Smart Laser Toy for Cats

Adriana Guevara, Xaria Davis, Carlos Ricard,
Benjamin Love, and Leife Francisco

Dept. of Electrical Engineering and Computer
Science, College of Optics and Photonics,
University of Central Florida, Orlando, Florida,
32816-2450

Abstract — **The Smart Laser Toy for Cats is a three-step device that integrates motion sensing, color detection, and laser movement to create a hands-free cat toy for pet owners whether they are not home, busy working, or have hand mobility restrictions. The system works by first detecting motion, then identifying the correct pet through color detection, and then displaying the laser scanning patterns for about 10 to 15 minutes. This eliminates the need to move the laser pointer around manually.**

Index Terms — **Laser scanning, passive infrared sensor, color image processing, microcontrollers, AC adapter**

I. INTRODUCTION

Currently on the market, there are several ways to entertain cats but very few require little to no effort from the owner's part. 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. This provided the opportunity to create a cost-effective cat toy that adds more flexibility and user control to a traditional toy for cats.

Another motivation for the creation of this toy is to make a device inclusive for those with hand restrictive mobility problems, limiting the amount of time and ability to move a laser pointer around for their pet cat. To combat this problem, the Smart Laser Toy for Cats is a three-step device that integrates motion sensing, color detection, and a laser lens system to fully operate the toy for the desired cat.

The first step of the process entails motion sensing. This is done with the use of a passive-infrared (PIR) motion sensor that is composed of infrared (IR) light emitting diodes (LED) and a phototransistor. The PIR sensor will emit light from the IR LEDs to the moving object. The IR light will then reflect off the moving object for the phototransistor to receive. When the IR light is detected, the phototransistor will then send an electrical signal to the camera to turn on, beginning the second step of the process.

The color detection system consists of two independent components, the camera for color detection and the LED color tags that will be placed on the cat. The LED color tags are composed of an LED and Fresnel lens housed in a 3D printed tag. The camera is programmed to detect only the color specified by the owner, in the case of this project, it will be red, green, or blue. Once the desired color is detected by the camera, the last step of the process will commence, the laser system.

The laser system is the last part of the three-step process of the Smart Laser Toy for Cats. This process consists of two ten-degree wedge prisms, a plano-convex, and a plano-concave lens. The plano-concave and plano-convex lenses are used to expand the beam from 3 mm to 15 mm. The wedge prisms are mounted on a motor rail that turns the prisms at different speeds to generate various patterns at the user's discretion. After approximately ten minutes of play time, the device will automatically shut off to not overexert the cat.

To allow the user to configure the device and see statistics on the cat's play time, a mobile application is developed. The mobile application will give the user the ability to create cat profiles, select colors, select the pattern that the cat will play with, and see the play time in a user-friendly format. To properly function, the device shall be placed approximately one foot off the ground, powered from the wall using an AC adapter, and the cat shall approach that device and wait for the system to go through the three-step process.

II. SUBSYSTEMS

A. Passive Infrared Sensors

The PIR sensor will always be on so long as the device is being powered. The circuit was created using a three-by-three array of 880 nm IR LEDs that have a radiant intensity of 25 mW/sr and a viewing angle of 40°. By creating the array of lights, it increases the intensity of the IR light as opposed to the singular IR LED, and in turn increasing distance. A singular phototransistor was placed on the circuit since the phototransistor selected has peak detection at 880 nm and a viewing angle of 160°. The circuit created can be seen in figure 1.

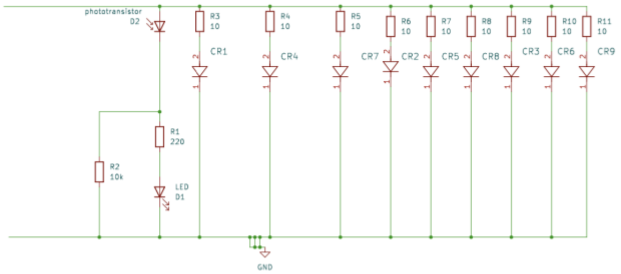

Fig. 1. The circuit drawing of the PIR sensor to detect motion.

In the drawing of the circuit, the IR LEDs are placed in a single row, however, when created on a perfboard, they are arranged in a square formation. A visible light LED is placed on the circuit for visual confirmation that motion is detected. For electrical current to flow to the visible light LED, the phototransistor must receive IR light at the 880 nm wavelength. This will turn the phototransistor "on" to flow current through the rest of the circuit. Once the electrical current reaches the visible light LED, the Raspberry Pi is programmed to turn on the camera.

B. LED Collar Tags

The LED collar tags are created to optimize the color detection process of the Smart Laser Toy for Cats. The selected colors for this project are red, green, and blue LEDs. The LEDs selected were of high luminosity to ensure saturation of the camera with the selected color. The LED will be powered using a 220-ohm resistor, 3 V button cell battery, and switch. It is important to note that because the blue and green LEDs selected have a forward voltage higher than 3 V, two batteries are placed in series to ensure proper lighting of the circuit. The Fresnel lens is placed over the LED at 20 mm distance for optimal dispersion of light. The lens used was from a school project kit, so to ensure that it would meet the requirements of the project, the lens was simulated on Zemax to test the dispersion of light, seen in figure 2.

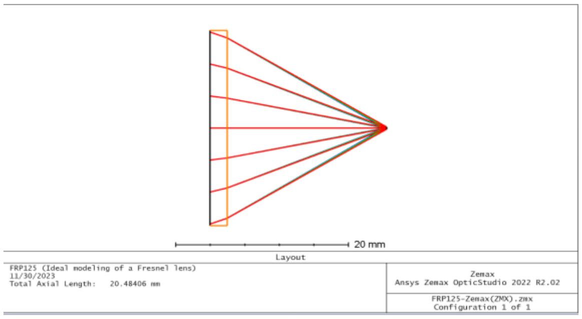

Fig. 2. The Zemax simulation of the Fresnel lens with a 20 mm focal length and 30 mm diameter.

The three wavelengths of the LEDs, 625 nm, 522 nm, and 470 nm were simulated on the drawing in figure 2 and show good dispersion of light. The LEDs will be detected by a Raspberry Pi Camera Module v2 with a viewing angle of 62.2° that will be placed on the front side of the external housing of the Smart Laser Toy for Cats.

C. Color Detection

The color detection system functions similarly to an authentication system for the device. When the owner is absent and the cat activates the motion sensor, the system initiates a search for the collar tag's color, as predetermined by the user. Should it confirm the presence of the cat through the identified color, the laser system activates. If the system fails to detect the specified color, it remains inactive.

This system incorporates a Raspberry Pi 4 Model B and a Pi Camera Module 2. It runs on OpenCV, employing a color mask to analyze the live video feed for saturation with the collar tag's color. The collar is equipped with a Fresnel lens designed to amplify the LED's color when the cat is close, with the collar tag itself also the same color to ensure additional verification. This setup ensures that the device only activates when it positively identifies the cat through its unique collar tag color, providing a smart, interactive experience tailored specifically for the cat.

D. Laser System

The laser diode is the light source that will be expanded and steered to entertain the owner's cat. For safety, the output power of the laser must be limited to less than 1 mW of optical power and operate in the red range of visible light. The VLM-650-03 LPT laser diode found on Digikey was chosen as it fits both standards as well as a beam size that passes through each optical component without being cut off while expanded.

The lens system in this device is designed to magnify the laser beam 5 times its original spot size. To accomplish this, two different lenses are required; a concave lens to expand the light and a convex lens to re-collimate it into a coherent beam. Both the plano concave and convex lenses chosen for this device are made with N-BK7 glass, giving it a refractive index of 1.52. The LC1054 plano concave lens was chosen for this device to expand the laser light that is incident on it. This lens has a thickness of 4.7 mm, a 0.5-inch diameter, and a focal length of -25 mm. The LA1986 plano convex lens was chosen to re-collimate the laser light that passes through it. This lens has a thickness of 3.3 mm, a 1-inch diameter, and a focal length of 125 mm. The pair of lenses must be spaced exactly 10 cm away from each other as the spacing is equal to the sum of the focal lengths. The lens system was simulated with Zemax to test the magnification, seen in figure 3.

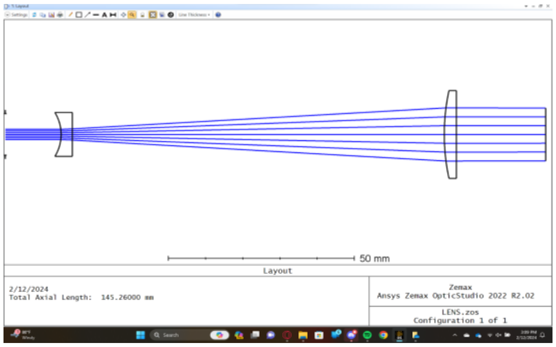

Fig. 3. Zemax simulation of the beam expander.

The wedge prisms in this device are designed to steer the expanded laser beam that passes through it by rotating them. For this device, two identical 1-inch diameter wedge prisms consisting of N-BK7 glass were chosen. When the two identical wedge prisms are rotated in the same direction and speed, the angle of deviation is double the value of one prism on its own. When the wedge prisms are rotated at different speeds or directions, a variety of rose curves can be generated utilizing the following equations:

$$y(\omega_1 + \omega_2) = (r_1 + r_d) * \sin(\omega_1 t) + r_2 * \sin(\omega_2 t) \quad (1)$$
$$x(\omega_1 + \omega_2) = (r_1 + r_d) * \cos(\omega_1 t) + r_2 * \cos(\omega_2 t). \quad (2)$$

Originally, two 2° wedge prisms were chosen for beam steering; however, when calculating the play area at a distance of 1 m by finding the value of tan(4°), we found that the play area was too small. The angle of deviation of the prisms was increased to 10° to increase the size of the play area.

The wedge prisms used to manipulate the laser beam into various patterns require two motors to rotate the lenses. Two motor technologies were discussed for the laser movement system: stepper motors and commercial "hobby" servo motors. Steppers are a common motor choice for optical systems in a stationary and/or lab setting owing to their extremely high positional accuracy. However, they have high current consumption during operation (around 1 A per motor), a continuous current draw when idle, and a general "bulk" to their size and mass.

The chosen motor type is instead an off-the-shelf hobby servo, so called because they are commonly used in remote-controlled model vehicles. These motors are small, all-in-one devices that consist of a brushed DC motor, integrated H-bridge driver, and reduction gearbox. Compared to steppers, these motors have less than half the operating current draw (<500mA), virtually no idle current, and are much smaller and lighter.

The specific motors chosen (DFRobot DF9GMS, figure 4) are "continuous movement." This means that the motor's output actuator is able to rotate infinitely, which is necessary for this project. A side effect owing to hobby servo design is that such motors lack positional sensing. Consequently, the driver board is designed for open-loop velocity control. This means that the PWM signal controls velocity of the motor with no feedback as to the armature's position or velocity. However, the wedge prisms are based on ratios of the two lens velocities respective to each other, as opposed to the exact quantified position or velocity of each lens. Testing has shown that such an open-loop control system is sufficient to generate the ratios needed for the desired laser patterns.

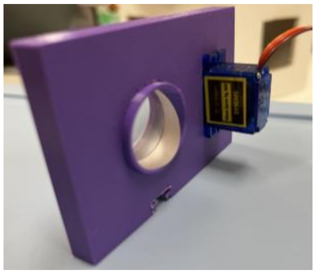

Fig. 4. The selected hobby servo, along with a wedge prism and mounting bracket.

The integrated driver controls motor position or velocity using a single PWM control signal. This signal operates at a 20mSec pulse interval (50 Hz), with a pulse width of 1 to 2mSec controlling position or velocity. For velocity control, the extremes in this range correspond to full velocity in either direction, and a width of 1.5mSec for a velocity of zero. The following figure shows a visualization of this. Note that the figure shows positional control, but velocity control uses the same signal.

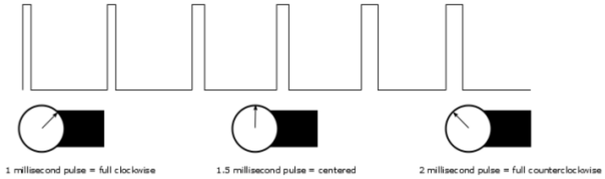

Fig. 5. An example of the 50Hz PWM signal used for hobby servo control.

E. PCB

Version 1 of the printed circuit board consists of a microcontroller, a Bluetooth module, and a power supply along with other peripherals to power and control the motion detector and the laser servos. The purpose of this original printed circuit board was to provide a development platform for the software team to develop with.

The microcontroller is an ATMEGA2560. The ATMEGA2560 (from here on referred to as the microcontroller) main purpose is to control signals, send commands, and receive signals. The microcontroller receives commands from the phone application via the Bluetooth module and then sends those commands using the GPIO pins to the laser, the servo motors, or the motion detectors. The microcontroller communicates using a serial peripheral interface to communicate with the Bluetooth module.

The original Bluetooth module is the NINAW102B. The Bluetooth module communicates with the phone application via Bluetooth and then communicates with the microcontroller via SPI. The Bluetooth module only communicates with the phone application and the microcontroller so that the data rate is not low and to avoid latency issues. Figure 6 provides a picture of a blank board.

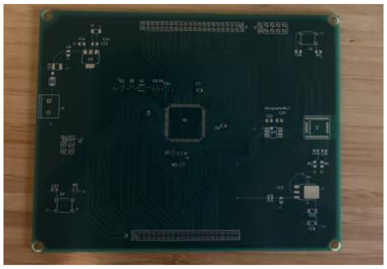

Fig. 6. The first version of the printed circuit board. This shows a blank copy of the first board to show the systems used.

The second version of the printed circuit board is essentially the same board with one major difference. The major difference is the addition of a charge controller. The purpose of the charge controller is to provide a charging feature to the customer. This goal was one of the stretch goals to provide a convenient feature to the customer.

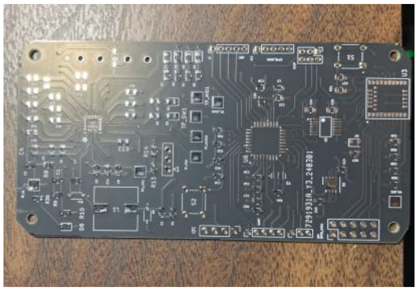

Fig. 7. The second version of the printed circuit board system. This printed circuit board provides a re-charging feature for the batteries.

The third printed circuit board reduces the complexity of the other boards. Its main purpose is to fulfill the requirements of the system without the complications of the other systems.

The third printed circuit board is a coaxial power connector adapter, a linear dropout regulator, and the ESP32-WROVER-N8R8, and a USB to UART converter.

The main purpose of this change from the second to third version of the printed circuit board is to reduce the complexity. The second purpose of doing this is that the group was able to easily use a development board to perform all the necessary requirements of the original board without needing two separate systems for the same purpose. Furthermore, another reason the group switched was that the cost of the module was significantly lower than the cost of the ATMEGA2560.

F. Power System

The power system for the toy comprises two core stages. The first stage is a 5v switched DC input. For direct current devices, a switching topology is desirable for the primary power supply due to its high efficiency compared to linear topologies. This is due to linear regulators using resistance to lower voltage, which wastes this voltage drop as heat. Conversely, switching regulators charge and discharge transient components such as capacitors and inductors by quickly switching the input power on and off. This can create ripple in the output voltage and current as a side effect, so decoupling capacitors are required for systems receiving power.

For the final device, this stage is a premade AC adapter. Original plans and testing considered an integrated lithium-ion battery, but this was vetoed due to increasing continuous current requirements, reliability problems encountered during testing, and pet safety concerns.

The 5v rail is used to provide power directly to multiple systems with high power requirements. These include the passive infrared motion sensors, laser motion system, and Raspberry Pi-based color detection system.

The second stage is a linear voltage regulator of the low-dropout (LDO) type. This is used to power the microcontroller and Bluetooth module. A linear technology was chosen for these components for a few reasons. The main reason was output current quality. As previously mentioned, switching regulators have issues with output noise. Microcontrollers and radiofrequency devices are especially sensitive to this noise, particularly fluctuations in current. LDOs are commonly used on microcontroller development boards to account for this problem.

G. Mobile Application

The iOS mobile application serves as the core of interaction between the user and their device. It aims to be more than a controller by fostering a sense of personability and ease of use. Users can create accounts to store various details about their cats in the Firestore database, including the cat's name, age, weight, breed, and sex. This toy is an aid for busy cat owners, keeping their pets healthy and active. Establishing baseline health information and keeping it updated is crucial. Moreover, owners can highlight their cat's favorite patterns for quick access on every page.

This mobile application is designed for any iOS device running iOS 17 or higher. Despite iOS 17's release in September 2023, the oldest compatible device is the iPhone XS, which is six years old, extending the app's reach to a broad audience. The choice to develop exclusively for the iOS platform, over Android or cross-platform options, was practical. Apple dominates the smartphone market share in North America and is the most popular among our target demographic: Gen Z and millennials.

As of 2024, Swift remains the preferred programming language for iOS app development, with SwiftUI emerging as the leading framework for designing user interfaces. SwiftUI's declarative syntax simplifies app development, providing a modern and cohesive appearance consistent with many existing applications. Alongside SwiftUI's components, we created custom components that align with our theme while enhancing usability and experience.

The dashboard welcomes the authenticated user with a profile card, showcasing their chosen image and name of their cat. Next, the activity card offers a quick overview of today's statistics, including the total playtime and the remaining playtime. Subsequently, a list of their preferred patterns is displayed in pattern cards, with each card presenting an image, the name, and a description of the pattern. Each component is designed for reusability throughout the app, ensuring a consistent user interface. The additional pages provide a detailed overview of the contents displayed on the dashboard. The patterns page displays a full list of all available patterns. On the profile page, users find their cat's health details. Lastly, the settings page presents information on device statistics and grants users the ability to modify any editable details.

To streamline development, the app's logic is also implemented in Swift. Authentication, database management, and binary storage functionalities are facilitated by Firebase, Google's comprehensive mobile development platform. Delegating these operations to a robust API allowed us to concentrate on delivering advanced features, such as offering owners analytics and insights into their cats' play behavior.

III. HOUSING

A. External Housing

The enclosure design to house all the hardware components of the Smart Laser Toy for Cats is a wooden 10 inch by 6 inches by 6 inches box that has cut outs specific to the components contained. The front of the box will have one 3-inch square cut out in the center of both the right and left side. This will hold two of the four PIR sensors to optimize detection from the front. In between the two squares is a 1.25-inch circle where the laser will exit out of. Under the circle is another 1-inch circle that will be where the camera is placed for optimal detection of the LED collar tag.

The right and left sides of the box are symmetrical in that they both have a 3-inch square cut out in the center to hold the remaining two motion sensors.

The back panel of the box will be where the power supply will be placed to power the device on with the AC adapter. The lid is placed using hinges so that the hardware components are easily accessible. The final box can be seen in figure 8.

Fig. 8. The final prototype of the housing enclosure for the subsystem hardware components.

B. Collar Tags

The collar tags are created using Solidworks to 3D print them. The tags are created with 30 mm in height to account for all the electrical components and distance needed from the Fresnel lens to have optimal dispersion of light. A small divert is created on the top of the tag, 2 mm in height, to hold the Fresnel lens and ensure is does not fall down if the silicone adhesive were to slowly remove itself from the tag. By 3D printing, the tag holder remains lightweight and should not bother the cat. The final design can be seen in figure 9.

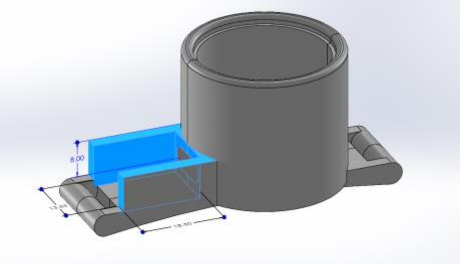

Fig. 9. The final design for the LED collar tag holder.

The LED, battery, and resistor will be housed inside the cylinder and the switch will be placed on the open rectangle on the side to allow the user to turn the light on and off. The tag will be placed on top of the cat's neck or underneath it, depending on the height of the cat.

C. Optical Mounts and Rail

The laser movement system has structure requirements with very tight tolerances as well as multiple moving parts. Additionally, commercial drop-in optical components were quickly ruled out for this project due to extremely high cost. Therefore, bare lenses and servo motors were acquired, and an optical rail system was designed, and 3D printed around it. All design was accomplished in TinkerCAD, seen in figure 10.

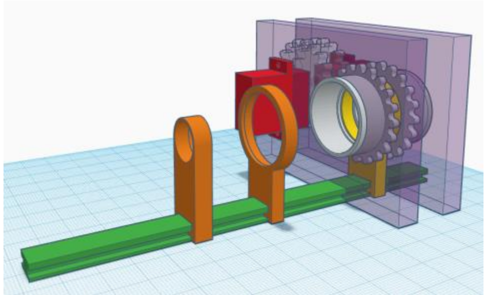

Fig. 10. Core components of the laser movement system.

The most challenging part of the design was the mounting of the wedge prisms. All 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 10 mm wide by 5mm tall rail with an I-beam cross section. All components are aligned with the center of each aperture 30 mm above the rail. This height was chosen to provide adequate clearance for the motor brackets and associated gearing. The final toy raises the laser system higher than this, 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 space below the rail for other components.

IV. TESTING

A. Passive Infrared Sensors

Initial testing of the PIR sensor in Senior Design I showed that the detection of the moving objects was at approximately four centimeters in distance. This did not satisfy our engineering requirement of 0.5 to 1.5 feet of detection. To combat this issue, it was decided to proceed with the circuit shown in figure 1.

By creating this array, the detection distance was increased to roughly 8 to 9 inches. Because this does not meet the requirements listed out at the beginning of this project, further testing was done by using a plano-convex of 25 mm focal length to increase the range of the IR light and that provided a detection range of approximately 1.5 feet. However, due to cost constraints of the project and the cost of lenses, with the approval of the CREOL Senior Design advisor, Dr. Kar, we will not be integrating the lenses into the final project. The final design of the perfboard can be seen in figure 11.

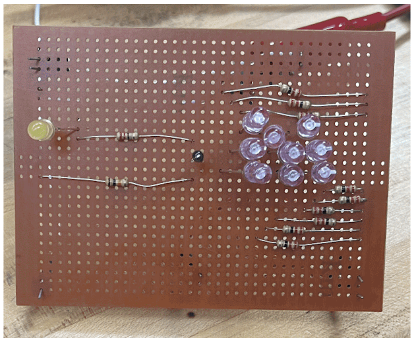

Fig. 11. The final perfboard used for the PIR sensors.

Using a 5 V power source for the circuit will draw approximately 0.3 amps of current which is good for the scope of our project.

B. LED Tag

To test the LED tag, the circuit was created on a one-inch perfboard to ensure that the LED does not move around while it is on the cat as it is imperative the LED shines in the center of the Fresnel lens to get optimal dispersion. The batteries are connected to the system by using electrical tape since they cannot be soldered onto the circuit. To prevent the Fresnel lens from moving, it is glued onto the holder using silicone adhesive to also prevent water from entering the collar. The final prototype can be seen in figure 12.

Fig. 12. A side-by-side view of the collar tag turned on with the Fresnel lens (left) and housing the electrical components (right).

C. Color Detection

Testing the color detection system required creating a simulation of the environment in which it would operate, with a focus on observing how effectively it identified the collar's color under various lighting conditions. A key discovery from these tests was the performance of HSV (hue, saturation, value) color values over RGB (red, green, blue), due to HSV's robustness against variations in lighting conditions. This insight prompted the switch from RGB to HSV values to ensure reliable operation in both well-lit and low-light environments.

Determining the optimal threshold values for activating the laser system was another aspect of the testing process. It was imperative to strike a balance between color detection and distance, as the farther away the cat is the lower the saturation value becomes. It's also important to account for any latency between the communication of the motion sensor and laser detection systems, as the cat may walk away immediately after triggering the motion sensor. Through experimentation, it was found that setting the threshold between 10 - 15% saturation was effective for recognizing the presence of the cat based on the collar's color alone. When the Fresnel lens directed the LED's light towards the camera, the saturation level increased to nearly 50%. This threshold calibration ensures the laser system activates only when it's highly likely a cat is present.

Trial	Distance (ft)
1	3.5
2	3.3
3	3.2
4	4
5	4.1
6	3.4
7	3.6
8	3.7
9	3.2
10	4.2
Average	**3.6**

Table 1. Results of trials to determine minimum detection distances for the color detection system.

D. Laser System

To test the laser system, the beam expander was created utilizing 3-D printed lens mounts. The laser diode is then turned on, and the spot size is measured without magnification. The laser diode is then mounted to the optical axis and the output spot size is measured. The magnification is found by taking the ratio of the expanded spot size over the original spot size, finding it to be 5.

E. PCB

The first version of the printed circuit board never functioned well and had several intermittent faults. The first intermittent fault was a short. After assembling the PCB, the power supply in the lab dropped from seven volts to three or four volts. First, the group tested an 'empty' printed circuit board by making continuity checks. The purpose of this was to make sure that a short was not designed into the board. The empty boards passed, and the group determined the short was due to soldering. With the help of Dr. Weeks, the microcontroller was resoldered on. The problem went away for a while and then reappeared intermittently. Under the recommendation of Dr. Weeks, the group reordered the microcontroller because it was likely that the board was exposed to too much heat during the assembly process.

The group ordered another microcontroller, and the power supply fault went away. However, the group needed to design and build a second version of the printed circuit board to provide battery charging so testing and troubleshooting attention went there. The second printed circuit board had similar problems as well with the power supply. However, for this board, since a charge controller was added the problem changed.

The initial problem with the second version of the printed circuit board was the same. The voltage of the power supply in the lab would rise, then drop to a lower voltage, and then the board would get hot. The group members doing the testing assumed there was a shorted pin during assembly. The group members removed several components: the reset switch, the boot switch, several connectors, and some capacitors. After doing this, the short went away however, a new problem arrived. The new problem was that the board would consume a constant amount of current but heat up to well above ambient temperature. Then once a threshold temperature was reached, the board's current consumption would jump, and the power supply would limit the power output. The group solved this problem by bypassing the charge controller that was a part of the second printed circuit board. After doing this, the circuit board worked however the other parts of the board were damaged and needed to be replaced. The third PCB is currently being ordered and testing is ongoing.

The following figures show the problems the group had with the second version of the printed circuit board.

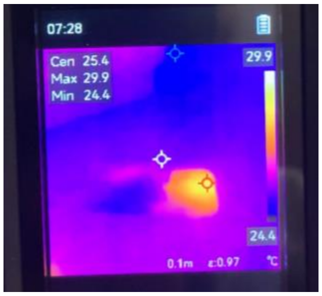

Fig. 13. Image of the power supply problems the group had with the second printed circuit board charge control overheating issues.

Fig. 14. Picture of the heat dissipation issues the board had.

V. RESULTS

After the design and testing of the Smart Laser Toy for Cats, the group has been able to meet the engineering specifications. The PIR sensor did not meet the specifications of the final device but is achievable using lenses if cost constraints were not a problem. The color detection system exceeds the detection distance by averaging to 3.62 feet of detection.

The color detection system is successful in accurately detecting the different color above a certain threshold level through color masking on OpenCV. The group is able to get detection at an average of 3.62 feet of distance over ten test trials.

After changing the wedge prisms from 2 degrees to 10 degrees, the amount of play area substantially increased to approximately a circle radius of 36.4 centimeters, surpassing our goals for the cat to play with.

The printed circuit board is still undergoing testing and assembly. The development module that was purchased can integrate all systems successfully and is a success. As long as the printed circuit board meets the same requirements as the development kit, the third board will be a success. However, the first and second board both had issues with their power supply.

VI. CONCLUSION

The Smart Laser Toy for Cats is successful in meeting the goals and objectives of the project and meeting the engineering specifications of the proposed requirements. There are improvements that can be made in future versions of the device, like adding lenses to increase motion detection distance. Overall, the project shows to be successful in integrating the three main subsystems and achieving the demonstrable engineering specifications.

ACKNOWLEDGEMENT

We would like to thank our senior design advisors, Dr. Lei Wei and Dr. Aravinda Kar for guiding us throughout the last two semesters in the completion of the project.

We would also like to thank Dr. Arthur Weeks and our committee members, Dr. Peter Delfyett, Dr. Mike Borowczak, and Dr. Qun Zhou Sun, for addressing all questions for the subsystems and providing their informative opinions throughout the entire process.

REFERENCES

[1] GlobalSpec, “Phototransistors”, *Globalspec*. [Online]. Available: https://www.globalspec.com/learnmore/optics_optical_components/optoelectronics/phototransistors. Accessed 18 Mar. 2024

[2] “Advanced Circuits.” *Printed Circuit Board Trace Width Tool | Advanced Circuits*, www.4pcb.com/trace-width-calculator.html. Accessed 1 Apr. 2024.

[3] “Round Wedge Prisms,” *www.thorlabs.com*. https://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=147

[4] Grusin, M., & J., B. (n.d.). Hobby servo tutorial. Hobby Servo Tutorial - SparkFun Learn. https://learn.sparkfun.com/tutorials/hobby-servo-tutorial/all