Laser Target Shooting

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***Abstract* — This paper contains information regarding the research, design, and testing of the laser target shooting system. This system, consisting of a smartphone app, laser rifle, and target board, is a safer variant of traditional target shooting that uses IR technology and other electronics to simulate the firing range experience. Overviews of the power systems, optical systems, and software functionality are provided.**

***Index Terms* — Infrared communications, imaging, Bluetooth, lens, modulation**

I. INTRODUCTION

Recreational shooting is a pastime that gun owners do to sharpen their shooting skills or do simply for fun. However, most people do not have the luxury of being able to shoot a firearm near their home and must go to a local shooting range for practice. At shooting ranges, for people who do not bring their own equipment and must rent, prices can easily get up to a hundred dollars per hour. Unequipped visitors not only have to rent expensive ear and eye protection, shooting lanes, and guns but must also purchase the ammunition being used in their firearm of choice. For visiting gun owners, they have to drive to their local range, bring their equipment, and rent a shooting lane. Overall, this process can be inconvenient.

This project aims to remove the disadvantages of using a live firearm while remaining as a realistic, but safe, way to train yourself to handle firearms and enjoy recreational shooting by using lasers. With lasers, the downsides of traditional target shooting such as safety issues, environmental pollution, and high costs are significantly improved upon, while portability and accessibility are increased as lasers are not as regulated as live firearms. Our project is not the first of its kind, but compared to similar market products, our project aims to be an improvement by allowing for increased customization and portability as well as full functionality in any lighting environment be it day or night.

Our project can be broken down into 3 primary systems: the laser rifle, target board, and the smartphone app. The laser rifle is paired with the target board, a large but portable 3D printed board containing IR receivers that responds to the infrared laser and provides visible feedback to one's shot placement using LEDs. Using the smartphone app, a user can configure settings on respective devices they have connected to. Figure 1 is a concept model for the different elements that we planned to include in our system.

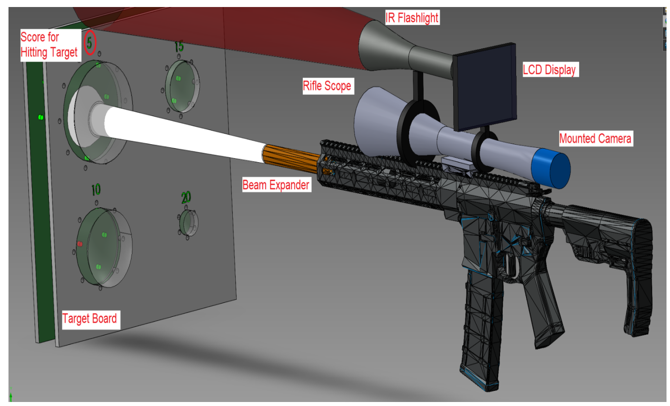

Figure 1. System Schematic

II. HARDWARE DESIGN

A. Laser Diode

The laser diode used in the laser rifle system was the RPMC Laser 8 mW VD-0940C-008M-1C-410 VCSEL diodes that come with built-in collimating lenses. These diodes have a wavelength of 940 nm with a beam divergence angle of 10 mrad and a 3mm collimated spot size. We chose to use 940 nm as the wavelength for a multitude of reasons mainly related to our intention to use our target shooting system outdoors. In order to achieve this goal, the effects of optical noise must be mitigated as much as possible.

We took inspiration from infrared communications systems that typically use an infrared LED modulated at 38 kHz paired with an IR receiver module that outputs a digital voltage signal in response to receiving the modulated light. These systems are resistant to optical noise due to the modulation requirement as well as the infrared wavelength chosen. 940 nm is typically used as the wavelength in these systems since solar radiation emitted by the Sun at this wavelength is significantly lower than other wavelengths. In our target shooting system, the laser rifle acts like a transmitter, while the target board acts like a receiver.

One of our main design requirements is to ensure that the system works at a distance of at least 15m from the target board to the rifle, so the divergence angle of the beam must be decreased in order to make sure that the spot size is not too large at 15m away. In our requirements, we set that the spot size must be smaller than 40mm at 15m away while the divergence angle must be less than 1.5 mrad. These requirements ensure that the target shooting system can be used at longer ranges past 15m. Since the beam outputted by the laser diode is already collimated, we needed to create a beam expander in order to sufficiently shrink the divergence angle.

In our system, we used a Galilean beam expander design, which consists of a negative and positive lens, in order to keep the total length of the expander down. We used a -25mm EFL biconcave lens and a 200mm EFL plano convex lens in the system resulting in an 8x increase in spot size and a 87.5% decrease in divergence angle to 1.25 mrad. Since we are using an 8mW laser, we also needed to decrease the optical power to less than 5mW for it to be considered a Class 3R laser for laser safety requirements. Since the spot size of the beam would also become quite large after passing through the beam expander and would expand further as it propagates, we included a circular aperture in the beam expander that would work to maintain a smaller spot size and block enough light to decrease power to below 5mW.

In order for the laser to be detected by the IR receivers, the laser diode must emit at a 38 kHz signal. This modulation can be provided directly by the MCU that we have chosen but the current provided by a single pin is max at around 20mA which is not sufficient to drive our laser to the distance we would like it to. In order to provide a sufficient amount of current to the diode we applied the use of an NPN transistor and a PNP transistor. In Figure 2 the diode is in series with a current limiting resistor and a regulated 5V signal is applied while the PWM signal is applied through the base of a 2N2222 transistor.

Since our IR diode is surface mount, it was imperative to utilize a potentiometer instead of a fixed resistor. After testing, we found that the resistance value should be around 33 to 220 ohms. The IR diode itself is located on its own circular PCB and connects to the main MCU PCB via pin headers.

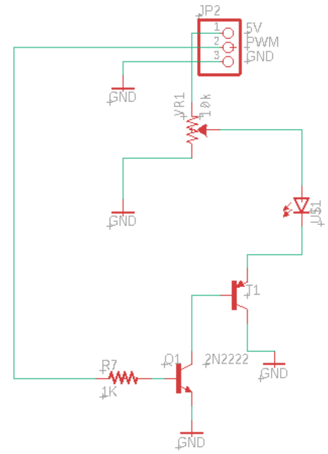

Figure 2. Laser Diode Schematic

B. IR Receivers

The IR receivers are essentially photodiodes with built-in preamplifiers that only react to modulated light and output a digital voltage signal in response. When in idle mode the IR receivers draw less than 2uA and 40uA when active; therefore, little to no current is utilized by these components. Due to the orientation that is needed for the lens implementation, we decided to include IR receiver modules instead of just the receivers themselves. These modules not only helped for testing purposes but also allowed for a more stable signal due to their onboard circuitry. On the target board, there will be 4 receivers all being powered by a 3.3V regulator.

As the receivers are mounted inside of the target board and need to receive the laser, we ran into a few design issues. We needed to ensure that the receivers are sufficiently protected from thermal and optical noise as well as physical damage. We also needed to reduce the amount of receivers in a given target area to at most one in order to minimize the amount of idle power used.

Our solution was the use of 3D printed PETG plano concave lenses that would be placed directly over the receivers. 3D printed lenses provide a very cheap and practical alternative to proper glass optics since the lenses can be printed as large as necessary. Since our target spots are 25mm, 50mm, 75mm, and 100mm in diameter while a single receiver is only around 5mm in size, each lens would work to expand the incoming beam, ideally making it so that we would only require a single receiver for each target spot.

These lenses would also have the same effect on incoming sunlight, effectively acting as a physical barrier that attenuates all incoming light. An issue that could occur from the lenses concerns the ability to receive the IR laser signal due to the attenuation and expansion of the beam, but this is not a major issue as the receivers are capable of receiving signals that are as weak as 0.2 mW/m^2. In Figure 3, the results of our testing with the 3D printed lenses is shown.

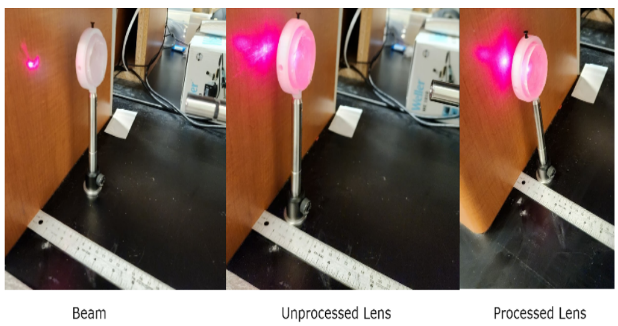

Figure 3. PETG Lens Testing

We printed a 50mm diameter lens with a -60mm EFL and used a 650nm laser with a 1mm spot size to test the performance of the lens. The distance from the wall to the back surface of the lens in the figure was fixed at 35mm, which is the spacing between the receiver and the lens in the target board enclosure. A comparison of how the lens performed before and after the lens was sanded and polished is provided in the figure. Only 50% of light was transmitted through the processed lens although the beam was greatly expanded through both refraction and scattering.

C. LED Strips

LED strips were placed along the outside of each target spot so that they would light up after the incoming laser was received. Figure 4 below depicts the schematic used for providing visual feedback on the target board. The strips are powered by the 5V regulator and receive commands from a specified pin on the microcontroller. Our design involves four different target areas, so it is necessary that we include four iterations of this LED strip design. The current draw on each strip exceeds no more than 100mA.

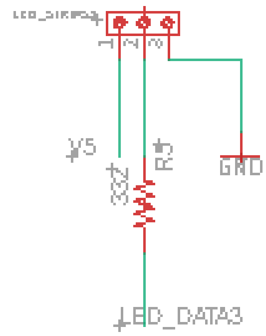

Figure 4. LED Strip Schematic

D. Power Systems

The idea behind the power systems for both the target and rifle were to create the same design for both in order to reduce testing time and optimize overall system uptime. Power is provided to both systems via a 9.6V NiHM battery that stores approximately 2000mAh with standard min-Tamiya connection for easy marketable battery replacement. It was important to find batteries that would seamlessly fit into the rifle housing so the nunchuck design made by Tenergy is definitely helpful.

Originally, the plan was to include a 5V switching regulator and a 3.3V linear regulator, however due to sizing constraints made by the rifle housing it was best to move toward a fully linear regulated system. Although there is an overall drop in energy efficiency vs using the switching regulators we are gaining efficiency in board space. The new system consists of 2 UA78M 3.3V linear regulators and 1 L7805 5V regulator. One 3.3V regulator is used solely to provide stable voltage to the microcontroller while the other powers the speaker feedback motor. The 5V regulator is then used to provide power to the IR laser system.

Each 3.3V regulator is able to supply about 500mA and the 5V regulator can supply up to 1.5A. The maximum current driving the laser rifle was 350mA while the MCU, motor and speaker were all in operation. Therefore the power system can drive all necessary functions while retaining a low quiescent current of 16mA for the rifle and 8mA for the target board.

E. Speaker

The Sparkfun Audio MAX98357A chip will drive the speaker inside our laser rifle by converting digital audio signals. The digital audio interface is flexible and supports

I2S data. The audio chip is single-supply operating in the 2.5 V to 5.5V range with the ability to deliver up to 3.2W of power onto the 4 Ohm load. Having a speaker inside our laser rifle adds to the realism aspect of our laser rifle. The audio chip allows us to program sound effects when the laser rifle is shot or when it hits the target. The MAX98375A audio chip is mounted to our PCB and the speaker is mounted to our PCB as well. In our system, the speaker activates each time the trigger of the laser rifle is pulled. Therefore, every time the IR laser diode emits light, the speaker corresponds with a sound.

F. Vibration Motor

The vibrational motor is meant to add another level of realism to our laser rifle by simulating recoil. Having a vibration motor is meant to set our design apart from similar laser rifles. The vibration motor activates for approximately half a second when the trigger is pulled. The vibration motor is in the pistol stock of the rifle to accurately simulate recoil after the trigger is pulled and the laser is fired. The user will instantly have feedback from the vibration motor when the trigger is pulled. The vibration motor is rated to operate at a speed of 9,000 revolutions per minute with a voltage rating of 2.7V to 3.3V and a current of 90 mA.

G. Rifle Scope

The rifle scope plays an important role since it is the only way to accurately aim when using lasers. Since the laser comes out of the rifle barrel as a straight line rather than in a parabolic arc like in ballistic firearms, normal methods of aiming such as using iron sights are not as effective. By using a rifle scope, this is not a problem since there are elevation and windage dials that physically move lens assemblies within the scope vertically and horizontally respectively. As a result, zeroing the scope's reticle at a variety of ranges is possible.

For our rifle scope, we chose our specifications based on generic rifle scope characteristics seen in the market. This includes eye relief distances that are above 2 inches as recoil from shots can cause the scope to injure the user and an exit pupil that is around the diameter of the pupil of the human eye. The scope must also be able to correct for parallax error, have good resolving power, have high light transmission, and be focused at infinity.

Our rifle scope includes a total of 6 lenses. The objective lens is a 60mm achromatic doublet with a 136mm EFL that introduces a large amount of negative spherical aberration into the system. The side focus, a lens that moves along the optical axis to correct for parallax, is a 25.4mm plano convex lens with a 175mm EFL that was selected so that a user can make precise adjustments when correcting for parallax. The erector assembly is made up of two 18mm achromatic doublets with 50mm EFL.

The erector assembly directly affects the calibration functionality of the rifle since the lenses are installed into a separate tube within the rifle that moves transversal to the optical axis via the elevation and windage dials. The aperture stop of the system is a 17mm aperture located at the front of the second achromat in the erector assembly which limits resolution but minimizes aberrations. The second focal plane is where the reticle of the rifle scope will be located. Finally, the eyepiece is a Kellner design with a 25.4mm diameter 50mm EFL double achromat combined with a 25.4mm diameter 225mm EFL plano convex lens. A Zemax layout of the system is shown in Figure 5.

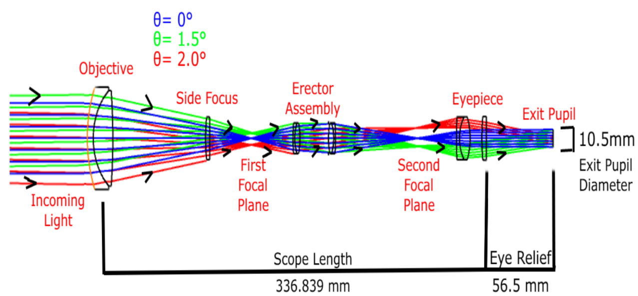

Figure 5. Rifle Scope Lens Layout

As shown in the figure, the total length of the system is 337 mm which is an average length for a rifle scope. The exit pupil characteristics are also standard with a 56.5mm eye relief and a 10.5mm exit pupil diameter, which is slightly larger than the human pupil in dark lighting at 8mm, but this was intentionally done in order to provide more leeway when aiming since the eye would have to be centered exactly at the exit pupil to get the best image possible, which is not realistic for a highly portable system like a rifle. The scope outputs an image with a standard magnification of 4x and has a maximum angular resolution of 0.125 mrad as shown in Figure 6. Finally, due to the combinations of AR coatings throughout the system, transmission of 650 nm light through the scope has been calculated and tested to be around 80% while 860 nm light transmission is lower at 75%.

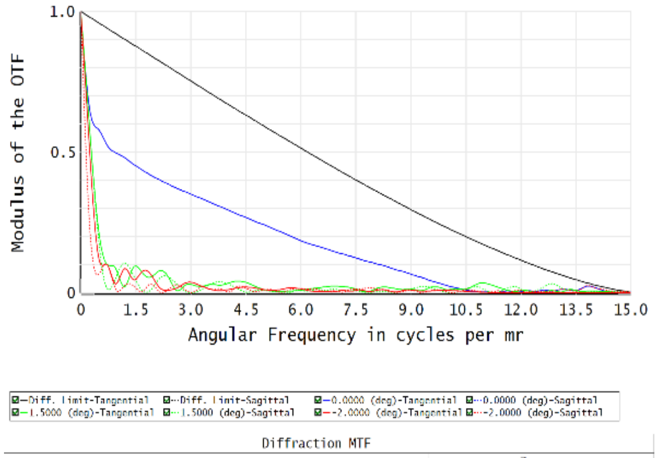

Figure 6. Rifle Scope MTF

H. Night Vision System

The reason why we mention 860 nm light transmission in the scope is because we intend to use our target shooting system in both day and night. For functionality at night, we made a night vision camera system that uses a PixelMan PMD2A CMOS camera without an IR filter that is connected to a Padarsey 5 inch TFT LCD monitor through analog video connections. Both the camera and display are powered by a separate rechargeable Tenergy 2000mAh 12V battery such that the entire system can be removed as they are treated as attachments.

The camera mounts onto the rifle scope itself and is positioned such that it looks into the scope like the human eye while the display is mounted elsewhere on the rifle, providing live footage from what the camera sees. A main problem we had with the camera is that the camera was designed to have a 170 degree field of view which would prove detrimental for our project as this means most of the image sent to the display is the interior walls of the scope rather than the object being viewed.

To counteract this, we made a lens system that was used to significantly decrease the FOV. However, a problem is that the camera we purchased did not provide any information about the optics inside of it, so we had to effectively treat it as a black box and had to go through trial and error different designs to find a design that worked well with the camera. Through our testing, we found that using too powerful of a lens increased aberrations such that the image quality is severely worsened, so we opted for a design that combined a 25mm EFL biconvex lens with a -25mm EFL biconcave lens that worked to minimize aberrations. A comparison of how the image outputted by the camera looking through the rifle scope looks is provided in Figure 7. Using this lens system, FOV was observed to decrease from 170 degrees to 110 degrees.

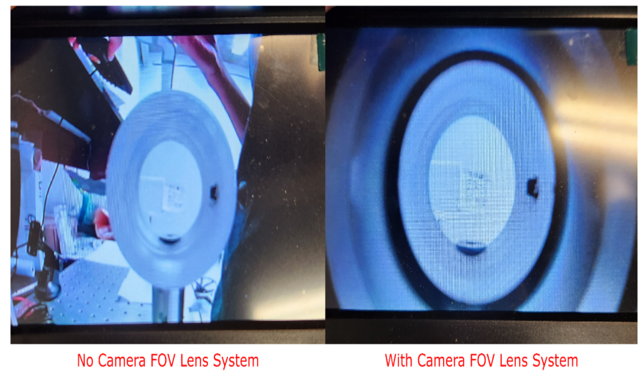

Figure 7. Camera FOV Lens System Testing

Another major component in the night vision system is the infrared light source. Since CMOS sensors have a low quantum efficiency compared to visible wavelengths, very powerful LEDs would be needed for the flashlight to work. We used 860 nm LEDs in the flashlight that had a powerful output but with a 10 degree viewing angle. In order to adjust the size and angle of the outputted beam, we designed a variable focus IR flashlight that used a 25.4mm diameter -100mm EFL plano concave lens to first expand the beam and a 50.8mm diameter 88.3mm EFL plano convex lens to alter the output divergence angle.

Like the rifle scope design, we took inspiration from market flashlight designs and opted for a compact design. The total length of the lens system not including distance to LEDs is 66.7 mm. The positive lens can be moved in a range of 15mm along the optical axis to alter the full divergence angle of the output from 5 degrees to 0 degrees as shown in Figure 8.

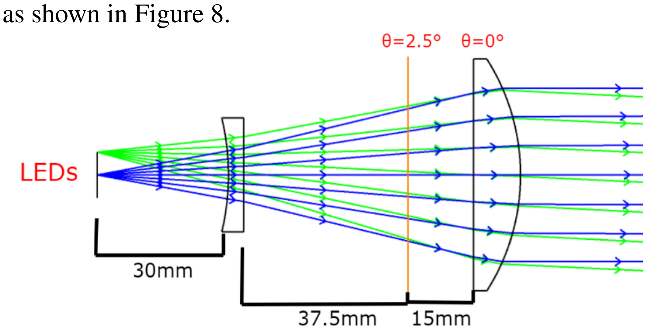

Figure 8. Flashlight Lens System

IV. SOFTWARE DESIGN

We developed the laser rifle and the target board to have Bluetooth Low Energy enabled. Our goal was to make our devices to be programmable, which allows the user to customize their rifle shooting sounds, patterns and more. We have created a mobile app acting as an operational app, connecting it to the rifle and the target Board through Bluetooth and configuring settings of both of the devices. Through the app, the user should have access to configure the rifle settings, the target board timer. The frontend design is shown in Figure 9.

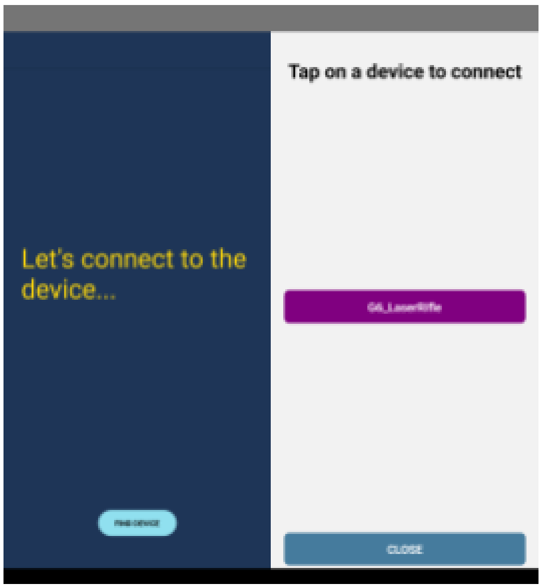

Figure 9. Mobile App Frontend Design

The app can access the built-in Bluetooth of the mobile device. The app is developed using a Bluetooth manager library to pair with our Bluetooth enabled devices. It can configure the recoil patterns of the rifle, track the ammo count of the rifle, as well as configure and modify the firing pattern and sound. Users can start the timer on the app and send it to the Target Board through bluetooth. The user can also view the current timer on the app as well..

The Main screen shown in Figure 10, shows the information about the Laser Rifle: the type of the recoil pattern, the ammo count, the Firing Mode, or firing pattern, and the current volume percentage emitted by the speaker. Recoil type is an element that can be configured by this app. We have multiple types of the recoil value. Since there's a built-in vibration motor in the Laser Rifle, each type will represent a different vibration pattern when the trigger of the gun is pressed.

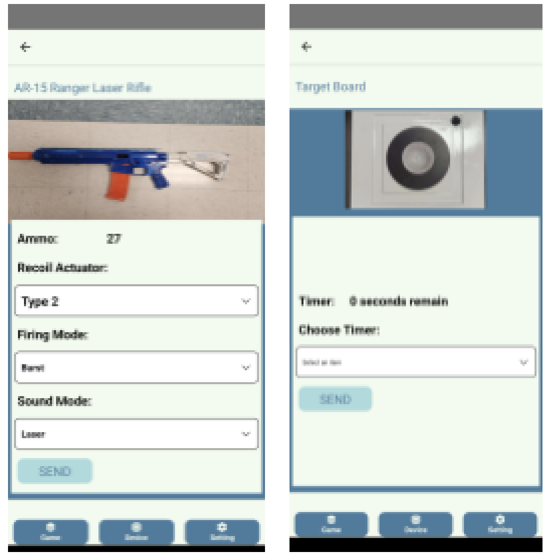

Figure 10. Main Screen

The Ammo element is a real-time counter that records the virtual magazine round number. When the trigger is pressed, the counter will be decremented until it reaches zero. And when the number reaches zero, it will show the RELOAD state. In this state, the app prevents the laser rifle from firing and forces a 5 second cooldown that the user must wait. After the cooldown ends, the counter will reset back to the original ammo count of 30. The Sound Mode element is showing the current sound effect outputting from the Rifle speaker after pulling the trigger. The app can change this element and can be configured into another sound effect.

In the Main screen, the user can switch between devices to configure the Target Board settings after both devices have been paired. The user can view the timer and send the timer preset to the Target board. To test our Bluetooth connectivity with the two separate devices, we power on each device. This sets them in the READY state awaiting to PAIR through Bluetooth. Our mobile app can successfully scan and find both of our devices and then populate the device list in the app.

V. INTEGRATION AND CHALLENGES

A. Integration

We purchased the rifle frame from online, meaning that we would have some limitations on the amount of space available to use within the frame. The physical dimensions of the PCB played a role in design since they needed to physically fit within the frame. This was especially the case for the IR laser diode because the diode would be emitting perpendicular to the surface of the PCB and had to be facing out towards the barrel for emission. This means that for the laser to exit the barrel of the rifle, the laser diode PCB must be placed perpendicular to the rifle as shown in Figure 11. This means the size of the PCB for the laser diode would not be able to exceed that of a 34mm diameter circle otherwise it would not fit within the design.

We had some problems fitting the main control PCB and other components within the frame as they could lay flat within the frame. We contacted the University of Central Florida Police Department about the laser rifle and we got feedback about how the rifle frame looked too realistic. We decided to spray paint the outside of the frame with bright blue and orange colors like a Nerf gun to make it look less realistic.

Figure 11. Laser Rifle Frame

The target board design was a simple square box that is 210mm x 210mm x 45mm. In Figure 12, the target board with its battery, PCB, and power switch is shown. The entirety of the target board was 3D printed and contained two separate parts consisting of a hollow box (left) and a lid (right). The box and lid have screw holes so that the box and lid can be connected together since the target board is run by batteries that need to be recharged. The lid also has a large 100mm hole where the 3D printed PETG lenses are installed. This is because the lenses are printed separate from the rest of the target board since they require significantly slower and precise print settings to achieve better optical properties. The lenses we used were 100mm, 75mm, 50mm, and 25mm in diameter.

We originally planned to use a larger target board that contained 4 separate target areas lenses with 4 separate receivers, but due to the IRAM limitations of the microcontroller, we were forced to use a single receiver in the final design. In order to emulate multiple target areas, we 3D printed 100mm diameter aperture rings that were installed onto each lens shown in Figure 13. This made it so that each lens could be easily swapped out with one another for a variety of target sizes. Around the target area, there were indents where the LED strips were installed. In the indent, there is a small hole for wires where the LED strips can be connected to the main control PCB contained inside of the target board. The IR receiver modules are centered in each target area hole to capture the laser light and are all connected to the main control PCB.

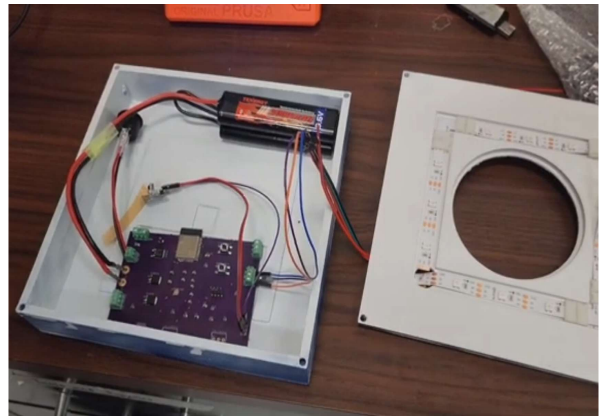

Figure 12. Target Board Enclosure Design

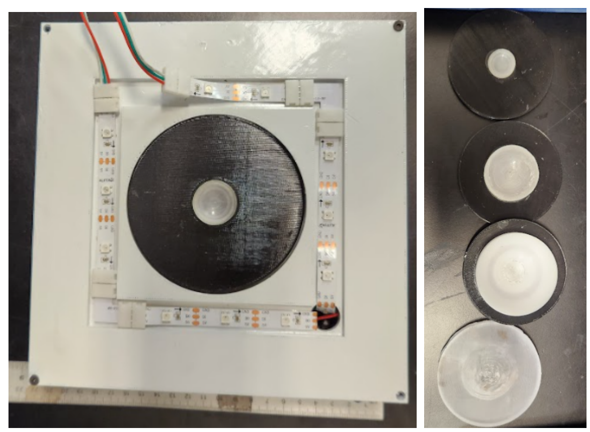

Figure 13. Assembled Target Board and Lenses

B. Challenges

Every project will have challenges and ours is no exception. We had many difficulties with the PCB design as it was difficult for us to get the laser diode circuit to work. We also faced challenges during the planning and creating of the PCB itself as we had to make our own custom footprint for the laser diode. Through our testing, we came to the conclusion that the issue with the IR Laser Diode arose when surface mounting it due to the very small gap between the positive and negative terminals.

We also had difficulties with developing the mobile app. We particularly had difficulties with sending and receiving commands using Bluetooth communication. We also had many problems during the integration phase of the project.

Since the amount of room in the rifle frame is limited, we were forced to modify the rifle frame by cutting sections to fit some of the parts into it. We also originally had a physical reload switch designed for the laser rifle, but this had to be removed due to space limitations. The speaker was not able to be integrated into the laser rifle due to issues soldering the audio chip even with a reflow soldering machine. We also tested using the smaller vibration motors as designed and found the vibration to be too weak. We replaced the vibration motor with a stronger one used in game console controllers, but this motor caused system overheating and resulted in the decision to completely remove the vibration motor in the prototype.

VI. CONCLUSION

As we come to the end of our Senior Design project, we come to realize and appreciate the amount of time and effort we have invested into seeing our hard work come into fruition. We have spent many long nights and days dedicated to research, design, and implementation with the objective of creating a successful project that would meet our goals. We have been put to the test while working under tight deadlines and taking on both individual and team responsibilities. We have grown professionally as engineers and stepped out of our comfort zones in order to ensure the success of our project. We look forward to using these skills that we have earned throughout our academic careers in our future careers as engineering professionals.

ACKNOWLEDGEMENTS

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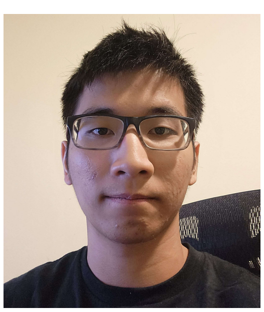
BIOGRAPHIES



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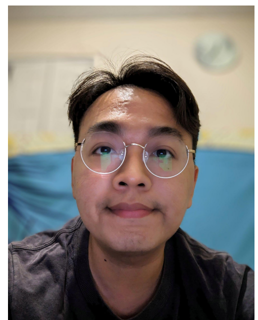

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