1	$20.00
9	Phototransistors	$2.63	4	$10.52
10	Planoconcave Lens	$35.79	1	$35.79
11	Planoconvex Lens	$38.76	1	$38.76
12	Wedge Prisms	$24.95	2	$49.90
13	Polarizer	$9.54	1	$9.54
14	IR LED	$0.56	36	$20.30
15	Red LED	$0.70	1	$0.70
16	Blue LED	$0.27	3	$0.81
17	Green LED	$0.57	1	$0.57
				$369.97

Table 45: Bill of Materials

11.2 Milestones

Milestone	Due Date	Status	Responsible Team Member
Senior Design 1			
Initial Meeting & Idea Generation	August 29th	Completed	Whole Team
10 Page Divide & Conquer	September 15th	Completed	Whole Team
Midterm Demo for Photonics Students	October 12th	Completed	Adriana, Carlos
75-Page Draft Due	November 2nd	Completed	Whole Team
Publish 75-Page Draft on Website	November 16th	Completed	Whole Team
Test Components	November 25th	Completed	Whole Team
Record Demo Video	November 26th	Completed	Whole Team
Publish Final Draft and Demo Video	November 27th	Completed	Whole Team
Final PSE Demo	Nov 30th	Completed	Adriana, Carlos
150-Page Final Report	Dec 4th	Completed	Whole Team
Senior Design 2			
CDR Presentation	February 29th	Completed	Whole Team
Passive IR Sensor Assembly	March 5th	Completed	Adriana
Laser System Assembly	March 7th	Completed	Ben, Carlos
PCB Assembly	March 20th	Completed	Leife, Benjamin
Integration Code	March 24th	Completed	Xaria
Initial Testing	March 25th	Completed	Whole Team
Midterm Demo	March 27th	Completed	Whole Team

Enclosure Assembly	March 30th	Completed	Adriana, Leife
Conference Paper	April 5th	Completed	Whole Team
Final Testing and Integration	April 11th	Completed	Whole Team
Final Presentation and Demo	April 18th	Completed	Whole Team
CREOL Live Demo	April 19th	Completed	Whole Team
Updated 150-Page Paper	April 22nd	Completed	Whole Team

Table 46: Milestones

11.3 Work Distributions

Task	Primary Person	Secondary Person
Motion Detector	Adriana	Leife
Color Detection Tags	Adriana	Xaria
Color Detection Code	Xaria	Adriana
Laser Movement System	Carlos	Benjamin
Laser Movement Structure	Benjamin	N/A
Printed Circuit Board	Leife	Benjamin
Power System	Benjamin	Leife
Enclosure	Adriana	Leife
Integration Code	Xaria	Benjamin
Mobile Application	Xaria	N/A
Bluetooth System	Leife	Benjamin

Table 47: Work Distributions

11.4 Conclusion

The Smart Laser Toy for Cats is a new and innovative laser toy for cats. It combines the use of optics and electronics to create an automatic toy that requires little, if any, user input to operate. On the current market, there are automatic laser toys, but none that automatically operate upon the detection of a cat. This device helps accommodate those pet owner's with a busy lifestyle, rarely home, or have hand mobility restrictions. We have set the goals and motivations of the design to relieve the stress of pet owners who feel overwhelmed in playing with their pet. This not only achieves that goal but also maintains the safety of the pet and owner in mind by denoting that the device must be placed on higher ground and uses lasers of low power output to prevent eye damage of the cat and owner.

Although the group recognizes that there are current market products that automate a laser toy for cats, the goal of this device was also to implement motion sensing capabilities. The overall design of the device detects the pet through a passive infrared motion sensor. Once the pet is detected, a color detection system is enacted through enabling a camera to turn on. When the camera detects the preselected color from user input on the user-friendly mobile application, the laser system turns on for a predetermined amount of time to stimulate the cat. The device also has an integrated mobile-app through bluetooth communication that enables the owner to keep track of how many times their pet has played and choose collar tag colors for specific pets.

Overall, the report details how every component selected was done with the goal to create a high quality device that reaches the group's specifications and design goals. All schematics were optimized to achieve these goals and the hardware testing was conducted to ensure the schematic not only worked through simulation but also through fruition.

12 Appendix

12.1 References

1. Agnihotri, N. (n.d.). *Arduino-based optical proximity sensor using IR leds*. Engineer's Garage. https://www.engineersgarage.com/arduino-ir-led-ir-photodiode-proximity-sensor/#:~:text=The%20IR%20LED%20or%20IR,range%20of%20distance%20and%20angle.
2. *A guide to selecting a bluetooth chipset*. Argenox. (n.d.). https://www.argenox.com/library/bluetooth-low-energy/a-guide-to-selecting-a-bluetooth-chipset/
3. And, E. E. (2023, July 3). Why Isn't Procreate Available on Android & Top 10 Alternatives. WolfofTablet. https://wolfoftablet.com/why-is-procreate-not-on-android-best-alternatives/#:~:text=Procreate%20isn%27t%20available%20and,the%20quality%20of%20the%20app
4. Angela, L. (2021, August 13). *What are the types of voltage regulators, and how do they work?*. EP-Power. https://ep-power.com/what-are-the-types-of-voltage-regulators-and-how-do-they-work/
5. Ardumotive_com. (2018, September 23). *Raspberry pi tutorial: How to use a RGB led*. Instructables. https://www.instructables.com/Raspberry-Pi-Tutorial-How-to-Use-a-RGB-LED/
6. Atlassian. (n.d.). Microservices vs. monolithic architecture | Atlassian. https://www.atlassian.com/microservices/microservices-architecture/microservices-vs-monolith#:~:text=A%20monolithic%20architecture%20is%20a,monolith%20architecture%20for%20software%20design
7. Atlassian. (n.d.-a). What is DevOps? | Atlassian. https://www.atlassian.com/devops
8. Atlassian. (n.d.-b). What is kanban? [Video]. Atlassian. https://www.atlassian.com/agile/kanban
9. Beast, D. (2023, May 28). Attention is all you need:: Summary & Important points. Medium. https://medium.com/@thedatabeast/attention-is-all-you-need-summary-important-points-40769b99d6f8#:~:text=Overall%2C%20the%20
10. Blair, I., & Blair, I. (2023, March 23). BuildFire. BuildFire. https://buildfire.com/programming-languages-for-mobile-app-development/
11. Blose, A. (n.d.). As ChatGPT enters the classroom, teachers weigh pros and cons | NEA. https://www.nea.org/nea-today/all-news-articles/chatgpt-enters-classroom-teachers-weigh-pros-and-cons
12. BLU products bold like us. (n.d.). BluProducts.com. https://www.bluproducts.com/blu-blog/articles/iphone-vs-android/#:~:text=The%20Android%20operating%20system%20allows,tablets%20with%20no%20setup%20required
13. Britannica, T. Editors of Encyclopaedia (2023, October 26). *Fresnel lens*. *Encyclopedia Britannica*. https://www.britannica.com/technology/Fresnel-lens

14. Brown, S. (2023, October 5). Best iPad drawing apps to try in 2023. CNET. https://www.cnet.com/tech/services-and-software/best-ipad-drawing-apps-2023/
15. BuildFire. (2023, October 14). BuildFire. https://buildfire.com/app-statistics/
16. Cao, P. (2015, October 31). *Should I use a linear charger or a switching charger?*. Fully Charged - Archives - TI E2E support forums. https://e2e.ti.com/blogs_/archives/b/fullycharged/posts/when-to-choose-linear-chargers-vs-switching-chargers
17. Chu, B. (2008, January 2). *Designing a li-ion battery charger and load ... - microchip technology*. Microchip. https://ww1.microchip.com/downloads/en/AppNotes/01149c.pdf
18. Clearbridge Mobile. (2022, October 13). 5 Key benefits of Native Mobile App
19. Client-Server Architectures. (n.d.). http://www.cs.sjsu.edu/~pearce/oom/ood/distArch/server.htm
20. DaJanchar, M. (2023, April 18). *IR led detection distance with a phototransistor*. All About Circuits. https://forum.allaboutcircuits.com/threads/ir-led-detection-distance-with-a-phototransistor.193094/
21. Development | Clearbridge Mobile. https://clearbridgemobile.com/benefits-of-native-mobile-app-development/
22. *Differential Phase Shift Keying*. (n.d.). https://www.tutorialspoint.com/digital_communication/digital_communication_differential_phase_shift_keying.htm?ranMID=49144&ranEAID=bI3pFuC5e6s&ranSITEID=bI3pFuC5e6s-kRSpF7uhVHCnSOU8J7faHw
23. Dilmegani, C. (2023, August 22). ChatGPT Education Use Cases, Benefits & Challenges in 2023. AIMultiple. https://research.aimultiple.com/chatgpt-education/
24. DPRNS. (n.d.). *Gaussian Frequency Shift Keying*. DPRNS Forum. https://www.dprns.com/forum/index.php?topic=34.0
25. Earl, B. (n.d.). All about Stepper Motors. Adafruit Learning System. https://learn.adafruit.com/all-about-stepper-motors/what-is-a-stepper-motor
26. Edmund Optics. (n.d.). *Advantages of Fresnel lenses*. Knowledge Center. https://www.edmundoptics.com/knowledge-center/application-notes/optics/advantages-of-fresnel-lenses/
27. Galla, S., & Periasamy, S. (2017, October 25). *Using Lithium-Based Batteries with Microchip Charge Management Controllers*. Microchip. https://ww1.microchip.com/downloads/en/DeviceDoc/90003171B.pdf
28. GlobalSpec. (n.d.). *Phototransistors selection guide: Types, features ... - globalspec*. Phototransistors. https://www.globalspec.com/learnmore/optics_optical_components/optoelectronics/phototransistors
29. *Grove - Infrared reflective sensor: Seeed studio wiki*. Seeed Studio Wiki RSS. (n.d.). https://wiki.seeedstudio.com/Grove-Infrared_Reflective_Sensor/#:~:text=The%20sensor%20consists%20of%20an,by%20the%20photosensor(phototransistor).
30. Grusin, M., & J., B. (n.d.). Hobby servo tutorial. Hobby Servo Tutorial - SparkFun Learn. https://learn.sparkfun.com/tutorials/hobby-servo-tutorial/all

31. Guise, L. (2022, June 2). *The Ultimate Pet Toy Safety Guide*. Prezzies. https://prezzies.com/pet-toy-safety/
32. Hardin, W. (2020, April 22). *IEC 62471 for LED lighting products*. Smart Vision Lights. https://smartvisionlights.com/resources/lighting-basics-resources/iec-62471-for-led-lighting-products/
33. Hetch, E. (2017). *Optics*. Pearson
34. *Introduction – What is a LDO? What is a linear regulator?*. ABLIC Inc. (n.d.). https://www.ablic.com/en/semicon/products/power-management-ic/voltage-regulator-ldo/intro/
35. *IR sensor: Basics, types, circuit, working, projects, faqs*. Electronics For You. (2023, August 29). https://www.electronicsforu.com/technology-trends/learn-electronics/ir-led-infrared-sensor-basics#:~:text=Proximity%20Sensors,-Proximity%20sensors%20employ&text=The%20photodiode%20receives%20the%20radiation,voltage%20to%20determine%20the%20distance.
36. Jain, A. (n.d.). *Understanding Battery Management Systems*. Engineers Garage. https://www.engineersgarage.com/understanding-battery-management-systems/
37. Karen Anderson. (2023, July 3). *The 13 best cat laser toys: Your kitty's favorite workout*. The Dog People by Rover.com. https://www.rover.com/blog/best-cat-laser-pointer-toys/
38. Kushnir, A., & Kushnir, A. (2023, March 1). Mobile App Architecture: the Ultimate Guide - Bamboo Agile. Insights. https://bambooagile.eu/insights/mobile-application-architecture/
39. Lathi, B. P., & Ding, Z. (2019). *Modern digital and Analog Communication Systems*. Oxford University Press.
40. *LDO ＜What is an LDO?＞*. ROHM Semiconductor. (n.d.). https://www.rohm.com/electronics-basics/dc-dc-converters/what-is-ldo
41. Lehman, M. (2023, September 28). The pros and cons of cross-platform app development GMI Software. GMI Software. https://www.gmihub.com/blog/cross-platform-app-development/
42. LLC, K. M. (n.d.). IPhone bluetooth support by model: Everyiphone.com. https://everymac.com/systems/apple/iphone/iphone-faq/iphone-bluetooth-support-by-model.html
43. Loron, A. (2023, March 16). GPT-4–100X More Powerful than GPT-3 - Geek Culture - Medium. Medium. https://medium.com/geekculture/gpt-4-100x-more-powerful-than-gpt-3-38c57f51e4e3#:~:text=GPT%2D4%20is%20significantly%20larger,GPT%2D3%27s%20175%20billion%20parameters
44. Lynch, M. (2023, June 23). Android: the most popular mobile operating system. The Tech Edvocate. https://www.thetechedvocate.org/android-the-most-popular-mobile-operating-system/
45. Mobile Application development. (n.d.). Amazon Web Services, Inc. https://aws.amazon.com/mobile/mobile-application-development/#:~:text=Mobile%2

0application%20development%20is%20the,work%20with%20remote%20computing%20resources

46. Monolith. (2023). In Merriam-Webster Dictionary. https://www.merriam-webster.com/dictionary/monolith
47. Nerdynav. (2023, November 7). 107 Up-to-Date ChatGPT Statistics & User Numbers [Nov 2023]. Nerdynav. https://nerdynav.com/chatgpt-statistics/#
48. Nilsson , D. P. G., Andersson, M., & Dahlberg, T. (2021). Step-by-step guide to 3D print motorized rotation mounts for optical applications. Optica Publishing Group. https://opg.optica.org/ao/fulltext.cfm?uri=ao-60-13-3764&id=450413
49. Pasternack. (2023).Friis Transmission Formula Calculator. Pasternack. https://www.pasternack.com/t-calculator-friis.aspx. (November 13, 2023).
50. Patoux, J. (2007, May). Ask The Applications Engineer—37: Low-Dropout Regulators. *AnalogDialogue*. November 9, 2023, https://www.analog.com/en/analog-dialogue/articles/low-dropout-regulators.html
51. PetMD Editorial. (2022, August 18). How Long Should You Play With Your Cats Each Day? PetMD. https://www.petmd.com/cat/care/how-long-should-you-play-your-cats-each-day#
52. Robocraze. (2021, March 18). *DIY IR sensor*. Robocraze. https://robocraze.com/blogs/post/diy-ir-sensor
53. Rocheleau, L. (2022, July 22). Designing a modern Lipo/Li-Ion Power Solution: Selecting an I2C switching charge controller: KSD. Kickstart Design - Product Design. https://www.kickstart-design.com/blog/designing-a-modern-lipoli-ion-power-solution-choosing-the-best-charger-ic
54. *Round Wedge Prisms*. (n.d.). Www.thorlabs.com. Retrieved November 9, 2023, from https://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=147
55. Ruby, D. (2023, August 1). 20 Android Statistics In 2023 (Market Share & Users). https://www.demandsage.com/android-statistics/#:~:text=Android%20Statistics%3A%20At%20A%20Glance&text=There%20are%203.3%20billion%20Android,Android%2012.0
56. Schmitt, J. (2022, August 24). Native vs cross-platform mobile app development. CircleCI. https://circleci.com/blog/native-vs-cross-platform-mobile-dev/
57. Schweber, B. (2018, September 11). *How to use Photodiodes and phototransistors most effectively*. DigiKey. https://www.digikey.com/en/articles/how-to-use-photodiodes-and-phototransistors-most-effectively#:~:text=The%20optical%20half%2Dpower%20acceptance,%2C%20lens%20arrangement%2C%20and%20spacing.
58. Tarantula3, & Instructables. (2020, October 30). *DIY - IR module*. Instructables. https://www.instructables.com/DIY-IR-Module/
59. Team, D. (2023, February 1). GPT-1, GPT-2 and GPT-3 models explained. 360digitmg.com. https://360digitmg.com/blog/types-of-gpt-in-artificial-intelligence#:~:text=The%20difference%20between%20the%20three,it%20the%20largest%20neural%20network
60. Technology, E. (2022, August 22). *Main difference between photodiode and phototransistor*. ELECTRICAL TECHNOLOGY.

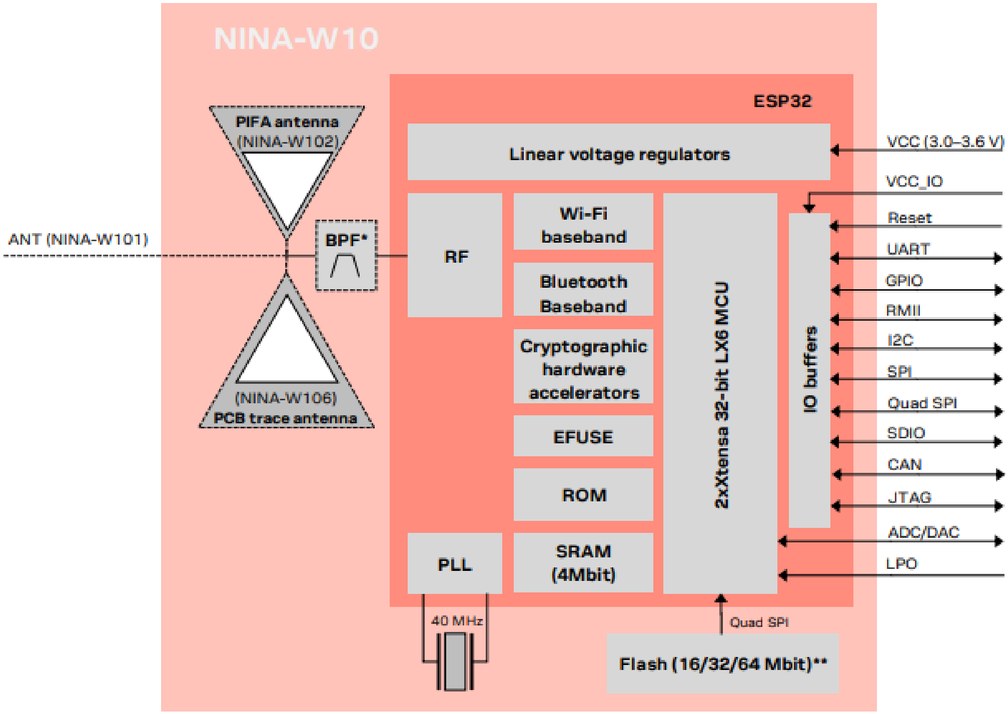
https://www.electricaltechnology.org/2022/01/difference-between-photodiode-phototransistor.html

61. The pros and Cons of hybrid app technology | CodeControl. (n.d.). https://codecontrol.io/en/blog/the-pros-and-cons-of-hybrid-mobile-app-technology
62. *Toy Safety Business Guidance & Small Entity Compliance Guide*. U.S. Consumer Product Safety Commission. (n.d.). https://www.cpsc.gov/Business--Manufacturing/Business-Education/Toy-Safety-Business-Guidance-and-Small-Entity-Compliance-Guide
63. Van Otten, N. (2023, October 30). Top 20 Most Powerful Large Language Models For NLP Tasks & Transfer Learning In 2023. Spot Intelligence. https://spotintelligence.com/2023/04/18/large-language-models-nlp/
64. Wagh, A. (2023, July 2). Architecture of OpenAI ChatGPT & Tips | Medium. Medium. https://medium.com/@amol-wagh/open-ai-understand-foundational-concepts-of-chatgpt-and-cool-stuff-you-can-explore-a7a77baf0ee3
65. What is microservices architecture? | Google Cloud. (n.d.). Google Cloud. https://cloud.google.com/learn/what-is-microservices-architecture
66. *What is a phototransistor: Tutorial & primer*. Electronics Notes. (n.d.). https://www.electronics-notes.com/articles/electronic_components/transistor/what-is-a-phototransistor-tutorial.php
67. What is Natural Language Processing? | IBM. (n.d.). https://www.ibm.com/topics/natural-language-processing
68. What is Scrum? (n.d.). Scrum.org. https://www.scrum.org/resources/what-scrum-module
69. What is software development? | IBM. (n.d.). https://www.ibm.com/topics/software-development
70. Wood, T. (2020, July 7). Transformer Neural network. DeepAI. https://deepai.org/machine-learning-glossary-and-terms/transformer-neural-network
71. Writer, S. (2022, August 16). 49% of Android users consider switching to iPhone due to privacy. 9to5Mac. https://9to5mac.com/2022/08/16/android-users-consider-switching-iphone/#:~:text=A%20survey%20shows%20that%2049,of%20Samsung%27s%20Galaxy%20S22%20Ultra

12.2 Datasheets

1. NINA-W102 Block Diagram.

1.3 Block diagram

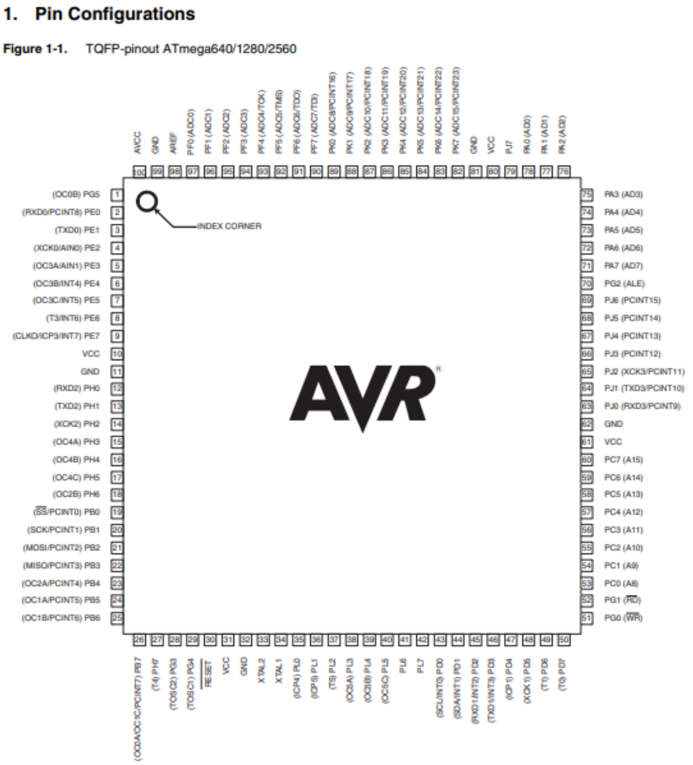


* Only on NINA-W101 and NINA-W102.

** 16 Mbit NINA-W101 and NINA-W102; 32 Mbit NINA-W106-00B; 64Mbit NINA-W106-10B.

NINA-W10 Datasheet

2. ATMEGA 2560 Pin Configuration

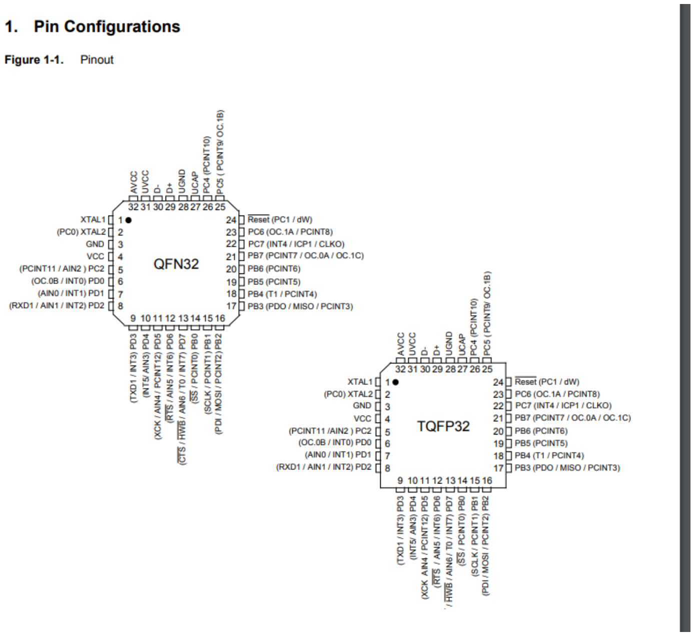


1. **Pin Configurations**

Figure 1-1. TQFP-pinout ATmega640/1280/2560

[ATMEGA2560 Datasheet]

3. ATMEGA16-U2

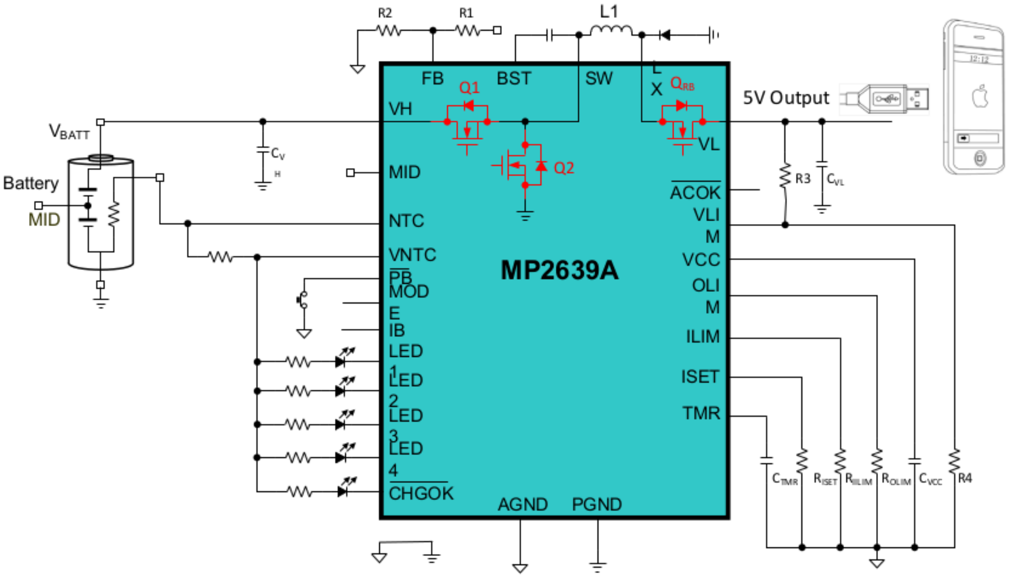


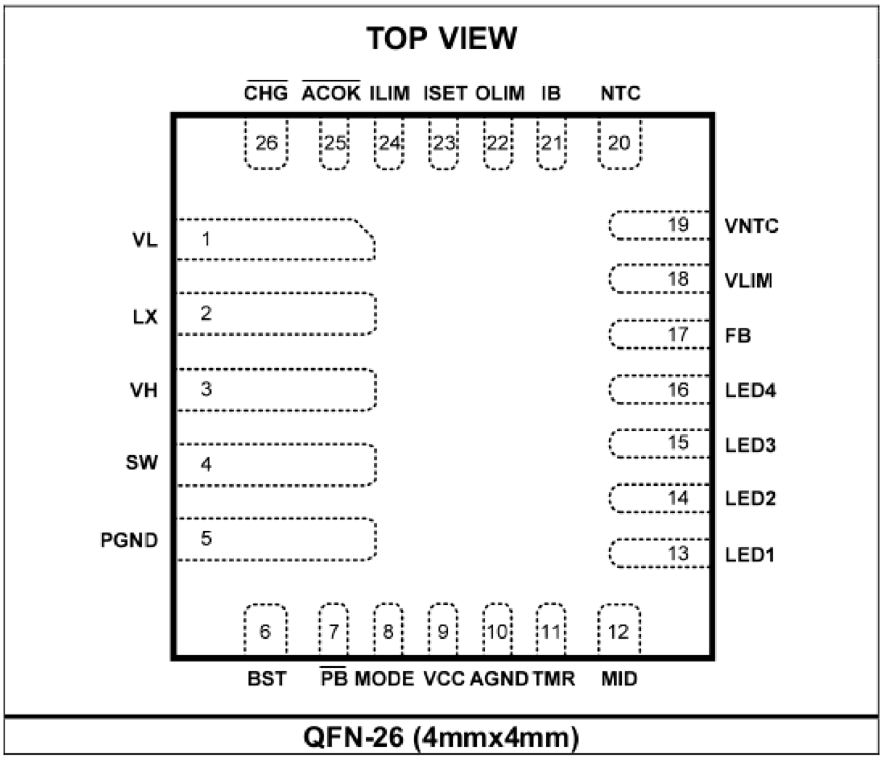
1. **Pin Configurations**

Figure 1-1. Pinout

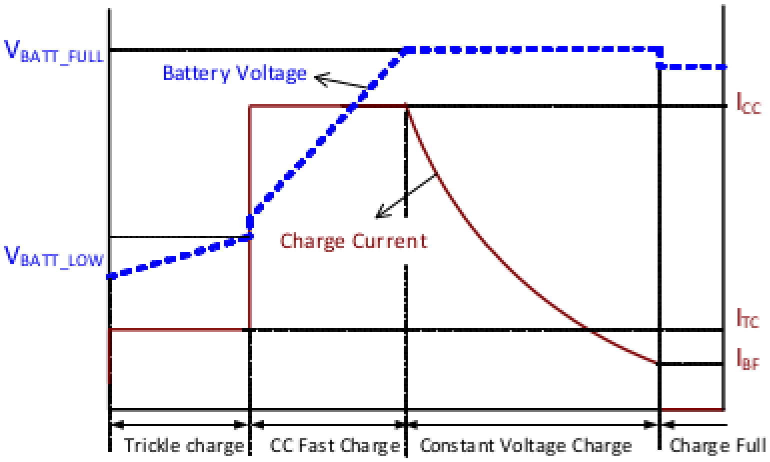
[ATMEGA16-U2 Datasheet]

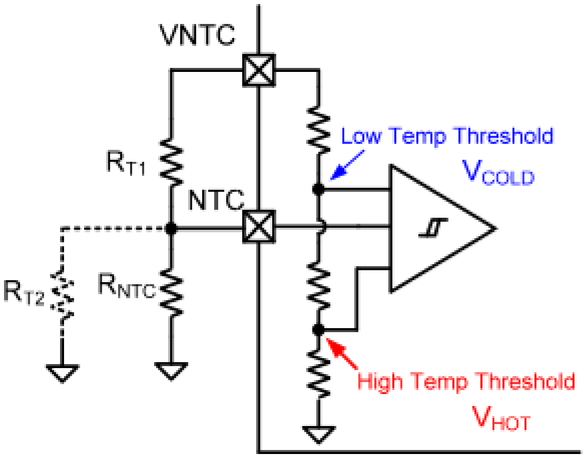
4. MP2639A Discharge application example, IC package, charging graph, and NTC schematic





QFN-26 (4mmx4mm)





[MP2639A Datasheet]

5. [MTD8000M3B-T Data Sheet]
6. [QED223A4R0 Data Sheet]
7. [WP710A10SEC/J3 Data Sheet]
8. [151054GS03000 Data Sheet]
9. [LTL2V3TBS3KS Data Sheet]