Laser Target-Shooting

EEL 4914 Senior Design I
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Group 6

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1.0 Executive Summary

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. Renting a fully automatic firearm from some firing ranges can be as high as three times the price of renting a standard semi-automatic pistol. For visiting gun owners, they must drive to their local range, bring their equipment, and rent a shooting lane. Overall, this process can be very inconvenient.

There are alternatives to firing ranges such as using Airsoft guns or living in areas where firearms can be fired in backyards, but these solutions involve firing lead and plastic rounds outside which can have negative effects on the environment or can cause accidental injuries or property damage if no precautions are taken. Regarding Airsoft in particular, firing these weapons are much safer than firing real firearms; however, the lack of recoil and the lack of power in the BB pellets fired makes for an unrealistic and unsatisfying shooting experience.

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. This was accomplished by replacing the ballistic ammunition used in a traditional firearm with infrared lasers. This laser rifle was paired with a 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. This project also contains other features not seen in traditional shooting ranges such as keeping scores for accuracy-based game modes and a versatile gun that can change firing characteristics such as fire rate with the press of a button on our smartphone app.

Naturally, we are not the first to come up with this idea. There are various market products being sold with the same premise and even Senior Design students at UCF have done similar projects in the past. As such, our goal is to make a product that excels over others in all fields such as safety and customization. With market prices ranging from a hundred dollars to over five hundred dollars for similar products, our project aims to work as well as high-end market products while improving by adding various features and keeping costs low. As designed, the prototype contains a realistic, highly portable rifle and target board pair that can be used in any lighting condition, be it noon or midnight. The laser rifle firing system is strictly controlled such that laser safety regulations are followed.

2.0 Project Motivation

Going to a shooting range is not something that everyone is able to spend their time or money on. Our project aims to bring the firing range experience to your home by creating a laser rifle and an electronic target board. By using lasers, the downsides of using live ammunition such as danger, environmental impact, deafening gunshots, and high cost are improved upon, while portability and accessibility is increased as lasers are not treated the same as live firearms. Overall, a cheaper, safer, and more portable shooting experience is created. This enables firearms to have a more approachable and friendly appearance to the public, making our project a way to entertain yourself or function as an educational firearm safety training tool for children or people who are concerned about the dangers of handling real firearms.

2.1 Goals

Core Goals

At its foundation, our project requires the use of a rifle that fires an infrared laser beam out of the barrel. This laser rifle will be used to strike a target board that reacts to the beam and lights up an area where the beam strikes the surface of the board. Without this fundamental setup, the system will not work. Another one of our core goals is to make a laser target-shooting system that is an overall improvement on market products. As most people go to firing ranges for entertainment and training for firearm handling, our project also keeps these core goals in mind when deciding project features, which are related to our advance and stretch goals.

Advance Goals

For our advance goals, we view these goals as our project features that supplement our core project to become a product that excels over others. Our project aims to make a laser rifle and target board that will have a plethora of features that prioritize customization, safety, and user convenience. Both the laser rifle and target board will be highly portable devices that will, ideally, be usable in any lighting environment ranging from broad daylight to pitch black midnight. For night time, this will be possible through the employment of a mountable night vision camera scope system paired with an infrared flashlight. Additionally, the camera will be removable, allowing the rifle scope to be used by itself for firearm training using gun optics. To deal with broad daylight, our system will use IR receivers, modified photodiodes that react only to light modulating at a specific frequency, in order to prevent unwanted light sources from activating the target board. The target board will also include some measures to deal with these unwanted light sources. This includes an “inherent lens system” that also reduces the amount of light reaching the IR receivers, essentially allowing only the powerful IR laser light to be detected.

As mentioned, our project also aims to provide a safe product. Not only will we implement a trigger safety system just like in real firearms, the laser rifle will also contain a dual laser beam setup that emits a visible red and infrared laser. While this red laser will be useful for calibrating other systems, this red laser plays a very important role in eye safety due to how the eye reacts to different wavelengths of light. Using an infrared laser by itself is dangerous for bystanders since it is indetectable, but adding a visible laser induces a blink effect that can make a high risk laser into a low risk laser.

The laser rifle will also need to be highly customizable and user convenient. This is why we decided to develop a custom smartphone app that controls every aspect we want to change. We plan to include options to change the fire rate, play different gunfire sounds, change the amount of recoil, and control the amount of ammo the rifle has by using this smartphone app. The smartphone app will connect between the target board and rifle wirelessly, allowing for different games that can be played where the score is kept track of through the app.

Stretch Goals

Ideally, we would like to have as many features as possible. Given the number of resources, components, and other features that we need to work on, many of these features will unfortunately be considered last priority. The features we would like to add but will likely not be able to include in our final design are: ability to switch firing mode (semi auto, burst, automatic, & spread), different game modes to be added within the phone application, ability to cycle through games with display on gun, ability to modify recoil intensity to simulate different gun variants, remaining ammo capacity on the gun display, infrared sensors determining shot distance, variable laser spot size, and other types of optics such as a red dot or holographic sight. This would make our rifle much completer and more versatile as a product and as a tool for entertainment and training.

One of our higher priorities stretch goals is a human detection safety system. Using a camera mounted to the rifle, the camera would provide a live video feed that would be processed using artificial-intelligence-based face or human body detecting algorithms. When a person is detected in the field of view of the camera, the laser will be forced to shut off as a safety measure. This is considered a stretch goal because this would require a large amount of processing power that would be difficult to accomplish on a highly mobile platform. Additionally, unlike security camera systems that use these detection algorithms, the rifle will be constantly moving around as intended. As a result, the performance of the algorithm could suffer and ultimately not work. This is a major issue as safety is one of our main goals when designing the project.

2.2 Objectives

The rifle frame will be a modified version of the AR-15 with a realistic feel and look. Utilizing rechargeable batteries as a power source, the rifle will be portable while having a weight similar to that of a real firearm. The laser rifle will feature a double laser system that simultaneously emits a visible light laser used for calibration and visible feedback and a 940 nm wavelength laser used for signal transmission to the target board. The IR laser will act as a transmitter and will be modulated at a 38 kHz carrier frequency that IR receivers in the target board will be able to react to. The visible light laser will be toggleable through a switch such that the rifle does not waste power if the laser is no longer needed. The light emitted from the laser diodes used will be collimated if necessary, interact with a beam splitter, and then both beams will exit the barrel after passing through a beam expander.

The laser rifle will be programmed so that gunfire sounds play and recoil-simulating vibration motors activate when fired. The laser rifle will also be able to fire at variable fire rates that can be changed via software. The rifle will have a software-based magazine system and ammo counter that requires magazines to be changed after depleting all rounds in the magazine. All features will be customizable using a smartphone app that communicates with the rifle using Bluetooth.

The main attachment for the laser rifle is a night vision system using a magnified scope, LCD display, and camera. First, a rail-mounted optical rifle scope that can be used to magnify and view the target will be designed and made. The rifle scope will contain a telescoping magnification system for variable zoom. A camera using an IR compatible CMOS sensor will then be mounted such that it is effectively looking through the scope like a human eye. The camera will also be removable, so the scope can be used to aim as a normal optical sight. A separate lens system will be made for the camera to set a desired field of view.

The camera will be hooked up to an LCD display mounted to the scope that plays live feed from the camera-scope system. Using a custom LED flashlight with a 860 nm peak wavelength, the surrounding area will be illuminated with IR light that is captured by the camera and streamed onto the display. Since the amount of IR light necessary to have a clear image will be not known without extensive testing, the flashlight will also include a telescoping lens system to change the intensity of the light. The role of the telescoping flashlight is to be able to change the spread of the light outputted by the flashlight so that most of the light is incident on the target board rather than being wasted by spreading around it. This allows more of the IR light to reflect and return to the CMOS camera for a higher quality image. Ultimately, this system can be used to view the target and fire at it by using the display to aim. Unlike other products, this makes it possible to use our target-shooting system in low-light environments where photodetectors will work best due to low noise from other sources. Of course, a simple white light flashlight could be attached to the rifle, but using this night vision system makes it possible to use the rifle to simulate night vision training scenarios where flashlights cannot be used.

We have provided a series of 3D model diagrams to show how our system works. The basic design for the target board will be based on an arcade Skeeball hole system with targets of various sizes as shown in **Figure 1**. A scoring system where successfully hitting smaller targets will award a user with more points will be made. Game rules and scorekeeping will be controlled using a smartphone app connecting to the target board using Bluetooth. Using rechargeable batteries as a power source, the target board will be used to give visible feedback to where the laser was fired at using LEDs and IR receivers. Receivers were chosen over standard photodiodes and phototransistors because they are more resistant against ambient IR lighting, ideally allowing the target-shooting system to be used in broad daylight. The IR receivers, placed in a target circle, will be used to sense where the shot was placed and cause the surrounding LEDs to light up. This concept is shown in **Figure 2**, where the laser is fired into the target area marked “5” and the LEDs light up in response, while the target area marked “10” remains off since no laser is detected. Simultaneously, if the user is playing a game, the smartphone app will award the user with 5 points.

As shown in **Figure 3**, the LEDs and receivers will be installed behind the front surface of the target board. There will be designated holes in the front surface of the board where the LEDs will emit visible light that the user will be able to see after hitting one of the receivers in an area. Unlike the LEDs, the tops of the receivers will be completely behind the target board with no holes present. Note that you can see the IR receiver in **Figure 2** because they are mounted behind transparent concave lenses that are used to expand the laser beam for more reliable laser detection as well as protect the receivers from being exposed to the elements.

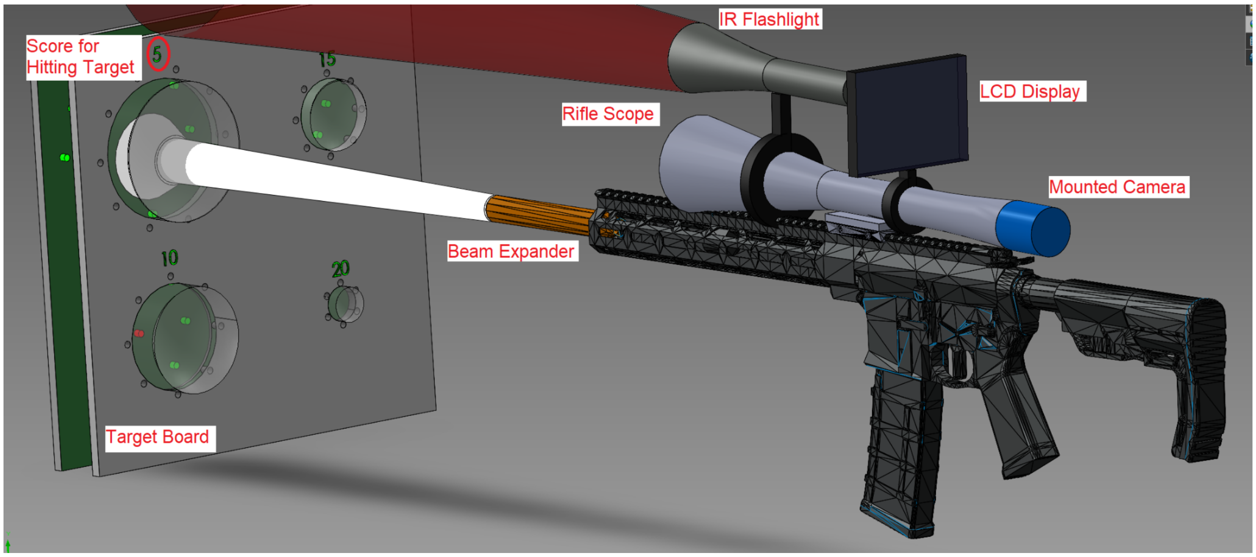


Figure 1. Full System Interaction Between Target and Rifle

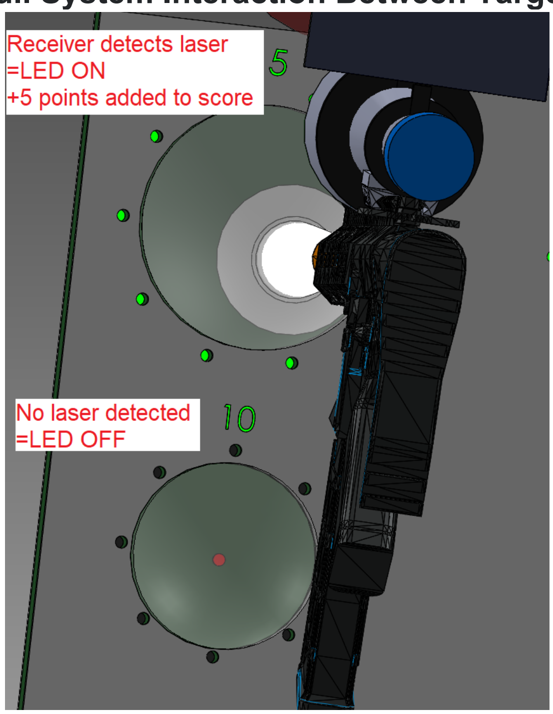


Figure 2. System Interaction Front Plane

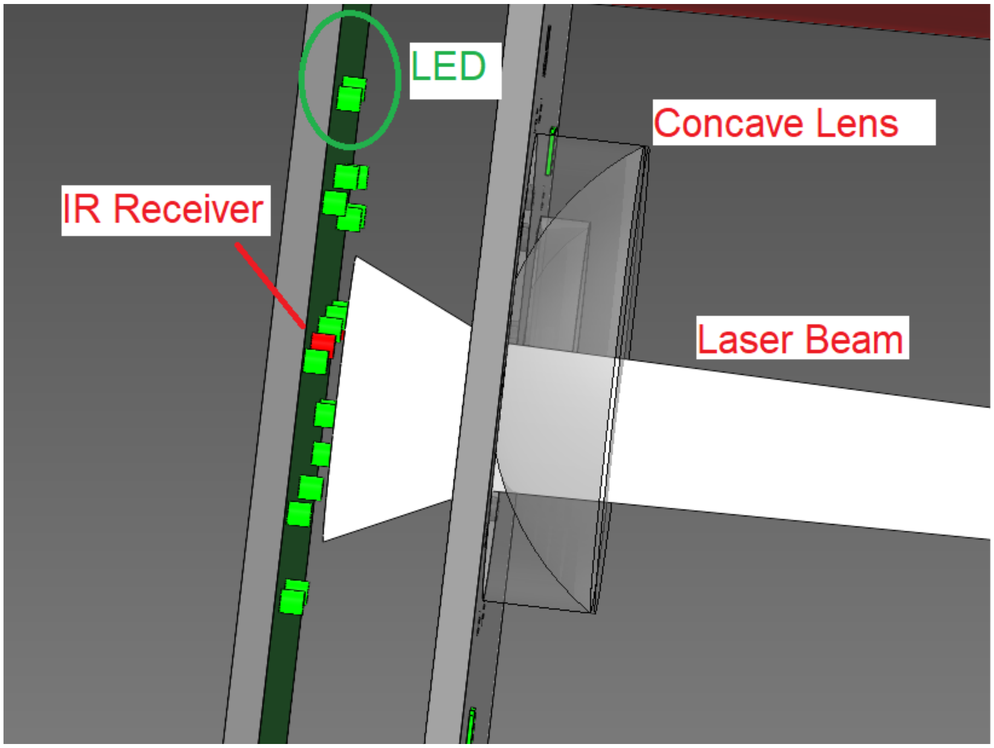


Figure 3. System Interaction Cross Section

2.3 Requirements/Specifications

In **Table 1**, the various system requirements for our project are listed. These requirements were decided based on what we thought were reasonable, as well as based on some real-world applications. For example, the “long range” distance was determined as 15m because real firearms are universally made and calibrated for usage at 25 yards. We chose 15m because 25 yards is a very large distance, meaning that it would be difficult to test the laser indoors. For the target board size, we decided these parameters based on what kinds of target boards other market products were using.

Requirement ID	Requirement/Specification	
1.0	The system will not exceed 10 lbs with all internal components.	5 - 10 pounds
1.1	The system will be pairable with a phone through Bluetooth and be recognized by the mobile app.	Bluetooth 5.0
1.2	The system will be powered by batteries that can be recharged with a compatible plug.	9V Lithium Battery
1.3	The system needs to perform at the shortest time interval between the pulling of the trigger and the visual response of the target.	< 1 second
1.4	The system controller should use power efficiently.	Efficiency > 30%
1.5*	The system should be in “ready for use” state within a short time after startup.	< 1 minute
1.6*	The system should have the controller stay running at a high uptime.	> 4 hours
1.7*	The system should operate without overheating.	< 50 $°C$
1.8	The system will include a mountable variable-zoom rifle scope with adjustable reticle.	> 3x max magnification
1.9	The system will be able to operate at a long distance between the rifle and target board.	>15m
1.10	The system will emit a laser beam that has low divergence such that it can be used accurately at long ranges.	<1.5 mm per meter (1.5 mrad)

1.11	The system will output a laser spot size that is small enough to ensure accurate shot placement on the target board.	<40 mm at 15m target distance
1.12	The system will emit a laser beam that is considered low-risk for eye safety.	Class 3R (<5 mW)
1.13	The system will use a 3D printed target board that is large enough to be clearly visible at long ranges while also being portable	> 12 in x 12 in < 10 lbs

**Highlighted blue section means that we can demonstrate using our group test method.*

Table 1: System Requirements

2.4 House of Quality

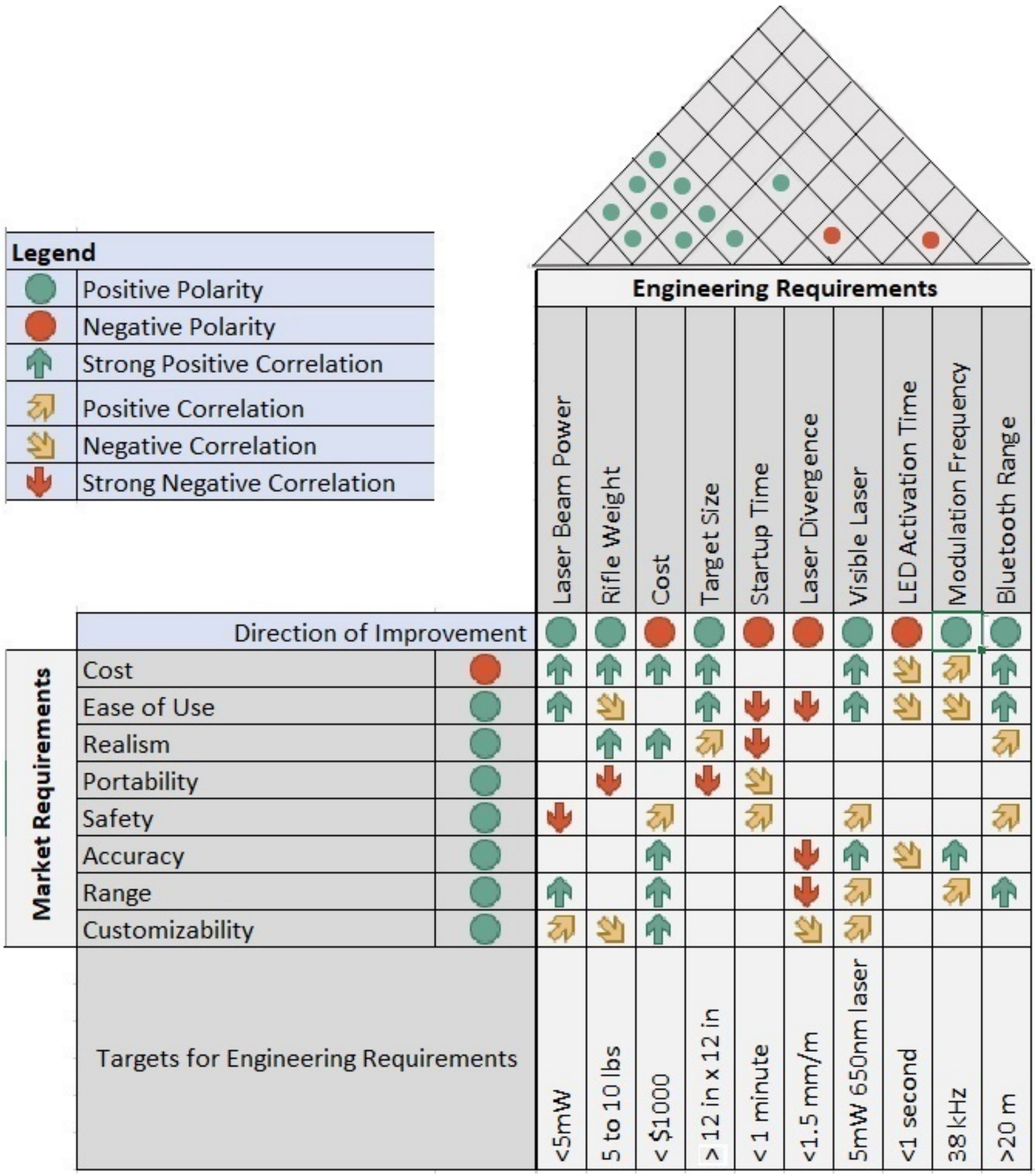


Figure 4. House of Quality

In **Figure 3**, our house of quality is shown. The house of quality was made for an analysis of the different design requirements that we have decided in our project and how these relate to the overall market requirements for these kinds of products. Additionally, the house of quality is important in the design process as they are used to compare the different requirements we have set and show how they relate to each other in a positive or negative way. For example, it is clear that the target size has a positive relationship with the cost of the project since more materials will need to be spent to increase the size.

3.0 Project Research

In this section we will describe the research done by each of the team members. This research includes comparing and selecting the optimal parts for the project as well as evaluating previous project designs for further inspiration and improvement. Performing this research is essential in the design of the Laser Target-Shooting project. Researching previous and/or similar designs will allow us to take note of what went wrong in prior projects to allow for improvements in our own design and implementation. This section will cover existing products, relevant technology, the system architecture, and part selection relevant to the design of our Laser Target-Shooting project.

3.1 Similar Products and Past Projects

While our project idea is not new in the market, our project also aims to improve on other products in terms of realism, safety, and convenience. With similar products prices going from $100 to over $500 for laser training systems, features vary heavily.

The cheapest systems include ones such as the Strikeman Training System and LaserHIT that involve using $40+ battery-powered “laser cartridges” that are placed into real firearms and fire visible light lasers when the trigger is pulled. These systems use custom software, such as an app using a phone camera, that tracks the location of where a shot is made on a physical target. The laser detection on the target seems to be done through a camera-based algorithm using a laser triangulation system. The laser light reflecting off the target is analyzed to find the position of the shot on the target. These systems are typically around $100 or more for physical components and the software is typically free. Since real firearms are being used, these systems are realistic in the handling and aiming aspect, but since no actual rounds are being fired, there are no shooting elements like recoil or even gunshot sounds. Pulling the trigger is no different from pressing a button on a TV remote. Every shot fired requires the round to be rechambered using the slide on a pistol or the pump on a shotgun, so no full auto is possible using these systems.

Larger scale systems such as Laser Shot and Laser Ammo actually provide training to military and police personnel. While offering their own simulation systems, prices are extraordinary at over $500 for the cheapest laser weapons they have to offer. Their laser weapons come with recoil simulating CO2 canisters similar to those used in Airsoft guns and have the option to either be visible or IR light. Gunshot sounds play when weapons are fired. These systems are typically used with simulation software that connects to large projectors where users can play various types of aiming training games. The laser detection systems seem to work on the same laser triangulation system described above and requires special camera equipment. They have many features that try to simulate real firearms at the cost of low portability as they are designed to be stationary.

Finally, systems like LaserLyte provide a different approach to the laser cartridge systems at around $150 for a pistol and $200 for a physical target board. These systems typically use pistols with visible laser diodes installed into them. The pistols are typically aimed at physical, electronic targets that play sounds and light up LEDs when fired at. Unlike the other two approaches described above, the laser detection system used in these target boards are some kind of photo detector such as photodiodes or phototransistors. Overall, these share the same flaws as laser cartridge systems and are fundamentally gun-shaped laser pointers. Compared to the more expensive systems, these are the most portable systems, but the targets used are typically very small. More expensive target boards have precise tracking that counts score depending on where a shot was made like in darts. These systems are the least realistic in all aspects but are highly portable.

In past UCF Senior Design projects, there are three main ones that we have used for reference. These include the Wirelessly Connected Laser Shooting Gallery from Spring 2022, the Laser Target Gallery from Fall 2019, and the Laser Skeet from Spring 2018. Across all of these projects, several approaches to communicate between the target board and gun were made including Bluetooth and RF. In particular, we took interest in Laser Skeet since our team composition was exactly the same (two EE, one CPE, one optics) and our projects are quite similar. In their project, they used a 980 nm IR laser beam modulated at 30 kHz. Phototransistors inside of their skeet target were used to capture the modulated light and light up the target and play speakers upon hitting the target. Their target design, which is designed at accurate skeet target dimensions, initially considered a Fresnel lens design for coupling light, but they report that it was not worth the cost and would increase optical noise. From a thorough reading of their project report, we can make more informed decisions regarding our project.

3.2 Relevant Technology

This section briefly covers some of the more important technologies related to the design and implementation of this project. It gives a brief description of said technology and its application towards the project.

3.2.1 Vibrational Feedback

The addition of a vibrational motor will provide an added level of realism to the user experience by providing a simulated recoil. Although it is actually a stretch goal for the project it is a feature that will set our design apart from similar designs. When the trigger to the rifle is pulled ideally the motor should activate for about half a second. The design should place the motor in the stock of the rifle to accurately simulate the recoil after the laser is fired. When considering the different vibrational motors we took considerations that included price, weight, and operational strength.

The vibrational motor will ultimately only have a positive and negative connection and will be connected to the trigger power system so that when the trigger is pulled the motor should instantly simulate the recoil and tactile feedback.Previously we considered using options of CO2 or a solenoid to simulate feedback but each came with their own drawbacks.

<u>*CO2*</u>

Despite the use of CO2 for recoil is very common and out of the three it would cause the most notable effect, using it in our design would have numerous advantages. Firstly the use of CO2 would create a need for refueling which we agreed would not be ideal for testing and prototyping. Also it would require a less than ideal design to create a trigger to open and close the valve of the CO2 canister. Lastly CO2 would be a more expensive option than using an electronic recoil system.

Solenoid

A solenoid is a device consisting of a coil of wire, the housing and a moveable plunger(armature). When an electrical current is induced, a magnetic field forms around the coil and that draws the plunger in instantly thus causing instant haptic feedback. There are three main categories of solenoids: push/pull, latching/bistable, and proportional. **Figure X** below is a push/pull solenoid and was the only solenoid that we considered for this project.

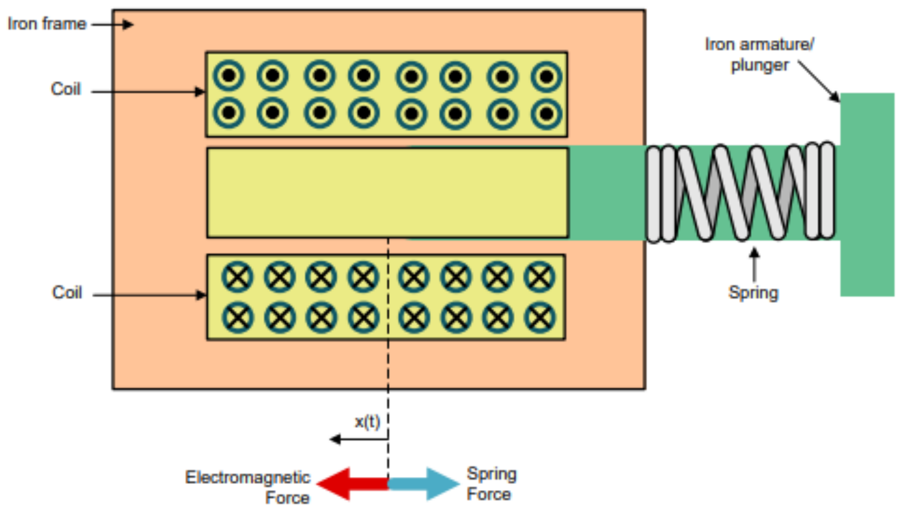


Figure X. Push/Pull Solenoid from Texas Instruments

Despite their interesting design solenoids come with their own set of drawbacks. Two main issues when using solenoids in a design is that since they have a quick pull and quick release, using one would create a somewhat double recoil; one forward and one backward. Also an issue is that they tend to be very energy consuming so the uptime for our design would be significantly reduced.

3.3 Part Selection

3.3.1 Wavelength Selection

First, it is important to discuss the wavelength used in our system. The main issues regarding wavelength relate to cost, safety, and optical noise. Since the power level used in our laser rifle will not be able to harm a person aside from their eyes, it is only necessary to discuss laser eye safety. The wavelength also relates to which part of the eye the laser will focus onto. Since the eye acts like a lens, different wavelengths will focus onto different parts of the eye. As a result, wavelengths above 1400 nm are generally considered to be eye-safe wavelengths and will not cause eye damage unless they are at extremely high powers.

The safety of the laser also relates to the visibility of the light. Some lasers are only considered “eye-safe” because they are visible. This is because when the intensity of light is too high, humans subconsciously close their eyes and block the incoming light before any damage can happen. However, if you are using a non-visible beam, this response will not happen and you could potentially be staring at a laser without even knowing. Even a low power laser could cause eye damage if you stare into the beam for a long period of time.

Additionally, optical noise is related to the detection of the IR receivers. Most photodetectors have a fairly large optical spectrum that are centralized around a peak wavelength, so noise may be of a concern depending on the wavelength. To determine what wavelength would experience the least optical noise, we referenced the optical spectrum of the sun in **Figure X341**. Based on the solar spectrum chart and previously discussed laser eye safety guidelines, one may think that it would be best to use a wavelength that is greater than 1400 nm due to the extremely low optical noise and inability to cause eye damage. However, when we researched for parts, we noticed that it is very difficult to find laser diodes that are made for these wavelengths. If they are available, they are usually at extremely high powers in the watt range. Naturally, these diodes are far more expensive.

In contrast, 940 nm diodes are more common and come at much more reasonable prices with a good variety of optical powers. We ultimately decided on the 940 nm wavelength despite being a potentially harmful NIR wavelength. Based on the solar spectrum, it is clear to see that the amount of optical noise caused by sunlight will be very low at 940 nm compared to other wavelengths. In fact, this is why many systems such as TV remotes use 940 nm LEDs that modulate at high frequencies. Light modulated at high frequencies is not common in sunlight, so much of the optical noise is eliminated from the photodetection systems when combined with 940 nm transmitters.

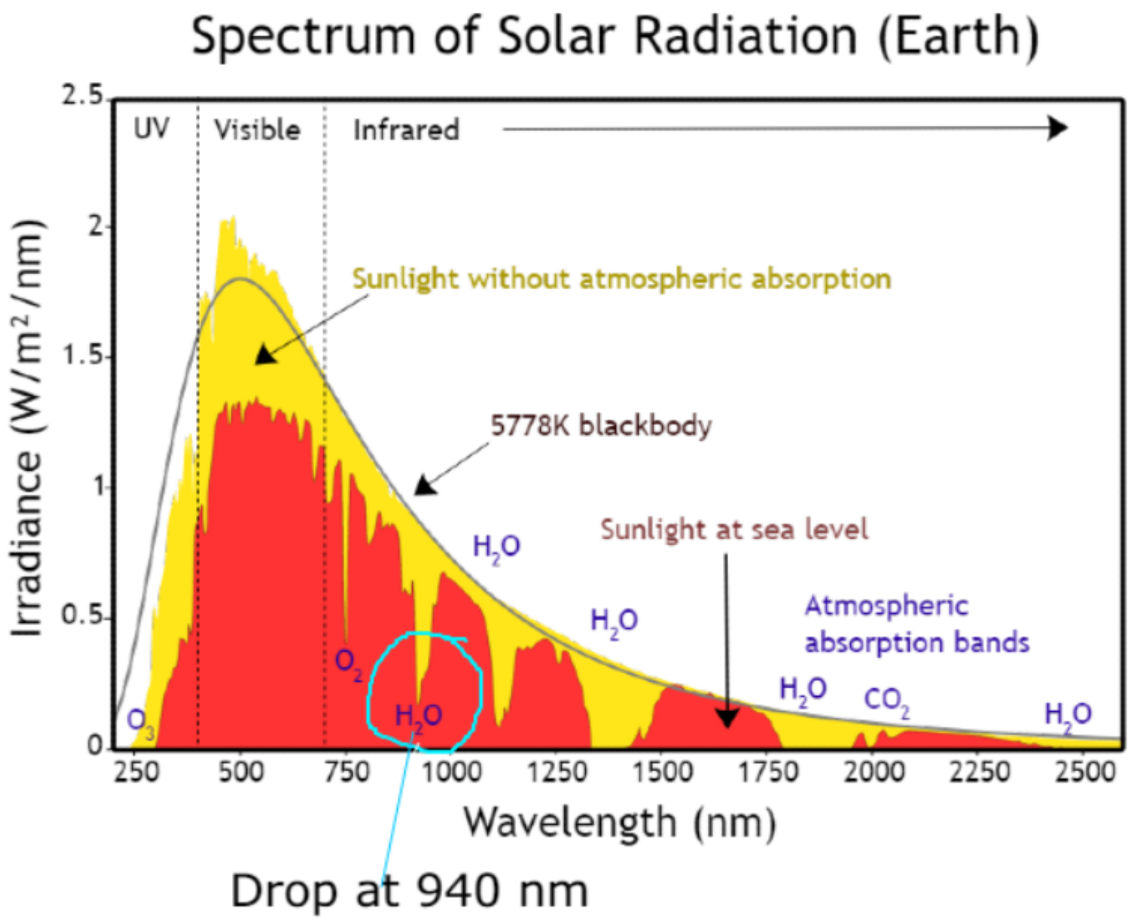


Figure X341. Solar spectrum

Since the laser was 940 nm, for the IR flashlight, we chose to use 860 nm as the NIR light source. This is due to the quantum efficiency of CMOS and CCD sensors. As seen in **Figure X2**, a standard RGB CMOS sensor with no modifications to improve IR sensitivity has very low quantum efficiency at IR wavelengths. 940 nm has an extremely low quantum efficiency while 860 nm has a relatively large quantum efficiency at around 15%. As a result, 860 nm is quite popular and is often used in night vision systems for security cameras. Additionally, 860 nm is a useful wavelength as it pairs well with the IR receivers. The IR receivers have a fairly large optical spectrum, but receivers with a peak wavelength at 940 nm tend to have around 20% sensitivity at 860 nm. As a result, we do not have to worry about significant optical noise coming from the flashlight.

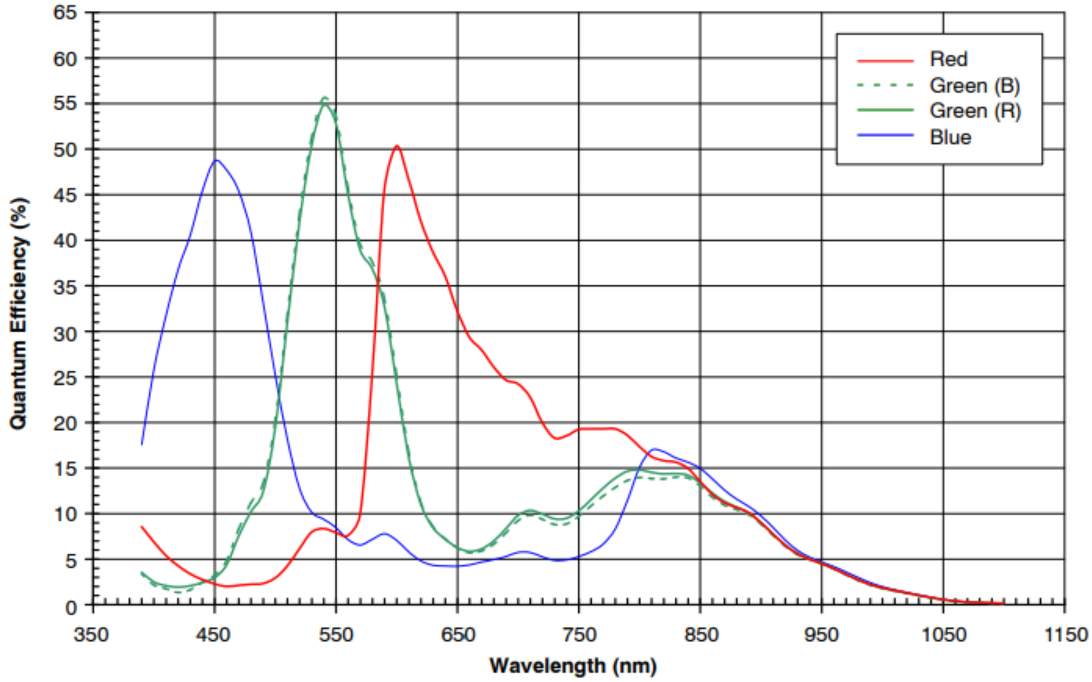


Figure X2. Quantum Efficiency of MT9M114 RGB CMOS Sensor

3.3.2 Laser Diodes

For our system, a laser diode is most appropriate as they are compact and come at low powers that are compatible with the laser class we plan to use in our system. However, that does not mean they do not have their disadvantages. Laser diodes have several problems including temperature dependence, high divergence angles, and becoming hot while operating.

As the laser diode increases in temperature, the wavelength of the light output by the diode increases. In many cases, this is an advantage that makes the laser diode a versatile tool. However, in the absence of a temperature controller unit, our system sees mainly disadvantages from this aspect. Since our rifle plans to be used outdoors and the laser diode will heat itself up as the rifle is used more and more, having a temperature controller unit would be useful, but it is simply not possible given we want a highly portable setup. Even though the temperature could be an issue in regards to causing damage to the diode, given the sensitivity spectrum of IR receivers, we believe that the performance of the system will not be significantly affected. The IR receiver we will be using in our project is sensitive to a relatively large optical spectrum as shown in **Figure X3**. Even with significant temperature changes, the laser-target system will still be able to perform well unless the IR diode itself malfunctions or breaks due to overheating.

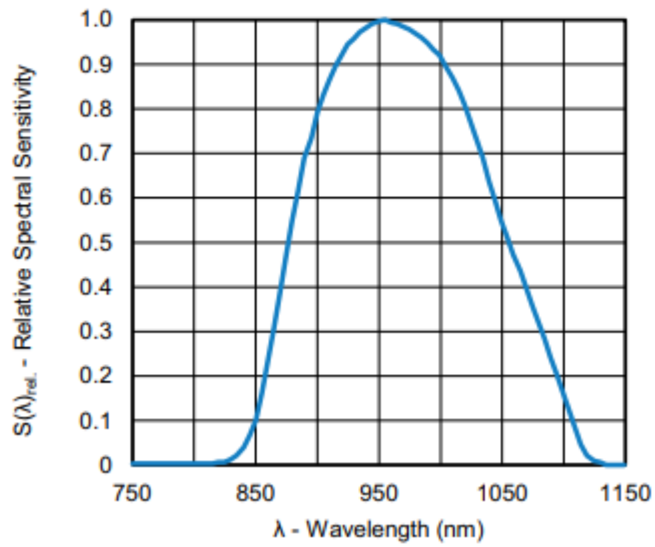


Figure X3. TSOP98638 IR Receiver Sensitivity Spectrum

Additionally, another point of concern is the divergence angle. Due to the way laser diodes are designed, they have a large divergence angle caused by diffraction from when light is emitted from the diode. They typically emit an astigmatic beam with a very large vertical divergence angle and a moderate horizontal divergence. Fortunately, since our project does not need a specific beam profile, this downside will not affect the project performance in that regard, but the high divergence must be accounted for using collimating lenses. Luckily, many commercial laser diodes come with collimating lenses preinstalled. The divergence shrinks even more after going through the beam expander. While these are all valid ways to counteract beam divergence, these involve increasing the beam size. As such, using a laser diode over other types of lasers forces us to make decisions on whether we want to prioritize a small spot size over a small divergence.

While searching for suitable 940 nm laser diodes, we came across vertical-cavity surface-emitting laser (VCSEL) diodes from RPMC Laser for quite cheap. We purchased their 8 mW VD-0940C-008M-1C-410 VCSEL diodes that come with built-in collimating lenses. These diodes emit a beam with divergence less than 10 mrad along with a 3mm spot size. Compared to standard edge-emitting laser diodes, VCSEL diodes offer some advantages. They produce a smaller divergence beam with a good circular beam profile. Since we are modulating our laser diode, it is also important to note that VCSEL diodes suffer from a negligible amount of relaxation oscillation. In standard laser diodes, when modulating the diode directly through electronics, the diode acts like an RC circuit and has a rise time where the laser power needs to stabilize. The optical power output from the laser diode spikes upwards for a short time before stabilizing at a designated power. For our project, this could cause the laser to become much more dangerous for the eye since the power output will be larger when modulating. In comparison, VCSEL diodes sufficiently damp relaxation oscillation effects and effectively output the same optical power even when directly modulated at kilohertz frequencies.

For our visible light laser diode, we chose a 650 nm 5mW edge-emitting laser diode installed with a preinstalled collimating lens. These are extremely cheap at less than 50 cents per diode, making them good for testing as well as easily replaceable in case of a malfunction. We considered getting green laser diodes because the human eye is most sensitive to this color, but these are significantly more expensive and harder to find at a good power in the form of a laser diode. You can purchase 5 mW green laser pointers, but these are typically DPSSL lasers that do not actually use 532 nm diodes and instead use infrared diodes to pump Nd:YAG crystals combined with frequency doubling crystals.

3.3.3 Target Board Material

The target board material plays an important role. For our project, we considered a variety of materials. The main choices we considered include metal, wood, or plastic. Regarding metal and wood, there are some downsides aside from their superior strength compared to plastic. First, we considered how we would actually make the target board after designing it. Given our team composition and respective experiences, our team is not very inclined towards machining work. Not to mention, our target also needs to be portable and lightweight, so picking these materials could lead to a heavier finished product. We also must consider how the receivers will catch the light. Given the properties of metal and wood, these materials have extremely low light transmission, so the receivers would essentially have to be exposed to the elements. As a result, we decided on using 3D printed filament. By using a transparent 3D printed filament, we provide a physical barrier to protect the IR receivers from the elements while also allowing them to work as intended. Precision designs for our parts and making fixtures becomes much easier when using a 3D printer.

There are some alternatives to standard filament-based 3D printers such as resin 3D printers. These provide extremely thin layers, meaning highly transparent designs that far surpass standard filament-based 3D printers can be made. Although, resin printers are generally much more expensive for both the resin used to print as well as the printers themselves. Resin as a material is also structurally weak compared to filament-based 3D prints. With more resources available online along with a cheaper cost, we ultimately chose filament-based 3D printing.

Additionally, many 3D printer filaments have fairly good optical properties if processed properly. Some of the most popular 3D printer filaments for making transparent or clear objects are PLA, ABS, and PETG. From research, PETG seems to be the most suitable of these three filaments. PLA is a very cheap filament that is easy to print with, but suffers from performance issues such as being weak and susceptible to heat, meaning that it will not be able to be used outdoors like we want to in our project. Additionally, these filaments are difficult to get to be clear. ABS is a good filament that can be very clear, but it is quite difficult to print. It releases toxic fumes when printing and requires very high temperatures of around 260 degrees Celsius to print as opposed to PLA at around 210 degrees and PETG at 230 degrees. ABS is strong and can be easily processed by using acetone to smooth the material, making the printed part transparent enough that it could be used to make the lenses on the surface of the board. PETG is similar to ABS but exceeds it in durability and strength and is much easier to print. PETG can become quite transparent when processed. PETG also works well at high temperatures and will not deform from being in the sun. For our project, PETG is the most suitable due to its ability to be used outdoors, transparency when processed, and structural strength.

3.3.4 Photodetectors

The main kinds of photodetectors we considered in our project are photodiodes and phototransistors. Both detectors typically have a large acceptance spectrum while peaking at a particular design wavelength as shown in **Figure X3** above. Since the laser will be using a 940 nm wavelength output, the peak sensitivity of the photodetector would also have to be at 940 nm for optimal performance. Photodiodes have average sensitivity with the fastest response times, while phototransistors have high sensitivity with average response time. For our project, the response time is the main objective since we will prioritize quick visual feedback upon hitting the target, so photodiodes are a good choice. Photodiodes produce a small photocurrent relative to the amount of light striking the active area of the diode. This means that each photodiode would require an amplification circuit to use the photodiode for any activation tasks like we need. Initially, we planned on using photodiodes by themselves, but we realized that there are some issues with these devices.

Since we plan on using our device outdoors, optical noise would be a problem due to the large acceptance spectrum of photodiodes. For example, if the target board was tilted towards the sun, the photodiodes would receive enough light and would consequently turn on the LEDs despite no laser being fired at it. Therefore we chose to modulate our light at 38 kHz. The effects of sunlight and other light sources will be significantly reduced as natural 940 nm sources do not oscillate at this frequency. As a result, we changed our photodetectors to TSOP98638 IR receivers. These IR receivers are essentially photodiodes with built-in preamplifiers that will only react to light that is both modulated at the matching frequency as well as having a wavelength that the receiver is sensitive to. This particular model is designed to react to 940 nm light modulated at 38 kHz. Upon sensing the modulated light, the receiver outputs a 0.3V digital signal that a microcontroller can use to do tasks such as turn on the target board LEDs.

3.3.5 LEDs

There are two main LEDs used in our project. These include the 860 nm LEDs used in our IR flashlight for the IR display scope and visible light LEDs used for visible feedback on our target board. LEDs have a variety of parameters that were used to guide our decision selection. The most important ones are the amount of power emitted, wavelength, and viewing angle of the LED. Ultimately, all of these parameters relate to the visibility of the LED. First, the amount of power emitted determines how bright the light will be, which is important as we will need to be able to see it at long ranges. Second, the wavelength is important due to how the human eye functions. The human eye reacts to different wavelengths differently and is the most sensitive to green light. Finally, the viewing angle is by far the most important for our project because it determines how the output light is distributed.

Standard LEDs have diffusive packages and typically have large viewing angles at over 120 degrees, meaning that someone looking at the LED from outside of this range will see a much dimmer light. However, for our project, the viewing angle needs to be small. Using a large viewing angle means that the light will be distributed over a larger area, which is useless and a waste of electrical power in our project. This is because the user will be typically standing roughly perpendicular to the front of the target board when firing as well as being at least 15m away from the target. Using a simple trigonometric relationship to describe the transverse size of the output beam $D = 2 * distance * tan(\frac{viewingAngle}{2})$, it is clear that a smaller $viewingAngle$ is more useful due to the $distance$ from the board. At 15m away, a standard 120 degree viewing angle LED would spread light over a 52m area while a 30 degree viewing angle results in a 8m area. However, we also must consider that a user may place the board at a closer distance, so the viewing angle cannot be too small. Taking into account the different variables of wavelength, viewing angle, and power, we decided on the C503B-RCN-CW0Z0AA1 624 nm red LEDs with a 30-degree viewing angle. While green LEDs would be preferred due to the optical properties of the human eye, the parts we found while researching online do not output enough optical power relative to the amount of electrical power needed for operation.

For the IR LEDs, the decision was based entirely on output power and wavelength. Since our design will use a telescoping lens design that can focus or defocus the LED light, the viewing angle of the light does not matter. As discussed before, CMOS sensors are relatively sensitive to 860 nm light, so the wavelength for these LEDs was selected based on that characteristic. The output power matters since the quantum efficiency of a CMOS sensor is quite low for IR wavelengths. Additionally, since the light will be reflecting off of the target board back into the sensor from at least 15m away, the power outputted by the LEDs needs to be large. We ultimately chose the SFH 4555 860 nm LEDs. These are extremely powerful at 550mW/sr at 100mA but only have a 10-degree viewing angle.

Programmable LED Strips

In terms of the manufacturability of our project, we have also found a good alternative for normal through-hole or surface mount LEDs. This is to use the LED strips for our LEDs in our system rather than individual LEDs. If we use individual LEDs placed around the target, then this means that our PCBs must be very large to connect to all of the LEDs in an area. By using LED strips, all of the LEDs are connected to one large strip that would only need a single connection to the PCB to control the LEDs. But as we have mentioned previously, there is a major concern in power efficiency in LED strips because the LEDs used in these strips typically have 120 degree viewing angles. The decision of choosing the LED strips may not be considered in our final design.

3.3.6 Beam Splitter

There are mainly two types of beam splitters that can be used in our system. These are plate beam splitters and beam splitter cubes. Beam splitters can be used to split one beam into separate beams or combine two beams into one. Plate beam splitters are essentially semi-transparent mirrors that transmit light coming from one side while reflecting light on the other side. Beam splitter cubes have the same effect but come in a compact glass cube. Since the beam splitter will have to be placed in the rifle internally, it needs to be small and easily alignable. Due to how plate beam splitters work, it would have to be placed at a precise angle within the rifle to properly combine both beams, making aligning difficult or future adjustments difficult. As a result, we chose the beam splitter cubes to use in our project.

Additionally, beam splitters come in a variety of percentages for splitting. Typical values for beam splitters include 50:50, 90:10, and 70:30. In our project, we will use a 50:50 20 mm beam splitter cube. Due to its small profile, the cube can be installed directly into the interior of the rifle. Although using a 50:50 leads to a combined 6.5 mW beam output (4 mW IR and 2.5 mW visible), this is to allow for more flexibility in the project. For example, if we find that the beams are too large when reaching the target, we can simply implement an aperture to reduce the beam diameter while cutting some of the optical power. We can also decrease the current going to either of the laser diodes to drop the net laser power below 5 mW which will save electrical power.

3.3.7 CMOS Camera and LCD Display

The CMOS camera and LCD display are the major components in the night vision capability of the system. In our project, the main concern regarding these two components is whether or not they interact through digital or analog transmissions. We discussed this previously, but using a digital camera and streaming the video to a LCD display would require a large amount of processing power that cannot be handled by a microcontroller like an Arduino. This would require a computing device such as a Raspberry Pi that would solely be used for digital data transfer from the camera to the LCD display. This is also one of the reasons why we stated that the human detection safety system would be hard to implement and considered it a stretch goal.

On the other hand, there is the option of using analog video transmission. Video transmission through analog is very cheap and typically involves using simple RCA and BNC cables for transmission. However, the quality of the video transmitted is often worse when compared to digital transmission. For our project, we ultimately decided on using analog transmission for the camera and display system despite their disadvantages. On the market, the main kinds of CMOS cameras sold with analog connections are CCTV and other types of surveillance cameras as well as rear view cameras used for parking cars. These types of cameras are perfect for our project because unlike standard CMOS cameras, these cameras do not have built-in IR filtering components that make night vision impossible. In fact, many of these surveillance cameras have built-in IR LEDs that make them specialized for night-time operations. We chose the Vanxse® CCTV Mini Spy Security Camera. This camera has a small frame using a 1/3 inch color CMOS sensor and outputs a 1000TVL (1280x960 in pixels) resolution image with a 90 degree field of view. This camera requires a 12V source for operation.

For the LCD display, there were really no specific requirements when guiding our selection other than its compatibility with RCA cables and its size. The size was a main deciding factor because the LCD display would need to be mountable to the rifle scope while also not being overly bulky. The monitor would also need to be large enough that it would be comfortable to look at while holding the rifle. Generally, the types of monitors that suit these requirements are dashboard LCD displays that are used in combination with rear view cameras in cars. For our project, we decided on the Padarsey TFT LCD Car Color Rear View Monitor. These displays have a 5 inch screen and output a 800x480 RGB image. Like the camera, these displays require 12V for operation. Since the camera and display will be removable, it is likely that we will use a separate 12V power source that is solely used for powering these two components.

3.3.8 Audio Amplifier

Since we are unable to output audio directly from the microcontroller to speaker connection, we need to add an audio amplifier to the system. The audio amplifier is necessary in order to act as a digital to analog converter between the microcontroller and the speakers that we choose. After doing some research we landed on the Sparkfun Audio MAX98357A chip. It is a 9-pin chip that is an easy to use, low cost digital pulse-code modulation amplifier. This chip is able to convert digital audio signals to drive the speakers. Its digital audio interface is highly flexible and supports I2S data. Its single-supply operation is 2.5V to 5.5V and has the ability to deliver up to 3.2W of power into a 4Ω load. This chip is also a great choice because it comes with a development board called the Audio Breakout MAX98357A that can be used for testing. Once done with testing the function of the breakout board we will integrate only the chip into our design to save necessary space in our design.

3.3.9 Speakers

Based on the constraints mentioned regarding the audio amplifier we had to choose a speaker to output the signal from the microcontroller that matched the parameters mentioned in the “Audio Amplifier” section. In order for the amplifier and the speaker to be compatible it was important to find one that was rated at an impedance of 4Ω and a maximum power rated at 3.2W. We were able to find a couple of speakers on various sites like Amazon and Adafruit that matched our specifications. The product that we found on Adafruit was a simple 3 inch diameter 4Ω 3 Watt speaker cone that comes with 4 mounting tabs that are 60mm apart. Its price comes in at $1.95 and comes in a package of 1 which would be ideal for our project since we would only be using 1 speaker. The 2nd speaker in consideration was the “MakerHawk 2PCs 4 ohm 3 Watt Speaker for Arduino” on Amazon. Each Speaker comes in a 30mm length, 15mm thickness, and 27 mm wide package and has a 2 pin terminal connected to the positive and negative power lines. These speakers come in at $9.99 but they come in a package of 2 which will allow us some wiggle room. Also since they are provided through Amazon Prime it will allow a very short wait time. We will purchase both speakers and test which works better in our system based on sound quality and overall packaging. In our system the usage of the speaker correlates directly to each time the trigger of the laser rifle is pulled. Essentially, every time the IR diode emits light, the speaker should correspond with a sound.

3.4 Processor Research

To ensure we design and implement a superior product we must determine an optimal microprocessor for our design. There is a vast variety of microprocessor products on the market and within the industry that many companies and independent developers use. To determine the processor that is well suited for our project design we must look at the requirements that need to be achieved. The microcontroller unit will be required for communication with peripheral devices such as the IR laser diode, visible laser diode, LEDs, IR LED, IR receiver, and vibration motor. Features still being researched are also under consideration such as, variable firing mode (semi auto, burst, automatic, and spread fire, ability to play a variety of games that will be interfaced through a mobile phone application, ability to modify recoil intensity, as well as the ability to control ammo capacity and reflect this on the LCD display.

Communication between the microcontroller unit and the rifle as well as communication between the microcontroller unit and the target are needed to input and receive data accurately and reliably. The most well-known communication tools used today are Bluetooth and Wi-Fi. Bluetooth and Wi-Fi are both advanced communication tools used to transfer data and information quickly and seamlessly across one device to another. Bluetooth has quickly advanced over the years with us now having Bluetooth version 5.0-5.2 which allows for an increase in the bandwidth capacity over prior versions of Bluetooth. The newest versions of Bluetooth also allow for lesser power consumption and multi-point connectivity which allows multiple devices to be connected at once. Along with Bluetooth, Wi-Fi has also seen serious technological advances over the years with us now having Wi-Fi 6. The newest version of Wi-fi also allows for the increased bandwidth capacity by nearly double over prior versions. The newest version of Wi-Fi also allows for quicker data transfer speeds over prior versions of Wi-Fi as well as increased safety which decreases the chance of leaking sensitive information. The choice between Bluetooth and Wi-fi is an important factor in the choice of our microcontroller unit as well as the development of our Laser Target-Shooting design. Comparing the data within our research allows us to make an informed decision to ensure optimal functionality within our project design.

Bluetooth

For our project, we considered Bluetooth because it is an advanced communication tool used to transfer data and information quickly and seamlessly across one device to another. Bluetooth technology has quickly advanced over the years with the most current versions of Bluetooth being Bluetooth 5.0-5.2. The newest 5.0 versions of Bluetooth allow for an increase in the bandwidth at approximately 2.0 Mbps capacity over the prior versions of Bluetooth 4.0 at 1 Mbps. An advantage of the newest versions of Bluetooth 5.0 is also lesser power consumption compared to Bluetooth 4.0 and multi-point connectivity which allows multiple devices to be connected at once. Bluetooth works by broadcasting a radio signal with a specific unique address to other transmitters in the vicinity such as a cellular device. The two devices connect and create a personal-area network. A known disadvantage to Bluetooth compared to Wi-Fi is the connectivity range.

Bluetooth is known to have a shorter connection range between devices compared to Wi-Fi. Bluetooth also only has the capability of working on a 2.4GHz frequency whereas most current Wi-Fi networks work on both 2.4GHz and 5.0GHz. Bluetooth overall is meant to be used for small-area networks to connect devices together without the use of an internet connection. Bluetooth provides a weaker signal overall at approximately 1 milliwatt compared to Wi-Fi but that is not necessarily a bad thing. Bluetooth is a great option to use for a more isolated project such as ours since the chance of interference with other wireless devices is much smaller. Bluetooth has the option of channel hopping, which means when another set of devices within the same vicinity are also connected using Bluetooth and they somehow end up on the same channel, they will switch channels within a second therefore the set of devices will not interfere with one another. A great example is when a phone is connected to a car's Bluetooth and you are driving, other cars in the area will also be connected to Bluetooth with their phones. To prevent any interference between vehicles, the Bluetooth transmitter in your vehicle will constantly switch frequencies to stay off the frequencies of the vehicles in the surrounding area. **[4]**

Wi-Fi

Wi-Fi, similar to Bluetooth, is an advanced communication tool used to transfer or download data and information quickly and seamlessly to a device or multiple devices. Wi-Fi has seen serious technological advancement over the years with the newest version being Wi-Fi 6. The newest version of Wi-Fi also allows for the increased bandwidth capacity by nearly double over the prior versions. The newest version of W-Fi also allows for quicker data transfer speeds over the prior versions of Wi-Fi as well as increased safety which in turn decreases the chance of leaking personal data or sensitive information. A significant difference between Wi-Fi and Bluetooth is that Wi-Fi has the capability of connecting a multitude of different devices while being used on the same Wi-Fi network.

The standard for today’s Wi-Fi networks is 802.11 which comes in many different varieties. Today's network standards include 802.11a which uses a 5GHz frequency band as its standard which allows data to move up to 54 Mbps. 802.11a uses an orthogonal frequency-division multiplexing technology to split the radio signal into separate sub radio signals to aid in reducing outside interference. Wi-Fi networking standard 802.11b is the slowest Wi-Fi network but also one of the most popular for the common consumer or user. 802.11b uses the 2.4GHz frequency band which only allows for data to move up to 11 Mbps. Wi-Fi networking standard 802.11g has common similarities to the 802.11b Wi-Fi networking standard. Wi-Fi networking standard 802.11g also uses the 2.4GHz frequency band however the 802.11g networking standard is capable of sending data at 54 Mbps similar to the 5GHz frequency band due to the orthogonal frequency-division multiplexing that’s also used in the 802.11a networking standard. The 802.11n networking standard is one of the most widely used Wi-Fi networks by the common consumer or user, even more so than 802.11b. The reason the 802.11b networking standard is so popular is due to its backwards compatibility to the prior versions mentioned, 802.11a, 802.11b, and 802.11g. The 802.11n also has far greater data transfer compatibility with the ability to use four data streams and transmit data at 150 Mbps using the orthogonal frequency-division multiplexing with the ability to use 2.4GHz or 5GHz frequency bands. This makes the

802.11n the most popular consumer Wi-Fi networking standard for home use. The newest networking standard is the 802.11ac which is essentially an updated and most efficient version of the 802.11n networking standard. The 802.11ac is still under development and review which is why it has not completely taken over the 802.11n networking standard. The 802.11ac is similar to the 802.11n in the sense that it also has backwards compatibility functionality with every other networking standard. The 802.11ac has the ability to function on the 2.4GHz and 5GHz frequency band but has the ability to transmit and transfer data at 450 Mbps. Wi-Fi and Bluetooth share a common spot on the visible spectrum graph between 300 MHz and 3 GHz. However, Wi-Fi is quickly advancing and is beginning to find itself in the 3 GHz and 30 GHz range. These separate bands are the reason we do not notice any interference between the Wi-Fi, radio, and television in our homes. **[4]**

3.4.1 Choosing Between Bluetooth and Wi-Fi

Choosing to use either Bluetooth or Wi-Fi is an important decision to make for our project's app functionality. We will weigh the pros and cons from our research in the previous section to choose the best option. Both Bluetooth and Wi-Fi have gone through serious technological advancements. Both Bluetooth and Wi-Fi are means of transferring data quickly and seamlessly across one device to another, or across multiple devices. Some advantages of the newest versions of Bluetooth include an increase in bandwidth at approximately 2.0 Mbps capacity over prior versions at 1 Mbps. The newest versions of Bluetooth also have lesser power consumption and multi-point connectivity to allow multiple devices to connect at once. When two or more devices connect with Bluetooth, a radio signal is broadcasted with a unique address to other transmitters in the vicinity so there is no interference with other devices. Bluetooth is a great option for small-area networks to connect two or more devices together without the use of an internet connection. Bluetooth's range is much shorter than Wi-Fi but for our project that is not an issue. The phone, laser gun, and target will all be within close vicinity of one another. Bluetooth is a great option to use for an isolated project such as ours due to the lesser chance of interference with other devices. Some disadvantages of Bluetooth are the capability of only working in the 2.4GHz frequency band, whereas most Wi-Fi networks work on both 2.3 GHz and 5.0GHz frequency bands. Bluetooth also provides a weaker signal at approximately 1 milliwatt compared to that of Wi-Fi. Due to Bluetooth's weaker signal, range is also sacrificed, the range on Bluetooth will only reach approximately 30 meters whereas the newest editions of Wi-Fi can surpass a 100-meter range. Data transfer speeds are also a disadvantage when considering Bluetooth vs Wi-Fi, for example, Bluetooth 4.0's transfer speed only goes to approximately 25 Mbps whereas the newest versions of Wi-Fi have transfer speeds up to 450 Mbps. Wi-Fi has disadvantages of its own over Bluetooth. When using Wi-Fi, you have to consider that on a public network, anyone can connect to your Wi-Fi connection. As more and more devices begin to connect to a Wi-Fi network, then bandwidth will start to become limited. Although more devices can typically connect to a Wi-Fi network over Bluetooth, Bluetooth for us is a better option to avoid outside interference and bandwidth limitations. Data transfer speeds are not a current concern of us right now, but it is something to consider in the future. The range is not a concern for us since our devices will all be within close proximity of one another. The weaker signal is not a current concern of ours since the phone, laser gun, and target will all be within close proximity to one another. The overall consensus is to use Bluetooth to lessen power consumption, avoid outside interference, and avoid bandwidth limitations. **[4]**

3.4.2 MCU Technology and Specifications

Arduino Mega 2560

The Arduino Mega 2560 is a popular and well-known microcontroller to use for personal projects. The Arduino Mega 2560 16 analog inputs, 4 UART serial ports, 16 MHz crystal oscillator, 54 input/output pins, USB connection, power jack used via computer or external battery, In-Circuit Serial Programming (ICSP) header, and a reset button. The Arduino Mega 2560 operating voltage is 5V with a recommended input voltage of 7V-12V. The clock speed of the Arduino Mega 2560 is 16 MHz. The Flash Memory is 256 KB with 8 KB occupied and the SRAM is 8 KB. The Arduino Mega 2560 does not have Bluetooth or Wi-Fi without installing external hardware to the microcontroller. [5]

MSP-EXP430G2ET

The MSP-EXP430G2ET is a 16-Bit microcontroller. The MSP-EXP430G2ET has 20 input/output pins, USB connection, Debugging and programming interface, two push buttons for feedback or device reset, a green and a red LED, and MSP430 application UART serial ports. The MSP-EXP430G2ET has 16 KB of Flash Memory, 512 bytes of RAM, a clock speed capable of 16 MHz CPU speed, 10-bit ADC, enabled Input/Output with capacitive-touch, and universal serial communication interface. The MSP-EXP430G2ET does not have Bluetooth or Wi-Fi without installing external hardware to the microcontroller. **[6]**

ESP32-WROOM-32D-N4

The ESP32-WROOM-32D-N4 supports 32-bit operations. The ESP32-WROOM-32D-N4 has 38 pins including input/output, 3V3, GND, Sensors, and clock. The ESP32-WROOM-32D-N4 peripherals include, SD card interface, UART support, SPI, SDIO, I2C, IR which is important to our project, and capacitive touch. The ESP32-WROOM-32D-N4 has a 40 MHz integrated crystal, a 2.4 GHz – 2.5 GHz operating frequency, a 2.7V – 3.6V voltage supply, a 4 MB integrated SPI Flash, 520 KB of on chip SRAM, and a clock frequency which is adjustable from 80 MHz to 240 MHz which has two CPU cores that can be individually controlled. A large advantage of the ESP32-WROOM-32D-N4 over the Arduino Mega 2560 and the MSP-EXP430G2ET is Bluetooth and Wi-Fi capability without requiring external hardware to be added. The ESP32-WROOM-32D-N4 uses Bluetooth 4.2 and Wi-Fi networking standard 802.11 b/g/n. Using this microcontroller will allow us to connect to a phone via Bluetooth to integrate our phone application. **[7][8]**

3.4.3 Arduino Mega 2560 vs. MSP-EXP430G2ET vs. ESP32-WROOM-32D-N4

This section is meant to compare the three microcontrollers Arduino Mega 2560, MSP-EXP430G2ET, and ESP32-WROOM-32D-N4 to determine which microcontroller is best suited for our project. When deciding which microcontroller is best for our project we need to consider all the hardware we will implement such as IR module, speaker, and IR receiver.

Clock speed determines how quickly instructions are executed for the specific processor. Using a microcontroller with a higher clock speed will allow more instructions to be executed overtime compared to a microcontroller with a lesser clock speed. There are some trade-offs for using a high clock speed microcontroller. Using a microcontroller with a high clock speed means a more intricate design which will directly increase the cost. A higher clock speed also leads to greater power consumption relative to a microcontroller with a smaller clock frequency. Keeping the cost and power consumption to a minimum is an important aspect to consider when selecting parts and designing an engineering project. Although price and power consumption will be increased, having a high clock speed microcontroller proves its' worth, being able to compute vastly more instructions in a shorter period of time. Having a microcontroller with a high clock speed will allow for data to be received and communicated very quickly across devices. For our particular project, the three microcontrollers we are comparing all have sufficient clock speeds, however, the Espressif Systems microcontroller we chose allows for higher clock speeds compared to the Arduino and Texas Instruments microcontroller.

Memory is an important factor to consider based on how strenuous the programs will be that are running on it. The memory found in a microcontroller is where data and information is stored once received. The data within the microcontroller's memory is used to respond to instructions based on the program being used [14]. The more programs and functions being performed at once will require more memory from the microcontroller. The read and write time on the microcontroller will be affected by the program(s) being run. As a program becomes more complex, the more data and resources needed for the microcontroller to store the information in its memory. When using a microcontroller we must consider that the memory capacity is significantly smaller than that of a present desktop computer. Choosing a microcontroller with a large amount of memory can quickly become expensive.

For our project we want to ensure the microcontroller we choose can handle our software without any memory issues. It's important to remember that long-term information or program memory is non-volatile memory. Non-volatile memory is information stored within the memory without requiring a power source. Storage of temporary data or data memory is volatile. Volatile memory is data that is held temporarily, meaning the microcontroller needs to be connected to a power supply to hold onto the data. Choosing a microcontroller with less built-in memory such as the Arduino or Texas Instruments microcontroller can potentially limit our software capability. To implement various functions such as games, number of targets, ammo capacity, and firing mode, it's a safer

bet to choose a microcontroller with more memory.
For our project, comparing the three microcontrollers, it’s seen that the Espressif Systems microcontroller we chose allows for the largest amount of on board SRAM compared to the Arduino and Texas Instruments microcontroller.

Table X357 below shows the main factors we considered when deciding which microcontroller to use. Considering the ESP32-WROOM-32D-N4 is the only microcontroller we researched that allows Bluetooth and Wi-Fi communication without additional external hardware being added, we believe the ESP32-WROOM-32D-N4 will be best suited for our project design and development.

Company	Arduino	Texas Instruments	Espressif Systems
Microprocessor	Arduino Mega 2560	MSP-EXP430G2ET	ESP32-WROOM-32-N4
Operating Voltage	5V	1.8V – 3.6V	2.7V – 3.6V
Bluetooth (Stock)	No	No	Yes
Wi-Fi (Stock)	No	No	Yes
Clock Speed	16 MHz	16 MHz	80 MHz – 240 MHz
Availability	Available and Own	Available and Own	Available and Ordered

Table X357: Microcontroller Comparison

3.4.4 Development Board

For our project we will use the ESP32-DevKitC core Board for ESP32 Development Board ESP32-WROOM-32D which is compatible with Arduino. A development board is needed for active prototype testing of our project before actual implementation takes place. We have two boards that will be used for testing the laser gun as well as the target.

3.5.5 MCU Pin Connection Layout

The ESP32-WROOM-32D microcontroller has 38 available pin connections. Each pin serves a specific function for which we will connect to hardware on our laser gun as well as the target.

1 GND			
2 3V3			
3 EN			

4 SENSOR_VP			
5 SENSOR_VN			
6 IO34			
7 IO35			
8 IO32			
9 IO33			
10 IO25			
11 IO26			
12 IO27			
13 IO14			
14 IO12			
15 GND			
16 IO13			
17 SD2			
18 SD3			
19 CMD			
20 CLK			
21 SD0			
22 SD1			
23 IO15			
24 IO2			
25 IO0			
26 IO4			
27 IO16			
28 IO17			
29 IO5			

30 IO18			
31 IO19			
32 NC			
33 IO21			
34 RXD0			
35 TXD0			
36 IO22			
37 IO23			
38 GND			

3.5 Power Research

In order to create any electronic design it is quintessential to utilize the appropriate power source. It is important to consider the appropriate methods, standardized practices and considerations when looking to manipulate a power in a manner that is safe and efficient for internal and external components in our design. This section will outline the methods and means that we considered in order to select, manipulate and regulate our power supply for both our laser rifle design and our laser rifle target. Both the rifle and target systems will require a source that can accommodate a microcontroller unit and various user end components.

3.5.1 Sources and Regulation

Laser Rifle - The main component of our system is the rifle itself. The power requirement for this system is that it should be able to supply at least an input voltage of no less than 5V to power the MCU that will control the trigger system and communication to the user end app. The rifle power source will also power the IR diode and haptic feedback. We would like for the rifle to retain a reasonable weight so that it is not too heavy but also not too light so it not exceeding 10 lbs is ideal. This allows for significant maneuverability when choosing the battery system design since the frame is no more than 4 pounds. Although it would come at a higher cost than disposable batteries, ideally a rechargeable battery pack would be well suited for the rifle.

Target Board - Power requirements for the target board will need to be as capable as the source as the laser rifle despite the target design being different. The target board will most likely contain a similar MCU, IR sensing and LED indication so that no less than 5V requirement will be necessary. A DC supply no less than 5V will also leave room for any stretch goals that will be considered later. Again both devices will provide a mobility aspect so this system should be powered by a rechargeable battery pack as well.

Regulation

When designing systems that include different components but one power source it is necessary to include voltage regulation. Power regulation will be pertinent for protecting integrated circuit components while supplying the necessary potential voltages. In order to not overload the 5V MCU which is integral to both the rifle and target board systems we will be looking to provide DC sources that can be stepped down or stepped up to acquire appropriate input voltages.

3.5.2 Battery Technology

Designating which battery technology to use is always an extremely crucial step to any electronic system design. The batteries that were considered for this project led us to research Lithium-Ion, Lithium Polymer, Nickel Cadmium and Nickel Metal Hydride. In order to choose the appropriate battery technology limitations such as weight, pricing and efficiency were taken into account.

Nickel Metal Hydride vs Nickel Cadmium

Ni-MH batteries are a type of rechargeable battery that is commonly used in many electronic devices like laptop computers, mobile phones, and cameras. The negative terminal of the battery is made of a hydrogen-absorbing material and often different inter-metallic compounds while the positive is made of nickel-oxide hydroxide. A couple of its advantages over Nickel Cadmium based batteries are that they have improved energy density with a higher capacity of roughly 30 to 40 percent, they require lower maintenance, have excellent safety performance and are environmentally friendly with few toxins. While disadvantages are listed, the Ni-HH batteries have longer charge times that require careful control of trickle charging and tend to be more expensive. Research also reveals that both have an average nominal voltage of 1.25V per cell.

Lithium-Ion(Li-ion) vs Lithium Polymer(Li-Po)

Li-ion batteries are mostly made of lithium while the cathode is made of graphite, cobalt or manganese. This type of battery utilizes a liquid electrolyte for electrons to flow. Li-Po batteries are similar to Li-Ion however instead they use a gel like electrolyte. The key advantages of Li-ion batteries are that a typical Li-ion battery can store 150 watt-hours per kg of battery, they hold charge pretty well, and they can handle more charge/discharge cycles. Li-Po batteries' key advantages are that they are compact in size, very safe compared to Li-ion, light weight and have a larger life span. The nominal cell voltage in a Li-ion battery is around 3.2V while the nominal cell voltage in a Li-Po battery is about 3.7V.

We made **Table X362** below to get a better numerical comparison of each battery. After strong consideration we found that the voltage level that best suited our engineering directives would be a power source ranging at around 9V. At this voltage we found fast charging speed to be a deciding factor. A quick recharging turn-around would surely benefit the user in the long run. Therefore we decided to choose a 9.6V Ni-MH rechargeable battery pack for both the target and the rifle. The extra weight that the 9.6V battery pack provides will also provide some stabilization for the target board as well.

Battery Type	**Nickel-Cadmium**	**Nickel-Metal Hydride**	**Lithium Polymer**	**Lithium-Ion**
Energy Density (Wh/kg)	45-80	60-120	100-130	110-160
Fast Charging time	2-4h typical	1h	2-4h	2-4h
Cell Voltage	1.25V	1.25V	3.7V	3.7V
Battery Cost	$50	$60	$70	$70

Table X362. Comparison of Batteries

3.5.3 Charging Technology

Constant Current & Constant Voltage

Constant current charging is a method of continuously charging a rechargeable battery at a constant current to prevent overcurrent charge conditions. Constant voltage charging is a method of charging at a constant voltage to prevent overcharging. The charging current is initially high then gradually decreases. These 2 are the most common battery charging methods. Both methods include their own sets of advantages that allow for battery charging efficiency so a dual method was introduced to include both. Constant voltage/ Constant current (CVCC) is the combination of the mentioned 2 where the charger limits the amount of current to a pre-set level until the battery reaches a pre-set voltage level. The current then reduces as the battery becomes fully charged. A Lithium Ion battery is being strongly considered for this project and the CV/CC method is a very typical method of charging Li-ion batteries. This method of charging is efficient for mobile devices and allows for higher device uptime.

Battery Management System (BMS)

Battery management systems are electronic control circuits that monitor and regulate the charging and discharging of batteries. The importance of the system lies in its ability to ensure the optimal use of the residual energy present in the battery. The system can be used to monitor characteristics like the detection of battery type, voltages, temperature, capacity, state of charge, power consumption, remaining operating time, and charging cycles. For the prototyping of our design the main focus will be on the BMS chips ability in Passive Protection and Basic battery life monitoring. Additional design considerations may fall into the realm of digital communication via Bluetooth between the devices and the systems app.

3.5.4 Voltage Regulators

A voltage regulator is a component used to ensure that a steady constant voltage is supplied through all operational conditions of necessary devices. It will usually take in a higher input voltage and emit a lower, more stable output voltage. It is needed to to keep voltages within the prescribed range that can be tolerated by the electrical equipment in using said voltage. For example, if there is a 12V supplied voltage but a component operates at a much smaller range say about 3V then one can use a regulator to drop that 12V to a range of 2.7-3.3V in order to satisfy that device. For this project the battery technology being considered is about 12V and above for our voltage supply. Ideally, we would like to utilize regulators to limit the current and voltage inputs the microcontroller and peripheral devices obtain to achieve optimum power efficiency in our system.

Linear Regulators

Linear regulators use linear, non-switching techniques to regulate the voltage output from the power supply. It operates by using a voltage-controlled current source to force a fixed voltage to appear at the output. They require an input voltage at least some minimum amount higher than the desired output voltage. Linear regulators are highly considered in the regulator selection due to the fact that their implementation is simple, low cost and low noise.

For our design it is necessary to utilize linear voltage regulators at optimal voltage levels to power the microcontroller, IR laser diode, IR receivers, LED array on the target board, and speaker unit. Although there are 3 basic regulator designs for regulators: Standard (NPN Darlington) regulators, Low Dropout or LDO Regulator, and Quasi LDO regulator, after extensive research it was found that the Low Dropout Regulator seems to be more optimal for our design. The reason being that it is best suited for battery-powered applications. **Figure X** below shows an example circuit for an LDO regulator.

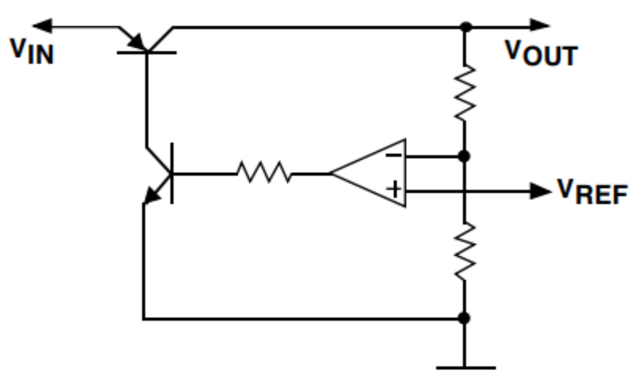


Figure X. LDO Regulator from Texas Instruments

TPS76333

The TPS76333 is a low-dropout voltage linear regulator that offers the benefit of low power operation and miniaturized packaging. The input voltage is limited to 2.7V minimum to 10V maximum[X]. It will provide a regulated output voltage of 1.6V to 5V while having a current of 2uA. It comes in a 5-pin packaging and although normally are provided as fixed voltage regulators it also comes in a variable version that can be programmed to output within the 1.6V to 5V range. Although the price of the regulator is a little higher than that of most, it can be very useful in providing the 3.3V and 5V outputs we are looking for. $1.24 per

LM7805

Unlike the TPS76333 the LM7805 is a 3 terminal linear regulator. It can accept an input voltage of 5V to 18V and retain an output voltage of 5V, 12V or 15V. It provides internal current limiting, thermal shutdown, and safe area compensation, making them very safe for PCB use[X]. The safety features of these regulators and the fact that we have used these regulators in a previous project make them a strong contender for use to step down our voltage from 9V to 5V. The price generally comes in around $1.82 per regulator which again is a little pricey but would be worth it.

TC1262

The TC1262 regulator is a fixed output high accuracy CMOS low dropout regulator. It is generally used for battery systems which is exactly what our rifle system and target system are based on. The CMOS construction eliminates wasted ground current, significantly extending battery life. We are looking to keep our system fairly low energy so that our devices can have an uptime of at least 4 hours. This regulator takes in a maximum input of voltage of 6V and provides a regulated 3.3V. The cost of this package is generally $.62 per. **[X]**

LD1117AS33TR

The LD117A is a low drop voltage regulator. It comes in adjustable and fixed voltages such as 1.2V, 1.8V and 3.3V. It also comes as multiple 3-pin variations that include through hole and surface mount. High efficiency is assured by NPN pass transistors. Ideally for our design we would like to include as many surface mounts as possible because surface mounted packages optimize the thermal characteristics while offering a relevant space saving advantage. The operating DC input voltage is 10V while the maximum rating is 15V. The price for this comes in at about $.90 per regulator and in high stock on Digi-key.

TPS82150

The TPS82150 is a 17V input 1A step down converter module that is optimized for small solution size and high efficiency. It comes in a 8-pin package and includes options for power save mode, where the device can operate with typically 20uA quiescent current. We could use this converter to provide an adjustable output thus allowing it possible to create the 3.3V and 5V voltage rails necessary to power our components. The price per each module comes in around $1.47 making it the most expensive regulator under consideration. We provide an overall comparison of these components below in **Table X364.**

	Max Vin (V)	Nominal Vout (V)	Voltage drop (V)	Output current (mA)	Additional component req
TPS76333	2.7 - 10.0V	1.6 - 5V Variable	0.18	800	1uF input capacitor
LM7805	5V - 18V	5V - 15V fixed	2.00	1000	0.33uF Vin, 0.1 uF Vout
TC1262	2.7 - 6.0V	2.5 - 5.0 fixed	0.35	500	1uF Output
LD117A	10 - 15V	1.2 - 3.3V Fixed	1.0	1200mA	10uF cap for stability
TPS82150	3-17V	0.9-6V Variable	(low)	1000	Resis divider, @ pin6

Table X364. Voltage Regulator Comparison

3.5.6 Battery Power Conclusion

With all the design requirements and standards taken into consideration we ended with a battery selection of a 9.6V 2000mAh Ni-mH rechargeable battery. Although providing a battery management system was highly considered in the initial design, we have proceeded with omitting that until the foreseeable future. Reason being that batteries that included the BMS system chip were only within the range of 3.7V and below. During the selection process we did consider a Lithium Ion 3.7V 4400mAh battery pack from Adafruit.com and a 2.4V NiMH 3700mAh battery pack from Digi-Key. While both products offer sufficient capacity for powering the laser rifle and target, including a low voltage system would require the use of a boost voltage converter and ideally, we would like to avoid the energy efficiency penalties. We found early on that a simple voltage buck/ step down regulator design was more efficient and flexible. The choice of 9.6V 2000mAh Ni-mH also comes with its own set of penalties since we will be working with a smaller current capacity, but we can more than make up for that by using dynamic sleep profiles for the ESP32 microcontroller that was chosen.

3.5.7 Voltage Regulator Conclusion

After finalizing the battery selection process the voltage regulator selection went under consideration. For our system it is necessary that we include regulator designs that can output stable and efficient 3.3V and 5V bus. The 3.3V bus will be essential in safely powering components such as the audio system in the rifle, the vibrational motor in the rifle, the IR receiver in the target and the microcontrollers on both the target and rifle . While the 5V rail will be important in supplying stable power to the IR diode inside the rifle, the IR flashlight on the gun and the indicator LED strip display on the target. A simple parallel system design would allow us to bypass the efficiency penalty incurred with a sequential voltage buck design and would allow us to eliminate any need for an expensive buck-boost IC. Ideally it would allow us to use the same power design for both the target and the laser rifle. **Figure X** below shows a general description of how ideally the voltage rails interact with various components.

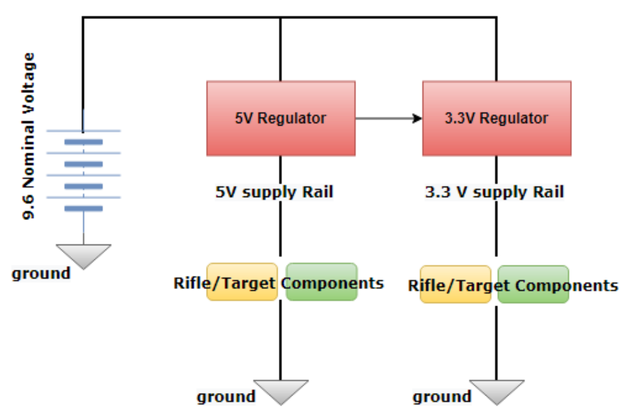


Figure X. Voltage Rail Description

Originally it was the opinion of our team to use the LM7805 voltage regulator since it is fairly common and can be easily applied; however, it only provides an output voltage of 5V and not a 3V3 rail. With that considered it is our team's opinion that we should use the TPS76333 voltage buck regulator for our 3V3 rail and a TPS76350DBVT to create our 5V rail.

4.0 Related Standards and Design Constraints

Standards are an integral part of our project. These standards provide the guidance of how we stand, operate, communicate, and develop new ideas. Constraints further enhance our awareness of the design. What constraints are defined as a rule, requirement, or limiting factor placed on the design as part of the project assignment. During the ABET lectures in the Senior Design class, several categories of constraints were introduced. Each one of these categories was researched carefully so that we can place down the relevant constraints for the section. This section will be used to discuss all standards and all known constraints. We will explain how they are applied to our project and what are the reasons behind these decisions.

4.1 Standards

The definition of standard is a “document that defines the characteristics of a product, process, or service, such as dimension, safety aspects, and performance requirement” **[2].** Standards development began by committees, organizations, or government departments. For example, groups consist of Institute of Electrical Engineers (IEEE), American National Standards Institute (ANSI), and Institute of Printed Circuits (IPC) and many more. Overall, standards are developed by hundreds of professional and technical organizations.

That is why analyzing and identifying related standards is an important aspect of the design process in the engineering project. Standards are to protect our health, safety, and environment. Therefore, many design decisions were considered to satisfy the need of system requirement standards.

This section will discuss several standards related to this project, including standards for soldering and hardware safety, prototype testing and software testing, product reliability, documentation, and programming language standards.

4.1.1 Hardware Soldering Standards

Since our project will require a significant amount of soldering, we found it important to include soldering standards. IPC J STD 001 is a soldering standard for electronic components and electrical assemblies. The standard identifies material specifications, process requirements and acceptability criteria. Originally this standard was accepted in 1992 and has had multiple revisions since. The current version of this document is J-STD-001 H. It outlines methods, materials, and verification criteria for creating quality, lead and lead free, soldered interconnections. The standard provides an in-depth explanation of the following elements and practices involved:

- Through-hole mounting
- Terminal and wire connection
- Material, component and equipment
- Soldering and assembly requirements
- Surface mounting of components
- Cleaning and residue requirements
- Coating, encapsulation, and adhesives

The J-STD-001 standard is used as a guideline and provides the best practices to follow for process engineers, supervisors, and technicians. These joint industry standards listed below will be crucial to our design and prototyping process as it will make the soldering process more reliable and consistent. The necessary requirements specified by the J-STD-001 are as listed.

According to the J-STD-001 cleanliness cannot be overlooked. In order to prevent the contamination of materials, tools and surfaces cleanliness must be practiced consistently. Corrosion can be caused by fluxes with powerful properties and so the board's structural elements may be susceptible to residue and cause it to collapse. Therefore, in order to prevent contamination, one must be constantly cleaning materials, processes and surfaces.

Another important requirement is temperature control. Heating and cooling rates ideally should be followed as closely as possible to the manufacturer's instructions. One should practice thermal profiling to determine the excursion throughout the soldering process by measuring many spots on the circuit board. Stacked and laminated chip capacitors are treated as temperature sensitive to prevent thermal shock.

It is also important that soldering must not cause any damage to the wire strands. When working the tinned section of the wire must be thoroughly coated with the solder.

A conformal coating is a protective sheet that acts as a protection against any external toxin to the board. The coating will serve as a protective covering for the PCB surface. Before installing the conformant covering and stacking, the soldering and cleaning operations are evaluated.

Solder alloys such as Sn60Pb40, Sn62Pb36Ag2, or Sn63Pb37 are acceptable according to J-STD-001. While on the other hand, high temperature solder alloys like Sn96.3Ag3.7 can only be used when it is specifically instructed by approved engineering drawings.

It is also important to note the significant differences in using Lead solder vs using Lead-Free Solder. Generally leaded solder is composed of tin and lead while lead free can be composed of tin, copper, silver, nickel and zinc. Leaded solder is easier to use, has a lower melting point, a lower cost and will cause much fewer problems in quality with the joints than a lead-free solder. However, there have been efforts to remove lead out of all electronic products in the United States due to concerns about its health and environment effects. Lead-free solder's most important benefit lies in the fact that it is much safer however it falls short due to the fact that it tends to not have a stable melting temperature and its melting range is higher which can lead to damage of the electronic components **[13].**

4.1.2 PCB Standards

Using printed circuit boards (PCB) is a way of removing or replacing the breadboarding aspect of project design. The Institute for Printed Circuits or Institute for Interconnecting and Packaging Electronic Circuits known as IPC is the organization most well known for producing PCB standards [9][10]. IPC is known for producing standards for almost all phases of electronic design and development regarding PCB design, purchasing, packaging, and assembling. IPC standards are used for all electronic designers for references and customized project designs. IPC standards are used to determine manufacturing issues and what needs to be done to comply to meet said requirements. A list of standards and qualified products is kept to help the project designer or design team to determine if the product is compliant with the IPC electrical design standards. PCB IPC standards are found in every stage of the PCB design and manufacturing process. For example, when a PCB is being designed and created, IPC sets standards in file formats, electronic product documentation, design guides, and PCB design software **[10]**. PCB design requirements play a role in choosing appropriate material for PCB board design assemblies, surface finishes, surface mounted devices, testing, and quality or acceptably of the PCB board once printed. Soldering standards also relate to IPC PCB especially for our project. In most cases the soldering standards refer to reflow soldering which we will need for our laser diode. Soldering standards are used to see if the electronic assemblies are deemed acceptable during the manufacturing process. IPC PCB standards are also used for cable and wire assemblies. IPC PCB standards are important for the manufacturing process, documentation, design guides, PCB software, as well as testing and inspection of electronic assemblies and enclosures to make sure the design is good for production before releasing a final product **[10]**.

IPC design standards are important in producing a working product that is also safe and reliable. The details are essential when producing a high quality and high-performing PCB. Within each step of the design, assembly, and production process there's an IPC standard to be implemented. Companies must comply and use IPC PCB standards when promoting or producing a product to a company to be used and put on the market. The most important thing about IPC PCB standards is to ensure that the product is quality and to keep catastrophic failures to an absolute minimum. Some added benefits of IPC PCB compliance standards include overall improved quality and reliability within products, improved communication, cost reduction, and improved reputation to further your name and reliability.

Improving quality and reliability with a company's products will be more easily achieved by following IPC PCB standards during the manufacturing process. Abiding by IPC standards will ensure more consistent quality of products over time. Creating a product that is reliable and functions properly will lead to more profit, competition, consistency, and happier customers overall. Using the appropriate IPC standards will also improve communication within and outside of a company. Using the same IPC terminology will allow for more fluid communication to lessen confusion and to ensure everyone is in agreement. Using IPC standards will make communication easier among employees within the company as well as the consumer or vendor. If everyone is familiar with the same terminology it will lessen the confusion over all which leads to more consistent production and happier customers. Reducing cost is always a very important thing to consider in PCB and electronics design in general. Following IPC standards will help reduce cost by improving the quality of products and minimizing any delays. Using IPC standards will allow companies to use resources more efficiently to help reduce overall cost. Improving reputation is important to allow for new opportunities to arise and to allow for more consumers to reach out to you. Immediately when you abide by IPC standards a company notices that which makes you more recognizable. Even when a company is smaller or not as well known, abiding by IPC standards shows that you are committed to quality. Abiding by IPC standards will attract more customers, allow for new opportunities, more profit, competition, consistency, and make the company more recognizable. **[10]**

4.1.3 Charging Standard

4.1.4 Coding Standard - Programming Standard

Computer languages evolve over time. In order for the programming language to be uniform and universally understood by engineers, programmers, compilers, or computers the language must be standardized. When we write a program, we need to ensure it compiles and does what it’s supposed to. For that to happen, we need to write correct code. In this case, we use Javascript as our programming language in the React Native for app development. When we looked into the coding standards for React Native, we couldn’t find any standards or practices provided by the community. But we found a web blog written by Gilsaan Jabbar with the title “React Native Coding Standards and Best Practices” **[12]**. Therefore, we’ve decided to follow the guidelines written in that blog, and then write our own guidelines as well using the references from React Native documentation. We plan to follow as many of our own guidelines to create a more robust, readable and clean code to make the code more clear for one of our teammates.

We have a few fundamental principles for creating a clear Javascript source code. They are as follows:

1. Naming Conventions: A folder and subfolder name should always start with small letters and the file belongs to the folders in pascal case. The definition of “pascal case” comes from the programming convention and it describes when the first letter of each compound word in a variable is capitalized. For example the company “ElectronicArt” or the video game “LeagueOfLegends”. To name the components we follow the pattern path based component naming which may include writing the component accordingly to its relative path to the folder components or to app. For example, a Button component that is located at: components/common/Button.js would be named as Button.js.
2. Putting *imports* in order: React import, library imports in alphabetical order, Absolute imports from the project, Relative imports in alphabetical order, then Import *as, and finally Import ‘./<filename>.<extension>. All of these are separated by an empty line.
3. Layout Conventions: Always end a statement with a “comma”. There are two types of data, State and Props in React native which control the component. The component that uses state is mutable which can be changed later if required. And when we use the State Hook, we should use a functional component. Indentation by one tab if the continuation lines are not automatically indented. There should be no line space between two similar looking statements.
4. Language Guidelines: *Data type* is a variable in React Native can contain any data. The *number type* represents both integer and floating point numbers. The *string type* is a type in React native must be surrounded by a single quote or double quotes. The *Boolean type* has two values: true and *false.* It can also represent yes/no values. There are more variables that are too much to include but they have been enough for us to be understood by everyone in the group.

There are a few more guidelines that we should include for code organization and code structure but there are enough details that we think are good enough for everyone to be understood by the group members. All of the details are too much to include in this section in this summary.

4.1.5 Documentation Standard

This standard provides the guidance for the development and determines what is the requirement for the project to satisfy some provisions. The documentation standard is one of the established ways of doing things that ensure interoperability. Since the documentation is a technical report that explains our team design professionally, it is important that we should conform our current document to the current class project documentation guidelines **[15]**.

For the document format, our written text needs to be a professional appearance, with a non-paper cover and bound. The length of the documentation needs to be one hundred and twenty. Contents written in our document need to be relevant to our Laser Target Shooting project. Also according to the class guidelines **[15]**, the document cannot contain any programming code, no debug window screenshot, no images of common electronic parts such as transformer, HDMI, USB, transistor or resistor. Combination of all images of some forms of testing should not be more than one or two printed pages. And all data sheet material should be limited to two printed pages. Then, our paper size must be 8.5” x 11””, with 1” margins on the top, right, and bottom of each page. When it comes to the use of copyrighted content, the appendix in the document needs to contain written authorization for rights to include. Next, all elements of the document which support the written text, such as Figures, table, drawings, code segment, etc.. must be references in the body of the text and the citation must appear before the element is shown. And finally, any supplementary material must be attached along with the current document.

These are all the guidelines that our Laser Target Shooting project has to have. However following guidelines aren’t just all and done, but should we have additions or deletions where appropriate for our current project.

4.2 Constraints

Constraints are required to be acknowledged because we cannot have our project design to be unreachable or not operate safely. As explained before, constraints consist of several categories for our intended product. Since we are working with lasers, which have a high performance, we must have constraints to limit the power of the product to some degree to meet the legal standards, ethical standards, and also power standards.

4.2.1 Laser Safety Constraints

For our product to be successful, our laser should be powerful enough to perform well at long ranges. However, the laser also needs to be eye-safe. Lasers are separated into a plethora of classes based on the output power and their visibility. Class 3R is from lasers 1 to 5mW, which is where our system falls under (10).

The main safety concern with class 3R is the visibility of the light. Class 3R lasers are considered low risk if accidentally looking at the direct beam due to the eye reflex when seeing bright lights. If the light is visible, then the eye will immediately close and prevent further damage. However, if the light is infrared and not visible, then the beam is no longer considered low risk since the eye will be exposed to the laser beam without closing in response. In our system, however, we are using both a visible and infrared laser beam. The output power of the combined beams will be below 5mW. Even though most of that light is infrared, the visible beam will cause someone who accidentally looks into the beam to close their eyes in response, so it will still remain a low-risk system by this standard.

To ensure safety and prevent accidental injury when using the rifle, there are a variety of safety mechanisms to prevent the rifle from being used. Two built-in ways include a trigger safety and a physical beam blocker. The trigger safety will work like a real firearm and will prevent the gun from firing, while the beam blocker will go over the barrel of the gun and block the beam. A digital way is the human detection camera that prevents the user from firing when someone is in the field of view of the camera.

4.2.2 Maintenance Constraints

Unlike real firearms, the laser rifle is quite sensitive as a system, and performance is heavily reliant on system alignment. From the consumer perspective, aligning two laser diodes, one being an invisible infrared laser that can only be seen using special equipment such as IR viewing cards, is a near impossible task. As such, user maintenance will be limited to simple battery changes like most commercial products. Our project will be like most products In the market that work under the model of offering warranty to give complete replacements to broken products rather than fixing the broken products themselves.

4.2.3 Social, Ethical, and Environmental Constraints

As the intention of our design is to look and feel realistic, our project may be used as a tool for or against gun rights. With a large split in opinion towards gun control, our product could be pushed or seen as a tool for instigating violence, while others may see it as a tool for safe firearm training or even a mere toy. With how common toy guns and Airsoft rifles are, our product may be put into the same category. Regardless, the rifle itself cannot be used as a firearm, so these may be unneeded concerns.

No ethical concerns have been found with the project. Given proper safety instructions, warnings, and documentation, the product will not be able to be used to harm people unless intentionally used to do so. There are also few environmental concerns with our project. The end goal of the project is to improve over ballistic firearms by using lasers to reduce the amount of lead or plastic being released into the environment. In addition to the physical waste, guns also cause significant noise pollution. The only environmental impacts would be the production process. Electronics manufacturing may produce harmful waste such as lead solder that can negatively impact the environment or become a health hazard.

4.2.4 FCC Regulation - CFR 47 Part 15 - Radio Wave Constraints

The Code of Federal Regulations (CFR) has section 47 which concerns the topic of telecommunication, in this section there is subsection 15 which goes into the regulations of radio frequency devices. This subsection contains the regulations needed to be met for this project to be safe and legal for the wireless communication aspects. Our purpose of this project is to have a functioning prototype that will be compliant with FCC CFR47 Part 15 Subsection 23. Part B of subsection 23 states "It is recognized that the individual builder of home-built equipment may not possess the means to perform the measurements for determining compliance with the regulations. In this case, the builder is expected to employ good engineering practices to meet the specified technical standards to the greatest extent practicable." This provision will be discussed and kept in mind throughout the process of testing and experimenting of the final design. Part B of subsection 23 also states that all requirements in subsection 5 must be met. The key parts of subsection 5 that must be met are that this device must not produce harmful interference intentionally, unintentionally, or incidentally. The Laser Rifle must be able to be turned off if requested by a commission representative. **[3]**

Our devices aren’t capable of letting the user break violations of regulation. The design should not affect the environment or cause any air pollution. The design should use the lowest field strength that will not pollute the air space with unnecessary noise. The design should note that even if all compliances are met it is not possible to stop harmful interference under all circumstances. The communication of the device will not invade any person's privacy or record any person communication. The device created must be engineered to be as minimally harmful as possible. Still following the FCC rule, the warning label must be permanent and not easily removed. The user manual for the device must state that if the user modifies the device in any way that is not expressly approved by the party in charge of compliance to the regulations the user can lose authority to operate the device. **[3]**

4.2.5 Manufacturing Constraints

As our team consists of optical, electrical, and computer engineering students, our work in fields not related to our majors will not be significantly in-depth or polished. As many of our designs will rely on 3D printing, our designs may not be mechanically reliable or function as well as they could if a mechanical engineering student worked on these tasks. As a result, many of our mechanical designs would be considered amateur and we may rely on purchasing or using open source designs for 3D printed parts such as cooling fins for temperature control.

Additionally, some of the components we will use will be surface mount components that are difficult to mount onto PCBs by hand especially when considering the complexity of the PCB designs. Without the proper equipment, such as reflow soldering ovens, we may have to look into getting online manufacturers who can solder the components onto the

PCBs. Otherwise, we risk damaging valuable components that may have to be repurchased, further delaying testing.

4.2.6 Resource Constraints

As there are only four members in the group while also having other classes and responsibilities, there is a limit on how much time we can spend working on the project. This can be burdensome especially since our schedules may conflict and limit when members can meet to discuss and work on the project together. Sudden design changes or ordering replacement parts that unexpectedly break down may not be viable due to long shipping times or backorders, which is an important element as we will realistically only have a semester to work on making the prototype for our project.

Our finances are also limited. As we are aiming to stay under a one thousand dollar cost, our project may suffer from some performance issues due to substituting with cheaper parts, be it the construction of the project or the parts selected to use in the design itself. There are also a limited amount of free tools available to us as students of UCF. While the Senior Design labs have a good amount of equipment for testing and prototype construction, some equipment and programs needed may be unavailable unless we pay out of pocket. There are also physical space constraints. Since the rifle will be similar to real AR15 dimensions, there is a limited amount of space we have to work with, internally and externally.

5.0 Project Hardware and Software Design Details

This section discusses the various design elements contained within the laser rifle and target board systems. Split into hardware and software, this section contains details regarding electrical schematics, optical designs, and software developed for use in our project.

5.1 Hardware: Optical Designs

In this section, the various optical designs used in our project's systems will be described.

5.1.1 Beam Collimator

For our system, a beam collimator may be needed despite both IR and visible laser diodes having preinstalled collimator lenses. This is covered in more detail in the testing section, but the output from the IR diode can change optical properties depending on how high quality of a solder we make, so the laser diode output could potentially not be collimated. As a result, we will include information about a beam collimator if it is necessary. For the collimator lens, there are two main parameters that need to be considered. One is the focal length of the lens. For light acting like a point source, the physical size of the source plays a role in the output divergence angle when collimated. The divergence angle outputted by a collimator when placed a focal length away from the source is equivalent to the size of the source divided by the focal length of the collimating lens. As such, the larger the focal length and the smaller the source, the smaller the divergence angle of the collimated beam. In a typical laser diode, there would be concerns about the difference in divergence angle between the fast and slow axis, but for our project, this is not a concern. Not only do we not need a specific beam profile, we are using VCSEL diodes that emit highly circular beams where there is little to no astigmatism.

The second main factor is the diameter of the lens. Since the light source will be expanding in size as it travels to the collimating lens, the collimating lens needs to be physically large enough to capture all of the diverging light. This is directly related to the focal length since the lens needs to be placed a focal length away from the light source. In summary, a larger focal length collimating lens allows for a smaller collimated divergence angle, however, this means that the beam itself will become larger. As a result, there must be a balance between these two parameters. Fortunately, since we are using a beam expander that will yield a similar effect, there is room for freedom when it comes to the selection of this lens. Until more tests are performed to characterize the performance of the IR laser diode, the collimating lens will be added to the design if necessary. Based on our testing, the visible laser diodes will not require a separate collimating lens as the one preinstalled works as intended.

5.1.2 Beam Expander

As mentioned previously, the beam expander plays an important role. There are two main kinds of beam expanders: Keplerian and Galilean. In a Keplerian expander, two convex lenses are placed at a distance equal to the sum of their focal lengths. In a Galilean expander, a concave lens and convex lens are used instead. The difference between these two types of expanders is shown in **Figure X21**. Due to the use of concave lenses, Galilean expanders have several differences from Keplerian expanders. Since the beam never converges to a point, the beam outputted by the Galilean expander is not inverted like it is in a Keplerian expander. However, this feature does not matter for our project since the shape of the output beam is not of massive importance. The main feature is the compactness of the design. Since concave lenses have negative focal lengths and the distance between the two lenses is equal to the sum of the focal lengths for both types of beam expanders, Galilean expanders can be made to be much shorter than Keplerian designs. In our system where the amount of space is limited, this is an important design choice to take into consideration.

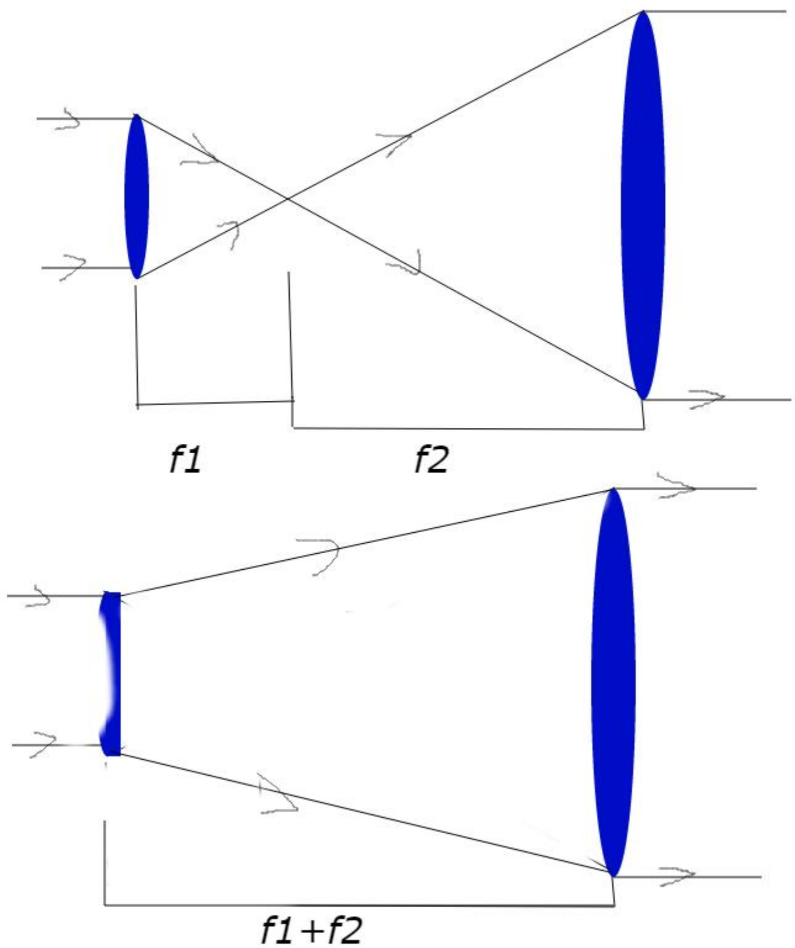


Figure X21. Keplerian and Galilean Beam Expander

Mathematically, beam expanders provide an effect similar to that of the collimating lens. The magnification ratio is equal to the focal length of the second lens divided by the focal length of the first lens. This means that for expanding a beam, a short focal length lens is used as the first lens while a longer focal length lens is used as the second lens. Additionally, the ratio between the divergence angle of the expanded beam to the input beam is equal to the focal length of the first lens divided by the focal length of the second lens. Regardless of what type of beam expander is used, these relationships are maintained in both systems. This means that, just like in the collimating lens, in order to have a smaller beam divergence, the beam must be expanded to a larger size.

In order to meet the divergence angle requirement, our beam expander will use a Galilean design with a 30mm focal length biconcave lens and 200mm focal length plano convex lens. This is equivalent to a 6.667x size magnification as well as a reduction in divergence angle by 85%. These lenses were selected based on the values provided in the datasheet for the IR diode, where the divergence angle was given as <10 mrad and the collimated beam diameter was given as 3mm. Depending on how close the beam expander is to the diode, after passing through the beam expander, this would result in an, at minimum, 20mm diameter beam with a 1.5 mrad divergence angle. At 15mm, this will grow into a

42.5mm diameter beam. This will be quite large, so we can implement an aperture to decrease beam size if necessary.

5.1.3 Target Board "Inherent Lens System"

For this system, there were many different designs that were considered. Ultimately, the goal for this system is to reduce the amount of receivers needed. Using an upscaled version of a microlens array was also considered, but due to the size of our target board, we found that making the surface of the board itself into a lens is significantly more cost-effective and more versatile for different types of designs. Initially, since we were considering using photodiodes at first, convex lenses are what we considered as a valid option. Since photodiodes require a substantial amount of optical power to produce noticeable current (which would later have to be amplified using an amplification circuit), a convex lens would solve two problems by focusing the laser light onto a smaller area, resulting in a need for less photodiodes spread out in an area, while also increasing the intensity of the beam.

However, this idea has its flaws. Since the lens is focusing the light, the angle and position where the light strikes the surface of the lens will affect the output spot position. This means that we will still need a quite large amount of photodiodes to cover the potential areas and angles where one could fire the laser at. Additionally, since we moved away from photodiodes and towards IR receivers that require very little optical power to output a digital signal, we moved towards concave lenses. Concave lenses will spread the incoming light to a much larger area, significantly reducing the amount of receivers needed at the cost of intensity. However, since the light needs to travel over a distance to become larger, and the distance between front surface of the target board and the receivers will only be 35mm, this could still require a moderate amount of receivers for the largest target areas. Ideally, we would only need one receiver per target area.

This is when we considered using a light diffuser combined with a concave lens. A light diffuser is a translucent object that works by scattering the incoming light and spreads it over a larger area. These are often used in LEDs to increase their viewing angle. Since PETG 3D printed objects are translucent without any post-processing, diffusers are very simple to make using a 3D printer. Fortunately, since our IR laser is quite powerful and IR receivers take extremely little optical power to activate, the laser beam that exits a diffuser and a concave lens will still be strong enough to activate the receiver. Essentially, the diffuser will expand the beam through scattering and then the concave lens will expand that light even further. In **Figure X5**, this idea was tested to see if it was a valid technique. The left image is using a diffuser (a simple 1mm thick 3D printed PETG disk with no post-processing) and the middle image is the spot produced by the -30mm EFL biconcave lens that will be used in the beam expander. In the right image, the diffuser is held very close to the front of the lens, and this combination clearly outputs a much larger beam than the two used separately. With the decrease in intensity and increased attenuation from passing through a translucent surface, optical noise will also be significantly decreased using this method.

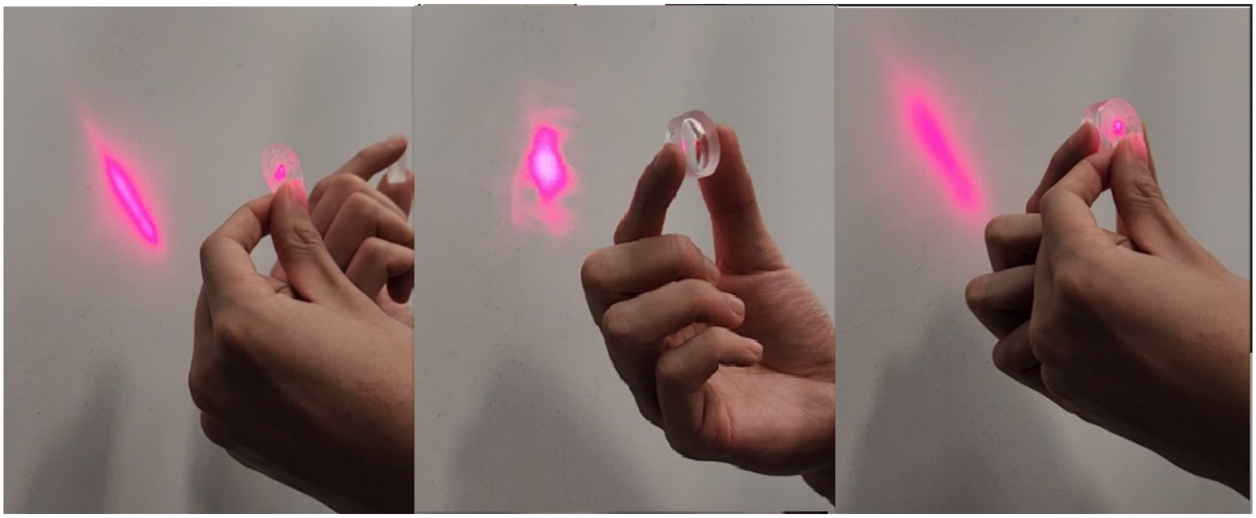


Figure X5. Diffuser+Concave Lens Proof of Concept

The lenses will be plano concave lenses with a radius of curvature that is 1.2x the radius of the lens. For a plano convex or plano concave lens, the focal length of the lens is double the radius of curvature. Ideally, the lenses would have a focal length as short as possible to increase the beam diameter as much as possible, but this means that the lenses would become very thick as the diameter of the lens increases, making for a much bulkier target board. Aside from the plano concave design choice, there is also the choice of doing a biconcave design to increase the power of the lens further, but this too would lead to a thick design that will also be very difficult to 3D print. This is due to the lens not having a flat base that lays flat on the hotbed of the 3D printer.

The reason we chose a radius of curvature that is proportional to the size of the lens rather than using one that is fixed (i.e. 50mm) is because we have a variety of lens sizes in the target board. For smaller lenses that only have a 12.7mm radius, having a 50mm radius of curvature would be wasteful since smaller lenses can have much shorter focal lengths without becoming extremely thick. In **Figure X513**, the 3D model design for the 50mm diameter lens used in our target board is shown. The radius of curvature is 1.2x the radius of the lens, so it has a 30mm radius of curvature with a total thickness of 18mm.

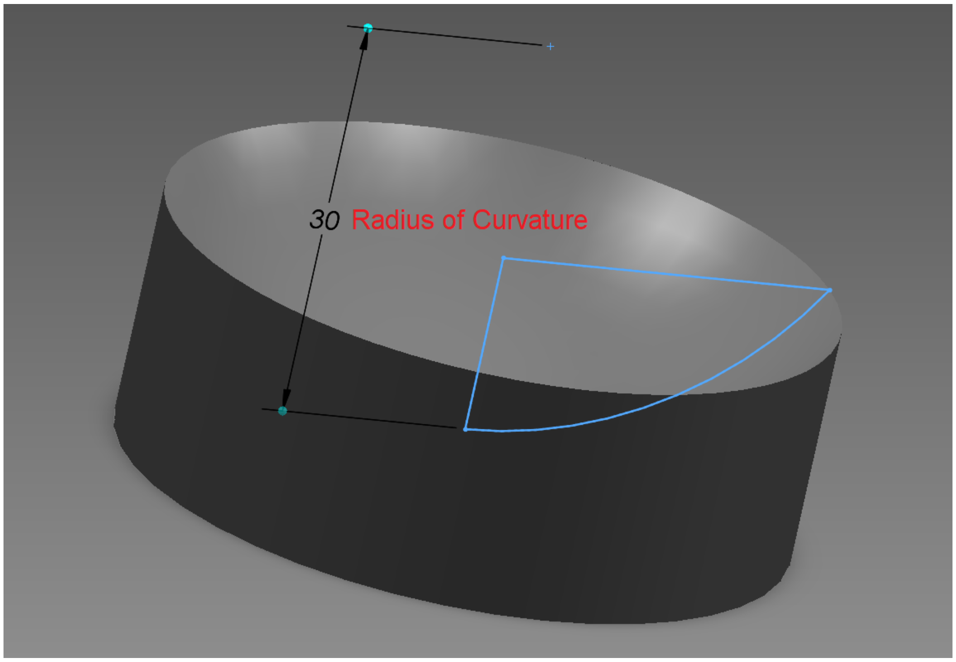


Figure X513. 50mm Plano Concave Lens 3D Model

We also provide a Zemax simulation for the same lens in **Figure X514** to understand how effective the lens is at expanding the beam in the 35mm space available. The lens was evaluated at a 940 nm wavelength and 0 degree field angle and at a 15m object distance. The refractive index of the lens was inputted at 1.57, as this is the refractive index of PETG. Since the rifle is being used at 15m away, both the angle of the beam relative to the surface of the lens as well as the divergence angle will be very small, so we did not think it was necessary to include non-zero field angles. From the ray diagram, a 32mm beam striking the center of the lens will double in size, expanding to a 65mm beam. With the inclusion of a diffusion plate, the output beam will become even larger. We provide images of our tests using this lens in the test section.

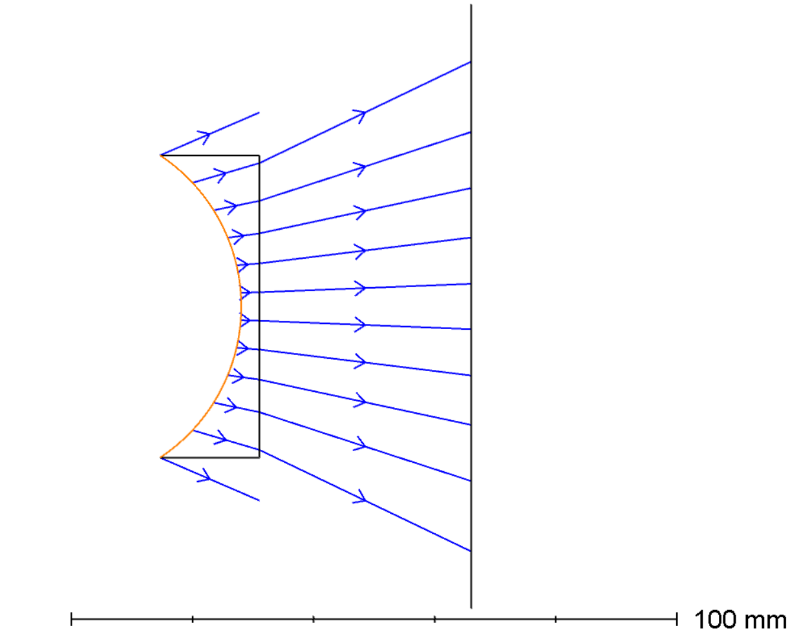


Figure X514. Zemax Simulation of PETG Lens

5.1.4 Variable Power Rifle Scope

In rifle scopes, there are many variables that need to be considered. A rifle scope is similar to a basic telescope design where it has an objective lens assembly and an ocular lens assembly where the image is output for viewing. However, rifle scopes also have an erector assembly that, since the image coming from the objective lens becomes inverted, is used to erect, or flip, the image back to its original orientation. The erector assembly is typically a telescoping lens tube that can move back and forward in variable power scope systems. The reticle can either be mounted in front or behind the erector lens assembly. An overview of a generic rifle scope can be found in **Figure X32**.

Regarding the reticle placement, there is a difference between being located at the first focal plane (FFP) and second focal plane (SFP). In an FFP scope, the reticle is located at the first focal plane, while it is located at the second focal plane in an SFP scope. The main difference between the two types relates to the magnification of the reticle image itself. In an FFP scope, the reticle grows in size as the magnification of the scope is increased. In an SFP scope, the reticle stays at a static size regardless of how the magnification is changed. For our project, we will use an FFP system so that parallax, described in more detail below, is easier to correct.

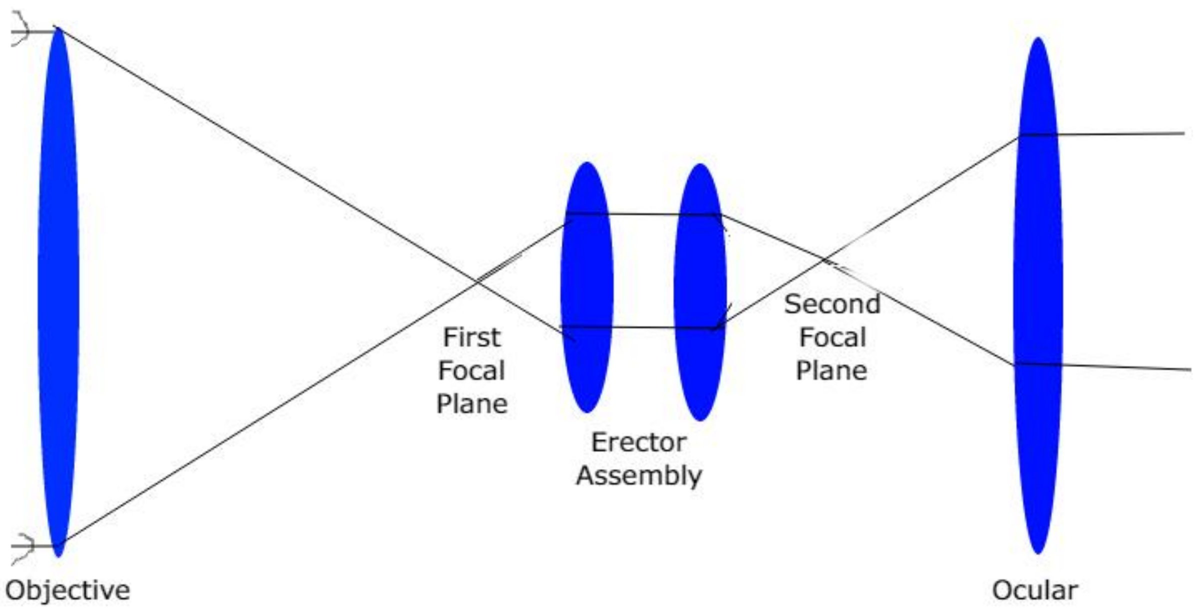


Figure X32. Generic Rifle Scope Lens Assembly

In rifle scopes, there is an optical effect called parallax. Parallax can be observed when the user looks through the scope at oblique angles. This effect is caused when the light coming through the system is not properly focused onto the reticle. In a scope, parallax manifests itself as a shifting of the reticle. When the user looks through the scope at different angles or positions, the reticle moves with the user’s head movements rather than staying at a fixed position. In **Figure X33**, this effect is illustrated. There are several ways to deal with parallax in scopes. The first method is to introduce an adjustable objective (AO) system. Essentially, a dial is installed onto the holder for the objective lens and when turned, the objective lens will move back and forward so that the focus can be moved back onto the reticle. Another method is using a side focus. A side focus introduces a new lens in between the first focal plane and the objective lens. A side focus dial is used to shift this lens back and forward for the same effect as an AO system. For our project, we will use a side focus system because the scope will be quite long, meaning that adjusting the position of the objective while holding the rifle will be difficult and uncomfortable for the user.

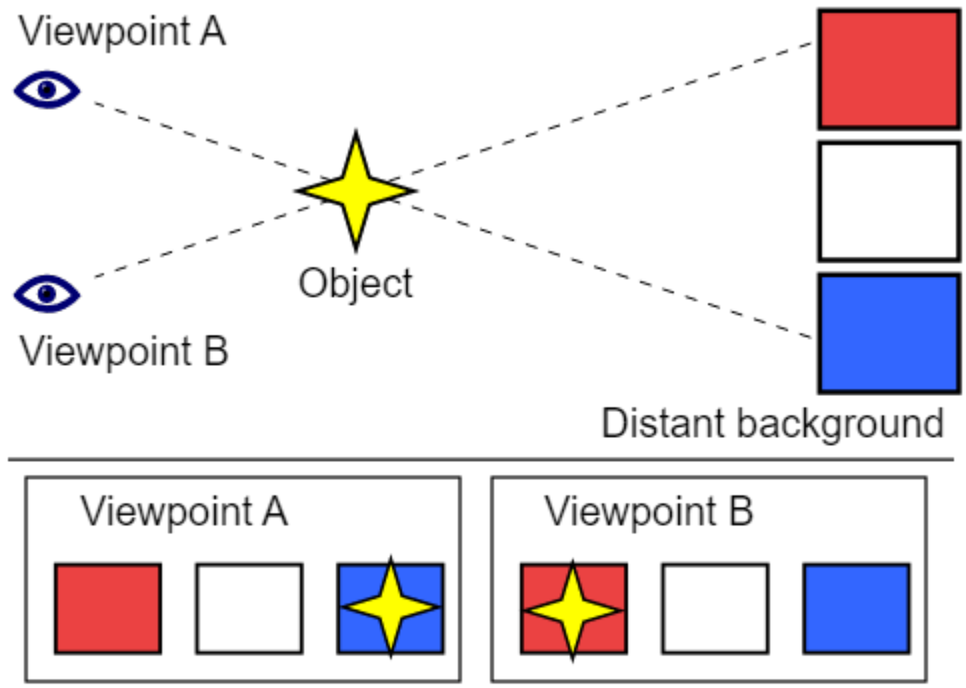


Figure X33. Parallax Error

For the lenses used, there are many system variables to be considered. Starting with the objective, this lens assembly must contain large diameter lenses with a longer effective focal length. The objective is the lens capturing all of the light, so it will need to have a large diameter for a higher resolution image. However, since many optical aberrations scale with the physical size of lenses and the length of the scope cannot be extremely long, some trade offs will need to be made. One example is increasing magnification at the cost of more aberrations and decreasing the diameter of the aperture stop to balance for these aberrations.

Regarding the image outputted by the scope, the parameters for the exit pupil are important. For most eyepieces used in optical systems, the exit pupil diameter is designed so that it is roughly the same size as the human eye. Exit pupil diameter is simply the entrance pupil diameter divided by the magnification of the system. The pupil of the human eye can change from 2mm to 8mm depending on the lighting conditions, with 2mm being in the brightest conditions and 8mm in dark conditions. The exit pupil diameter determines how bright the image will appear to the human eye. If the exit pupil is significantly larger than the pupil of the eye, then most of the light will not be captured by the eye's pupil due to its size. Therefore, when compared to a system where the exit pupil perfectly matches the pupil of the eye in diameter, the brightness will be perceived as the exact same. However, if the pupil of the eye is much larger than the exit pupil, then the image will be perceived as dark. We will design our exit pupil so that it is around 10mm in size. Although some light will be wasted, this is to increase the amount of leeway the user has when aiming. If the exit pupil is exactly the size of your pupil, then your eye has to be positioned exactly at the position of the exit pupil to get the brightest image possible, which is not realistic for a highly portable system like a rifle.

Additionally, there is also the eye relief, or the distance from the exit pupil to the ocular lens assembly. The image is best when the user's eye is located directly at the exit pupil. Naturally, the eye relief needs to be a realistic distance such that a user can easily use the scope without being too far or close to the lens. Binocular systems normally use around 15mm eye reliefs, but for rifle scopes, these are typically around 65mm to 100mm depending on the magnification. This is because rifles have recoil when firing and the impact can cause the scope to injure a user if the eye relief is too short. Aside from this, using a longer eye relief is useful because the eye relief will shift position as the magnification of the scope is changed. This also accounts for people wearing eyeglasses or safety goggles who cannot put their head too close to the lens. For our scope, we plan on using an eye relief around 75mm to follow this standard.

It is also important to note that the light emitted from the scope must be collimated. This is to reduce the eye strain on the user when looking through the scope for extended periods of time. Since the system is a variable magnification system that relies on the position of the erector lens assembly, the system will not always output collimated light for all magnifications. As such, we chose to optimize the system for a 4x maximum magnification where collimated light will be outputted.

For the lenses used, we chose to use stock lenses rather than custom lenses in order to keep costs low. The optical scope system consists of 6 total lenses which the data for is provided in **Table X34** below. **Figure X35** shows the layout of the entire scope system. The blue rays are at a field angle of 0 degrees, green at 1.5 degrees, and red at 2 degrees. The evaluated wavelengths included the F, d, and C lines (486 nm, 588 nm, and 656 nm respectively) as well as 860 nm. It is vital that we evaluate performance at 860 nm in the design process since the rifle will need to be used with the IR flashlight for night vision. The object of the system was set as 15m since this is the distance that the scope is planned to be used at.

	Surface Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Chip Zone	Mech Semi-D
0	OBJECT Standard		Infinity	1.500E+04			531.205	0.000	531.205
1	(aper) Standard	KPX201	116.712	5.797	BK7		25.400 U	0.000	25.400
2	(aper) Standard		Infinity	150.763 V			25.400 U	0.000	25.400
3	(aper) Standard	#45-895	180.400	3.200	N-BK7	EO_...	12.000 U	0.500	12.500
4	(aper) Standard		-180.4...	69.832 V		EO_...	12.000 U	0.500	12.500
5	(aper) Standard		89.358	1.500	SF8		9.000 U	0.000	9.000
6	(aper) Standard		22.470	4.460	SK11		9.000 U	0.000	9.000
7	(aper) Standard	PAC358	-32.160	81.368 V			9.000 U	0.000	9.000
8	STOP Standard		Infinity	0.000 V			8.500 U	0.000	8.500
9	(aper) Standard	PAC358	32.160	4.460	SK11		9.000 U	0.000	9.000
10	(aper) Standard		-22.470	1.500	SF8		9.000 U	0.000	9.000
11	(aper) Standard		-89.358	124.351 V			9.000 U	0.000	9.000
12	(aper) Standard	#45-892	103.000	4.000	N-BK7	EO_...	12.000 U	0.500	12.500
13	(aper) Standard		-103.0...	9.508 V		EO_...	12.000 U	0.500	12.500
14	(aper) Standard		Infinity	4.800	BK7		12.700 U	0.000	12.700
15	(aper) Standard	KPX591	-45.803	0.000			12.700 U	0.000	12.700
16	Standard		Infinity	0.000			15.043	0.000	15.043
17	IMAGE Standard		Infinity	-			15.043	0.000	15.043

Table X34. Optical Scope Lens Data

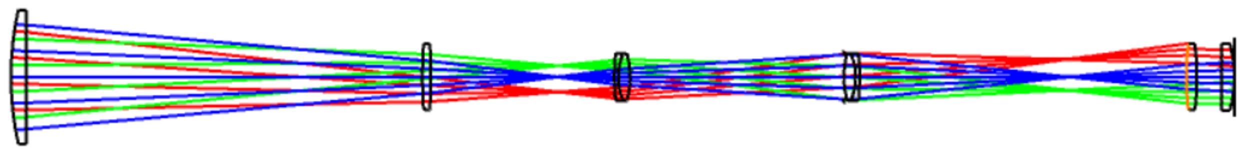


Figure X35. Optical Scope Lens Layout

The objective lens, Newport KPX201 ($60), is a 50.8mm diameter uncoated plano convex lens. Using a large aperture for the objective captures more light, allowing for a higher quality picture. Plano convex lenses are well suited for objective lenses and eyepieces used in infinite conjugate systems because they lead to less spherical aberration compared to biconvex lenses of the same focal length. The second lens is the Edmund Optics #45-895 ($49), a biconvex lens that is used as the side focus lens for parallax correction. This lens has a 25.4mm diameter and is coated with Edmund Optic's VIS-NIR coating, a visible and near infrared visible AR coating that reflects less than 1.25% of light from 400-1000 nm.

The lenses making up the erector assembly are two Newport PAC358 ($90) 18mm diameter double achromats. The doublet achromats work to correct some of the spherical aberration and chromatic aberration in the system. The aperture stop of the system is located at the front surface of the second achromat. Due to the physical size of the achromats, the amount of light exiting the system is limited, but this also plays an important role by significantly reducing the amount of optical aberrations. These lenses are coated with single layer MgF_2 anti reflection coatings that reduce reflections from 400-700 nm such that reflections are, on average, less than 1.5%.

Finally, the ocular lens assembly consists of the Edmund Optics #45-892 ($49) biconvex lens followed by the Newport KPX591-C ($27) plano convex lens which are coated with VIS-NIR and MgF_2 AR coatings respectively. The ocular lens assembly is important for characterizing the exit pupil of the system as well as the output magnification. Just like the objective lens, a plano convex lens was selected as the ocular lens since it decreases spherical aberration used for an infinite conjugate. The biconvex lens is used to increase the magnification and adjust the position of the exit pupil. By using two lenses instead of a single plano convex lens with an equivalent focal length, the amount of curvature is split across the lenses, reducing aberrations at the cost of some light transmission loss. Overall, when combining all of the lenses in the system, the total amount of light transmission is calculated to be around 80% for 650 nm light with 860 nm light being near 75%.

The specifications for the previously discussed design parameters are listed in **Table X36** below. First, the EFFL, or effective focal length, of the system is over 100m, meaning that the system emits collimated light. TTHI is the total thickness of the system, meaning that the entire system will need to be housed in a scope that is at least 465mm long. For a rifle scope, this is quite long, but not unrealistic. The reason why we chose such a long design, which can be attributed to the relatively long focal length of the objective, is to decrease the overall amount of aberrations in the system.

The values for the various aberrations such as spherical aberration, coma, astigmatism, distortion, and axial chromatic aberration are listed below in the table while a chart showing the aberrations at each surface can be found in **Figure X37**. Note that the chromatic aberration of the system is quite high. This is because we included 860 nm as one of the evaluated wavelengths rather than using the standard RGB wavelengths. Correcting the large spherical and chromatic aberration in the system while keeping other aberrations low would require the use of more complex and costly lenses such as achromats for the objective and eyepiece. EXPD and EXPP are the exit pupil diameter and position respectively. The parameters for the exit pupil are very good and are ideal for use in a rifle scope as described earlier. Finally, AMAG is the angular magnification of the system and is listed for a 4x zoom. Since the magnification is adjustable, the exit pupil diameter and position will decrease as the magnification is increased and vice versa. It is also important to note the position of the first lens in the erector lens assembly (Surface 5) from **Figure X35**. This is very close to the first focal plane, which will be the position of our reticle used for aiming. This means that the angular magnification will essentially be maxed out at 4x, and the erector lens assembly can only move towards the eyepiece, which will reduce the magnification.

Future design iterations will include an achromat for the objective lens. We will also use a Kellner eyepiece, which contains a plano convex lens and achromat. Both of these elements will work to correct the spherical and chromatic aberration in the system. With these components, we can also decrease the total length of the system.

Type	Surf	Wave							Target	Weight	Value
EFFL		2							5000.000	0.000	1.095E+05
TTHI	1	15							0.000	0.000	465.538
SPHA	0	2							0.000	0.100	20.918
ASTI	0	2							0.000	0.000	19.518
COMA	0	2							0.000	0.000	1.789
DIST	0	2	0						0.000	0.000	6.025
EXPD									10.000	1.000E-02	10.098
EXPP									0.000	1.000E-02	73.521
AXCL	1	4	0.000						0.000	0.000	-2.753
AMAG		2							4.000	-10.000	4.007

Table X36. Optical Scope Merit Function Parameters

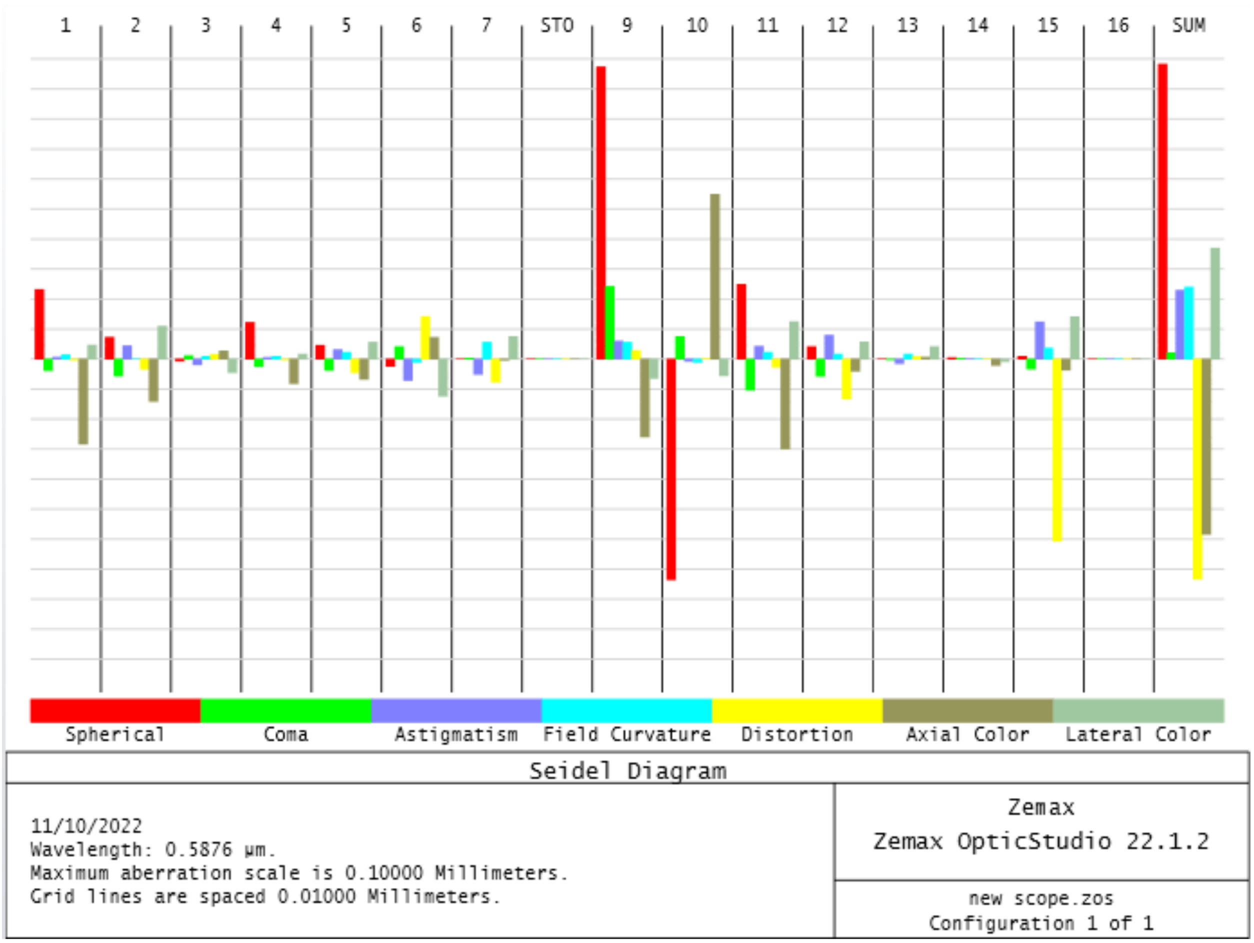


Figure X37. Optical Scope Aberration Chart

5.1.5 CMOS Camera Lens System

5.1.6 Variable Focus IR Flashlight

Given the extremely small viewing angle of the 860 nm LEDs, the design for the IR flashlight has a lot of freedom for design. The main goal of the flashlight is to be able to control the focus of the light such that it is a desired size and angle. We will discuss the various design parameters surrounding the flashlight. Since it is a flashlight, the most obvious design parameter is the light transmission. We need light transmission as maximized as possible for 860 nm light, meaning we will need to minimize the amount of lenses in the systems while selecting lenses with near IR antireflection coatings to maximize transmission. Another parameter is the position of the LEDs. Depending on the type of lens system used, the position of the LEDs will significantly alter the size and angle of the output light. However, we have decided to fix the position of the LEDs at a 30mm distance away from the first lens. This is a decision we made when considering the construction of the housing for the flashlight rather than an optics design decision, so the optics design will be designed under this constraint. Finally, the main parameters we focused on in our design were the focusing sensitivity and compactness of the flashlight. We define the focusing sensitivity as the change in divergence angle of the output beam in relation to the amount of distance a lens moves to adjust the focus. For a system with large focusing sensitivity, the divergence of the output beam will rapidly change with slight adjustments to the lens. Greater focusing sensitivity leads to more compact lenses at the cost of less precision when adjusting the lens.

For our design, we will use a concave lens to expand the LED light and then focus that light using a convex lens for an efficient and compact design. In this system, we will keep the concave lens fixed and move the convex lens to change the focus. The focusing sensitivity of the system increases with the power of each lens, so we needed to pick a combination of lenses that would balance between compactness and precise selection of beam spread when moving the convex lens. In terms of numbers, we wanted the convex lens to move at most 20mm for a 5 degree change in full divergence angle with the total axial length of the system to be less than 75mm.

For the lens selection, we chose the Edmund Optics #45-932 ($55) 25.4mm biconvex lens with VIS-NIR coating (0.4% reflectivity at 860 nm) and the Newport KPX184AR.16 ($93) 50.8mm plano convex lens which has 0.3% reflectivity at 860 nm. We simulated the lens system in Zemax and evaluated it at a 860 nm wavelength. We set the angle of the rays emitted from the object to 10 degrees to simulate the viewing angle of the LEDs. The positions of the fields were at 0mm and 5mm relative to the center of the concave lens. This is because the diameter of the LEDs are 5mm each, and we plan on using multiple LEDs when we actually construct the flashlight. **Figure X516** shows the lens layout when the output beam has a 5 degree divergence angle**.**

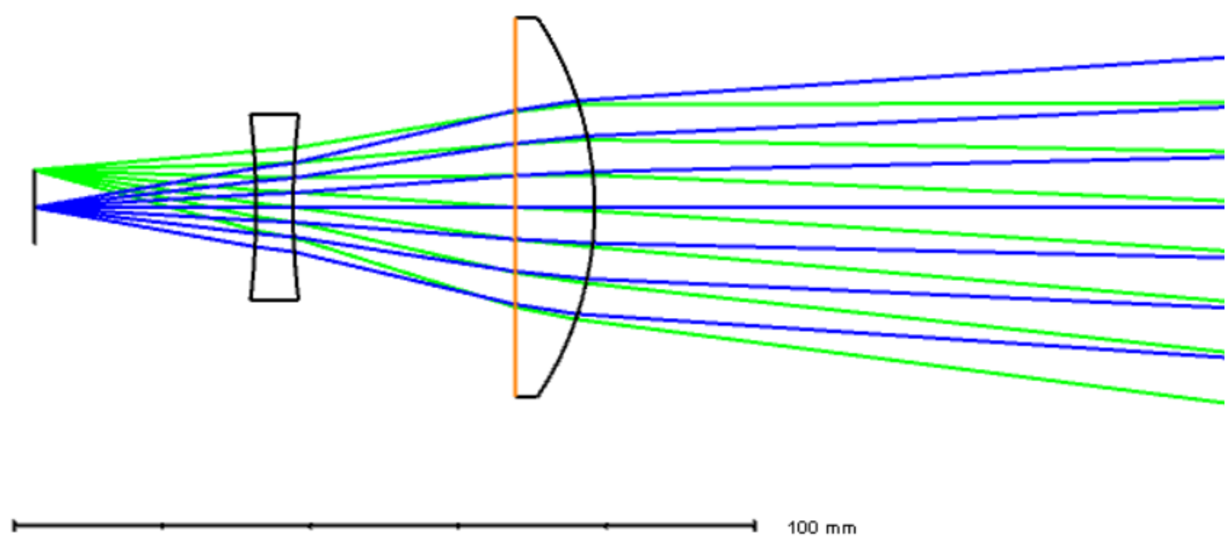


Figure X516. IR Flashlight Lens Layout

In this design, the convex lens moves a total of 15mm away from the concave lens to change from a 5-degree divergence angle to outputting a collimated beam. The total axial length of the system is 68mm. This makes for a highly compact lens system that can allow for precise adjustments.

5.1.7 Stretch Designs: Safety Camera and Other Rifle Optics

In this section, we discuss the optical design elements that we consider as stretch goals. The main two stretch goals for the optical design include the human detection camera and a lower magnification optical sight such as a reflex sight.

First, there is the human detection camera. Since there is a chance that we may not implement this system into the final design, we will briefly describe what kind of design will be necessary for this camera. Generally, in terms of optical design, the design would be very similar to that of the night vision CMOS camera, especially if a camera with lenses preinstalled was used rather than a raw CMOS sensor. We will discuss the case of a raw CMOS sensor since the explanation would be essentially the same as the night vision CMOS section.

For our camera, we would want a low field of view at around 20 degrees to increase depth of field for a clearer image at a variety of distances away, which is important since the algorithm would need to recognize a person's facial features whether they are standing close or far away. The main parameters affecting field of view are the sensor size and the focal length of the lens being used. With larger focal lengths, the field of view decreases and vice versa. On the other hand, as the sensor size increases, the FOV also increases. This relationship is shown in **Figure X517.** If we assume that we would use a standard 1/3 inch CMOS sensor, then for a 20 degree vertical FOV, a lens of focal length 4.945 mm would have to be used. More complex lens systems can be made such that combinations of lenses produce the same FOV while correcting system aberrations, but this will not be delved into further.

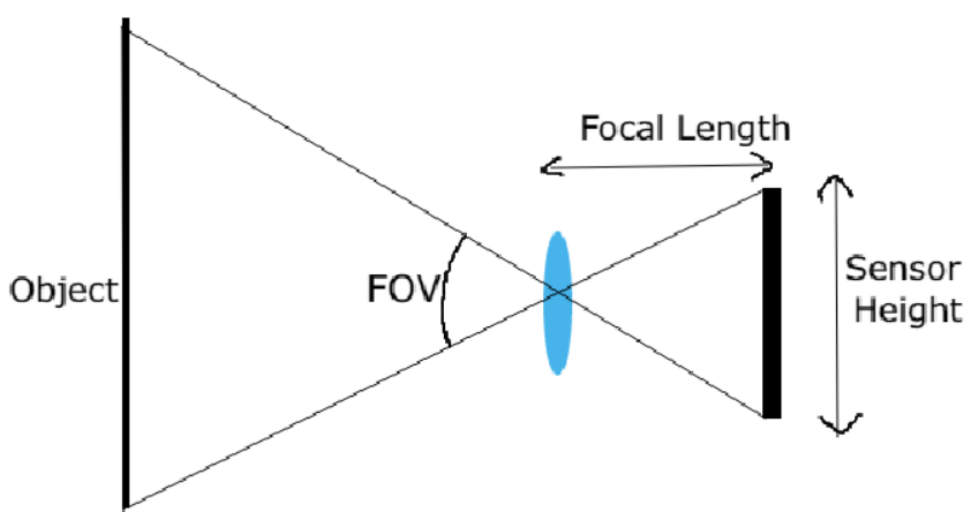


Figure X517. Sensor Field of View Visualization

The other main stretch goal is to include a low power optic sight for the laser rifle. Compared to holographic sights, which require the use of holographic gratings and laser diodes, reflex sights are quite simple to make, although the materials needed to make them are hard to acquire and expensive. Mentioned earlier in the rifle optics section, parallax is the main issue that reflex sights are used to correct. Without parallax correction, the reticle of the sight will move as the user moves their head, which means that the reflex sight is about as effective as a dot painted onto a piece of glass. There are a variety of ways to make reflex sights, but the most common design uses a half-silvered curved mirror and a point source such as an LED illuminating some form of reticle. In the case of red dot sights, the LED or an aperture in front of the LED is the reticle. We consider this a stretch goal because finding a half-silvered concave mirror that is of a suitable focal length and size is difficult and expensive, but we have managed to purchase one for use in our project. In **Figure X518,** a ray diagram of a reflex sight is shown. The LED is placed at the focal length of the curved mirror so that the light reflecting back to the user is collimated. The user's eye focuses the collimated light of the reticle, allowing the reticle to be seen when looking through the mirror.

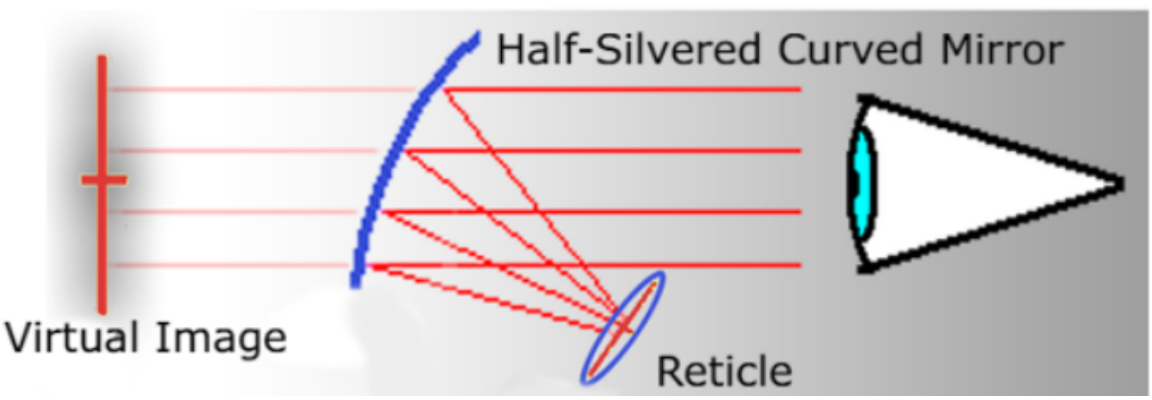


Figure X518. Reflex Sight Diagram

The half-silvered concave mirror we will use is a 103 mm focal length with a 62.5 mm diameter. The mirror works like a 90:10 beam splitter with 10% of the light being reflected. As stated previously, the design for this reflex sight is quite simple and is essentially a collimation task. Most of the design will be through the construction of the sight itself rather than optics used in it. The Solidworks 3D model used in the design will be shown and discussed further in the Prototype Construction section.

5.2 Hardware: Electrical Designs

In this section, the various electrical designs such as schematics will be provided. In **Figure X8**, a block diagram maps out the interactions between the various hardware components that will be used in our project design and who is responsible for each component.

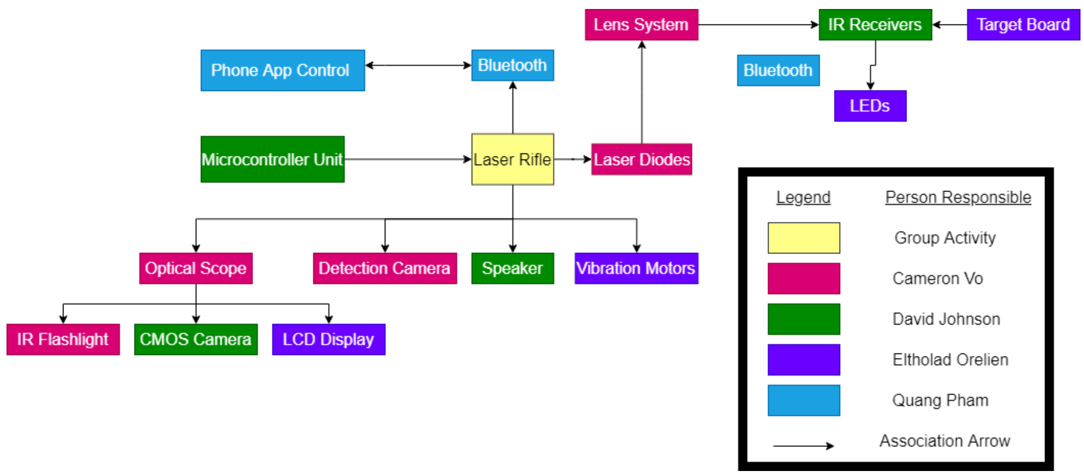


Figure X8. Hardware Block Diagram

For a better understanding of what our system will look like in action, we have come up with the **Figure X111** below. This is a block diagram that demonstrates our fundamental hardware system and how each component interacts with one another on a more intuitive level. This is simpler than the final design approach completes with all system components, but this shows the primary concept that will help our team design as well as guide our design iterations later.

When the “Trigger” button is being pressed, it sends a signal to the Laser Rifle microcontroller unit that will send the instruction to the Transmitter. The Transmitter will then send a serial signal to the IR Laser diode that will cause the diode to emit modulated light defined by the signal. The Sensor will capture the light from the diode and send that data to the Receiver (the Sensor and Receiver are both integrated into the IR receiver). The Receiver will accept the data and send the acknowledgement data being represented as a Serial Signal to the Target Board microcontroller unit.

Our software is represented as the mobile app communicating with both microcontroller units through Bluetooth. The wireless communication is done through the onboard antenna of each microcontroller.

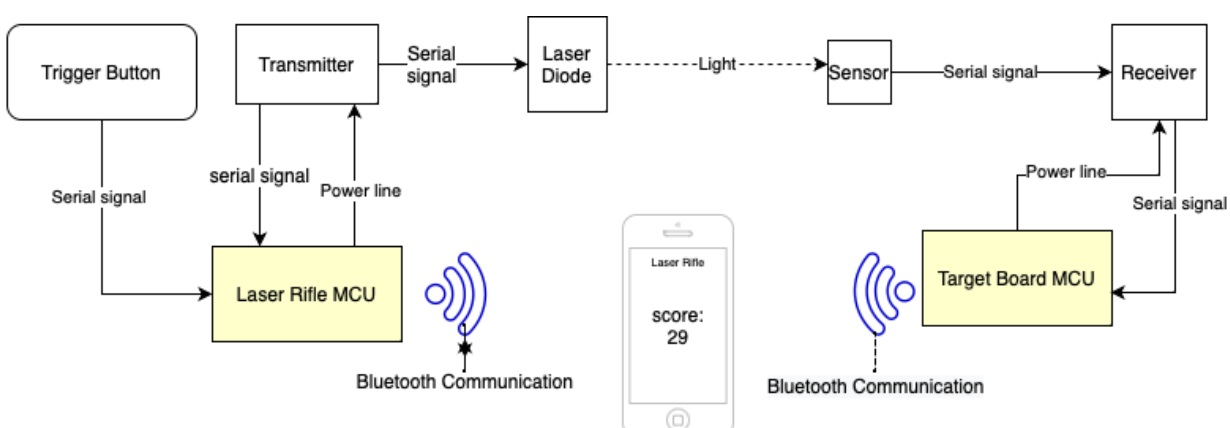


Figure X111. Prototype Operations Block Diagram

5.2.1 Audio System

In order to have sufficient audio output that would signify pulling the trigger to the laser rifle it was necessary to not just have a speaker but also a system that could be controlled by the MCU and output a firing noise. We ended up choosing the MAX98357A as the in between for our speakers and ESP32. In order to test the audio amplifier, we purchased the MAX98357A Audio Breakout board from Sparkfun. Although it was our intent to significantly test this audio system before committing to including it in our design, there have been unfortunate delays in shipping. One significant reasoning towards choosing this component from Sparkfun is that not only do they provide a more than adequate method of testing the chip but also, we figure that we save space on our board by only integrating the necessary portion of the test board for our overall PCB design. Doing so would allow us to save space on our PCB thus lowering our overall footprint.

When looking to create the schematic design through our selected choice of PCB designer, Altium, the construction required no effort due to Sparkfun providing an easy to download and utilize schematic file for Eagle. Currently **Figure X** below is an Eagle schematic but the plan is to use the Import Wizard feature on Altium to import this schematic and edit it as needed. As previously stated, we would like to only include the necessary portion of the test board to our overall system. One feature that will be struck from our design is the option to select an audio channel. This system allows you to select between the left and right audio channel, allowing you to drive two separate speakers if needed. This speaker selection option is made possible through 2 jumpers on the board. Since we only plan on using a single speaker to output for the laser rifle, neither jumpers would be necessary. The speaker selection feature is made as a separate piece of the schematic and was not included in the figure below. Also, the Sparkfun schematic includes a pin header placement design that was removed since the connections from our circuit will be contained within our PCB.

Figure X9 displays what our ideal audio amplifier circuit and connector that goes to the speaker will resemble. The MAX98357A IC chip listed below is the audio amplifier that was mentioned from the Parts selection section. The chip includes 9 pins VDD, DIN, BCLK, LRCLK, SD_MODE, GAIN, GND AND the output pins. Its input voltage pin is VDD which will be connected to a 3V3 supply bus. As per the data sheet this should sufficiently power the chip. There is a ground pin which will be connected to the 3V3 bus ground as well. The GAIN pin is used to set the gain in decibels of the amplifier depending on its configuration. According to the datasheet, when the pin is not connected to anything the default gain is +9dB which should be more than enough output for the user. So, we will likely leave this pin unconnected unless we decide later that we want a larger decibel output. The SD-MODE pin is meant to be the shutdown and channel select pin for the amplifier. The datasheet states that the pin can be pulled high to select the left channel, pull-up using a small resistor to select the right channel, pulled low to place the device in shutdown, and or pull-up using a very large resistor to combine both channels into a single channel and drive a single speaker. Our design only includes the use of one speaker, so the optimal choice was to include a large resistor and combine both channels. In **Figure**

X9 a 1MΩ resistor is connected to the 3V3 bus to control this pin. The DIN is the digital input pin, and the LRCLK and BCLK pins are both clock inputs. These 3 pins will be connected to the ESP32, so they are currently left unconnected. The OUT plus and minus pins are connected to a 2-pin terminal block which will then connect to the speaker.

As stated in the hardware test plan, once the MAX98357A breakout board is delivered this system will be tested on a breadboard to check if it is all viable.

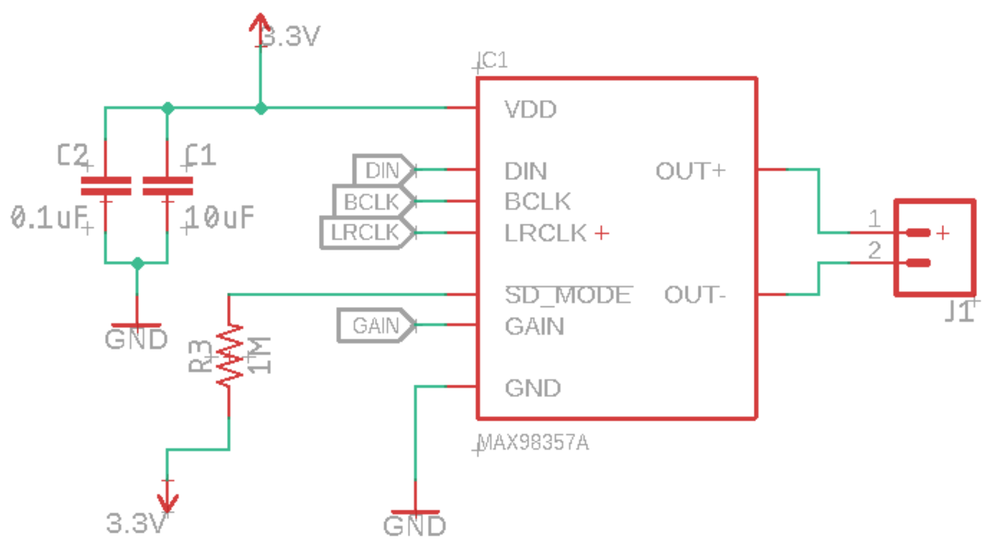


Figure X9. Audio Amplifier and Speaker Connector

5.2.2 LED Driver Circuit

Typical LED driver circuits consist of an NPN 2N2222 transistor, a switch, LED(s), a battery or power supply, resistors, capacitors, and in our case, we added a fuse as an extra precaution **[16]**. An LED driver is used to regulate current drawn from the LED. The current that runs through the LED is sensitive to slight changes in the voltage within the LED. A LED driver is a critical component so that the LED doesn't continue to draw current resulting in the LED burning itself out. The LED driver we use will match the electrical specifications of the LEDs we are using. This will help the LED compensate for any changes in voltage while keeping a constant current within the LED. After testing and prototyping the LED, we are looking at, we will take note of the LED specifications and choose the appropriate drive currents to prevent the LED from burning out and causing excess amounts of heat. To determine how many LED we can use with one driver, we will need the formula $\frac{V_0\ Max\ (of\ the\ driver)}{LED(s)\ Voltage}$. We must also determine the power, to do this we use the minimum and maximum input voltages for the LED drivers. Our input voltages are equal to the maximum output voltage for the driver we are using. For finding the input voltage we have the formula $V_0 + (V_f\ x\ LED) = V_{in}$. In the formula for the input voltage V_0 represents the overhead voltage for the driver being used (usually 2 Volts), V_f represents the forward voltage of the LED(s) being used, LED is just the number of LED(s) being used, and V_{in} represents the input voltage of the driver. Using this formula, we can determine the minimum input voltage needed for the LED driver. To ensure the input voltage is appropriate we can also find the wattage of the LED circuit we are using. For the LED wattage we will use the formula $V_f\ x\ current = The\ total\ wattage\ for\ the\ circuit$. To ensure the circuit has an ample amount of power, it's a good idea to use a higher wattage than what was calculated by approximately 15% - 20%. For example, for a 20 W total for the circuit, it would be safer to choose a 24 W power supply to prevent the power supply from being overworked **[17]**.

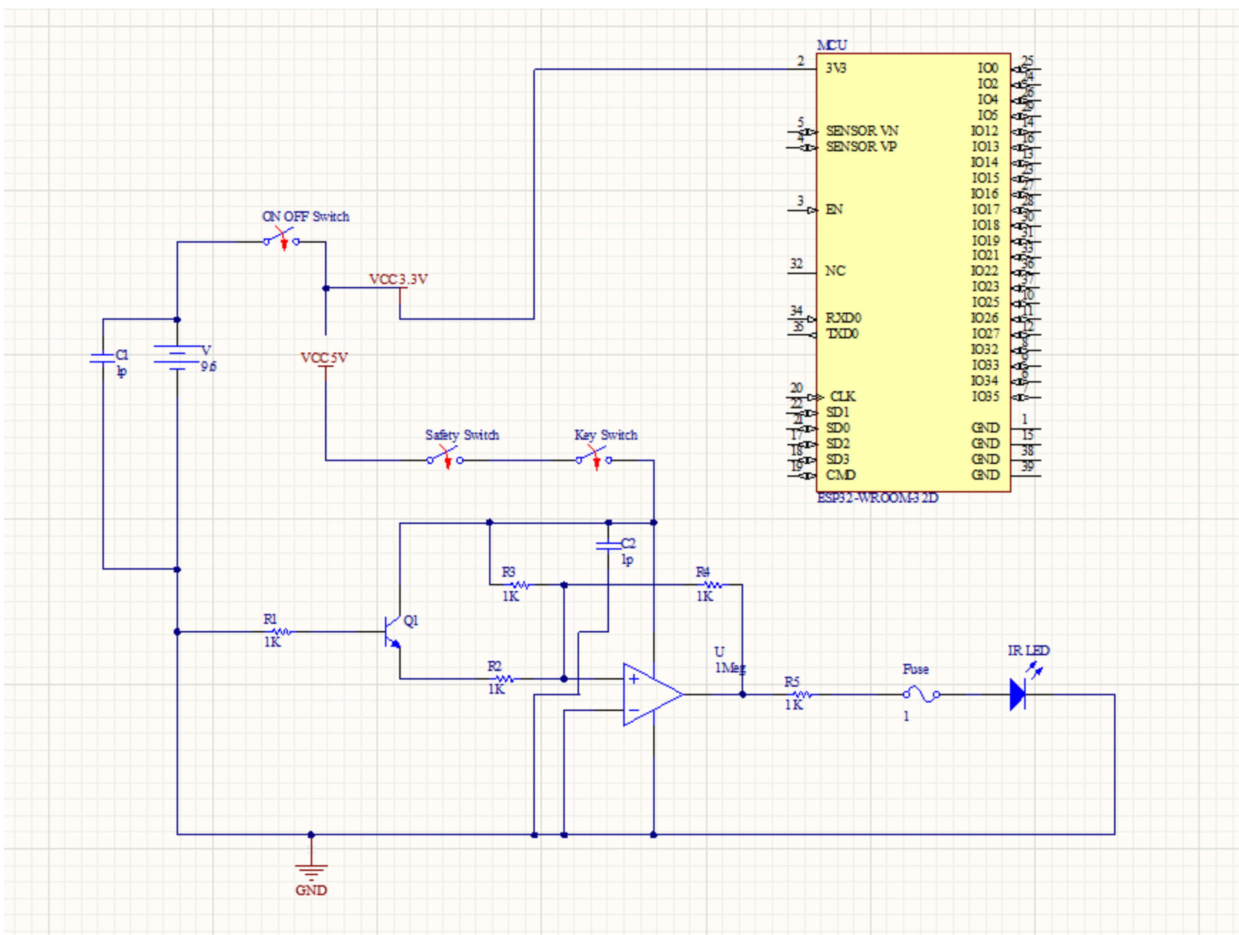


Figure X10. LED Driver Circuit

5.2.3 Vibration Motor Circuit

5.2.4 Target Board IR Receiver Circuit

The IR receiver is just a receiver module for infrared remote-control systems. It is made to receive long burst codes which are essentially just the IR signals that we will be sending using the IR diode. Since the purpose of the sensor is to read the IR signal once the rifle trigger is pulled and the laser diode emits it should always be in a powered-on state once the Target board is powered on. The IR receiver module chosen, the TSOP986, is a 3 pin through hole component so for the footprint we used a 3-pin header. We were unable to find a footprint that corresponded to this component so for the time will be using this header. It is important to keep the design of this footprint simple because currently the enclosure for the target system is still under consideration. However, we have decided that there will be multiple sensors on the board corresponding to the different target areas on the board. **Figure 1** in the Objectives section goes into more detail behind the concept. The receivers themselves only require small amounts of current (0.45mA) and consume a small amount of power (10mW) at a maximum. The overall idea is that the IR receiver module will be excited by a 38kHz signal from the IR diode. Once the IR sensor detects this beam it will output a signal to the MCU which will then complete any task such as lighting the LED indicators around the affected sensor.

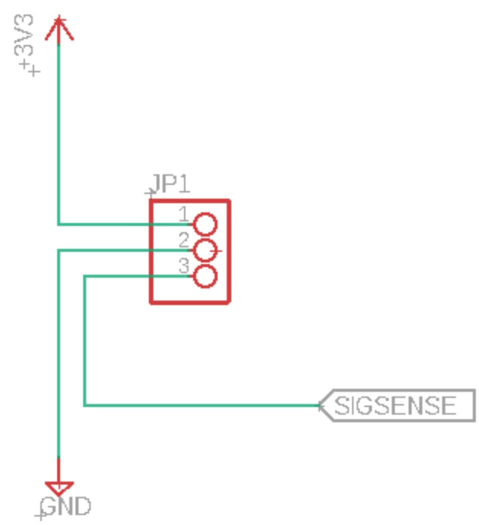


Figure X11. IR Receiver Schematics

We are still currently testing the range capabilities of this design and the reaction speed of this system.

5.2.5 IR Flashlight Circuit

In our project we are using an LCD display as an alternative option for target visibility. The IR flashlight will be used to complement the LCD display we are using to essentially act as a night vision system. We are using the LCD display along with the IR flashlight to further the realism of our laser gun. The addition of the IR flashlight will allow the user to see their target better in dark and or poor lighting conditions. Using IR LEDs allows for good sensitivity without being easily affected by any ambient light. IR LEDs are a great option that allow for low power consumption and are relatively inexpensive **[18]**.

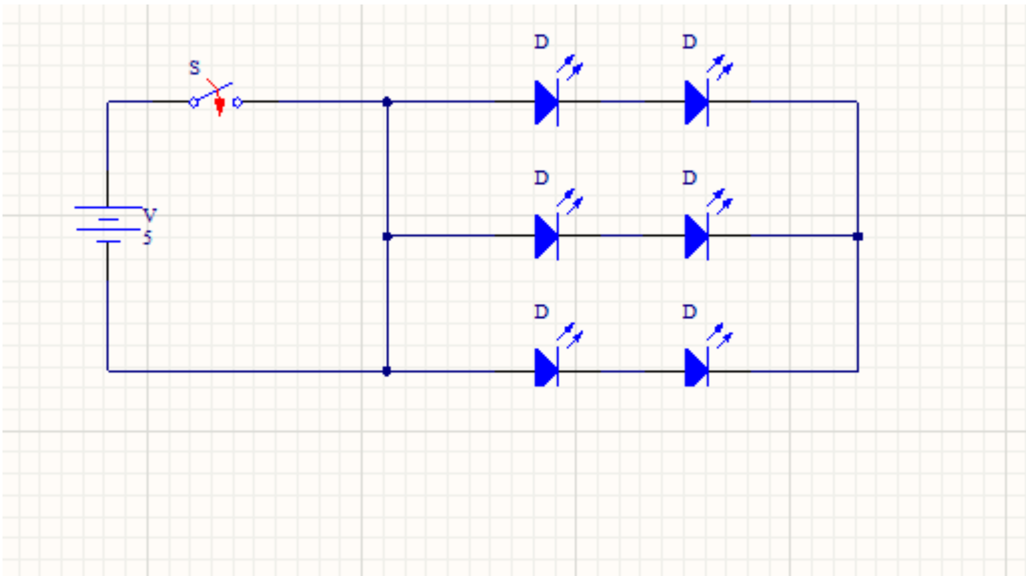


Figure X11. IR Flashlight Circuit

5.2.6 Power Design

The devices that will be receiving power are the laser rifle and the laser target. This section's purpose is to identify the flow of the power systems for each device and the possible monitoring method to assure proper operation. Both the Laser rifle and laser target will be receiving power from internal 9.6V rechargeable batteries in order to keep the design simple. Both will also provide current to the microcontrollers and peripheral devices attached to them. The sources will need to be regulated and adjusted to better fit the PCB and meet requirements. The 9.6V supply is selected not only for high potential and peripheral power delivery but also the recharging capabilities will allow for longevity and cost savings. However the 9.6V will need to be regulated down.

It is ideal to provide a longer lasting device system therefore we looked towards overshooting some of the power capabilities as much as possible. The general scope of overall efficiency will be lowered but this will be helpful for peripherals and stretch goals.

It is necessary to understand which components of the system require which voltages in order to operate correctly.

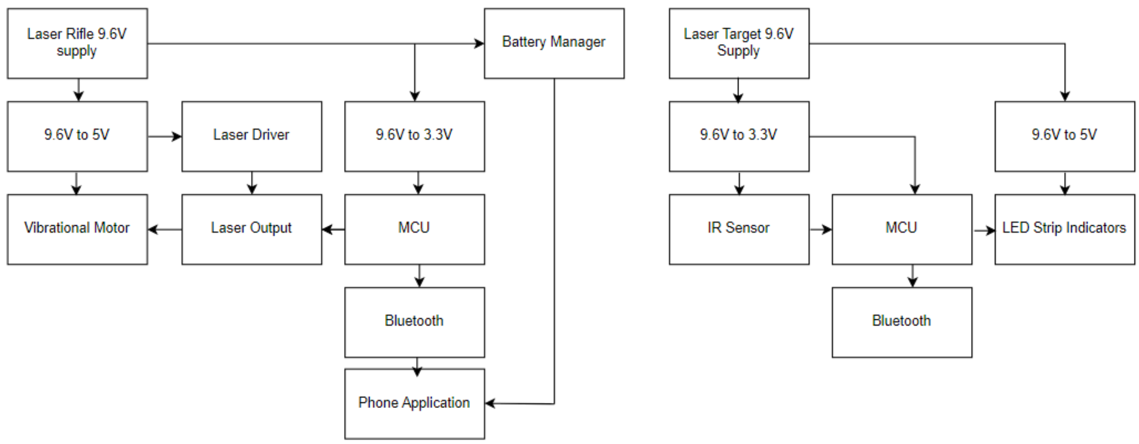
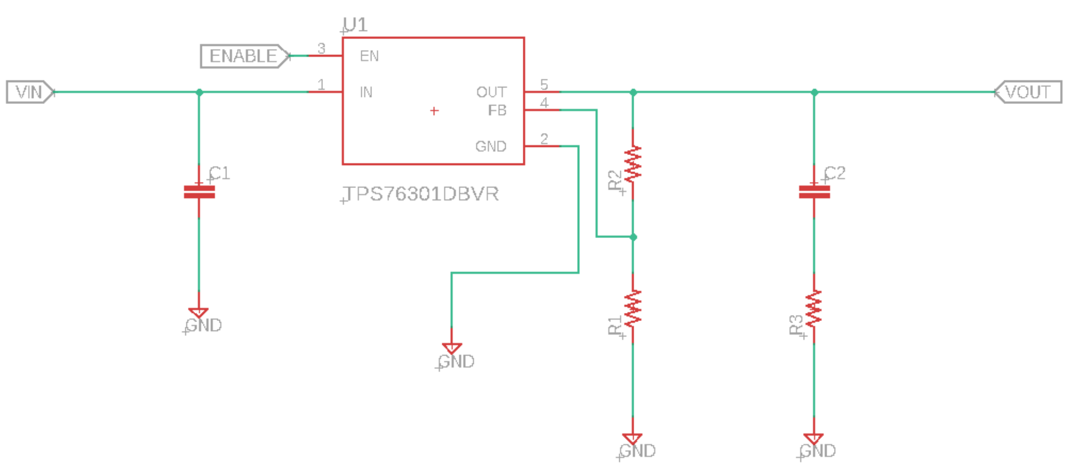


Figure X. Power System Design Rifle and Battery

In order to reduce the 9.6V battery supply to stable DC voltages of 3.3V and 5V it was necessary to use a voltage buck regulator. That is why we choose the TPS76xx regulators to do such a task. It is our opinion that using 2 of these fixed regulators would make the PCB design fairly simple. According to the data sheet, the difference between obtaining a 5V regulated voltage and a 3.3V regulated voltage is simply making minor adjustments to the voltage divider of R1 and R2. The output of the TPS6301 adjustable regulator is programmed using an external resistor divider where the output is calculated using $Vo = 0.995\ x\ Vref\ x\ (1 + \frac{R1}{R2})$. As per recommendation of TI the R2 value will be set to 169k ohm while the R1 resistor will be varied. To provide the 5V regulated voltage we are going to set R1 to 549k ohm and to provide 3.3V it will be set to 301k ohm. These values have not been included on the schematic currently because they will need to be simulated and tested first. Also the capacitor values can vary based on the material used so those must be tested as well.



5.3 Software

In this section, we introduce a companion mobile app to operate the laser rifle and the laser target. The section will dive into low-level details, about this app, and design decisions in addition with multiple interfaces of the software. We will also describe the constraints that come along the way that become our limiting factor so that the programming can be more approachable and easily develop.

5.3.1 Software Overview

The app will pair with the Laser Rifle and the Target device using the Bluetooth technology. It can configure the recoil actuator of the rifle, track the ammo count of the rifle, configure and modify the firing mode in any way a user desires. Users can start a game on the app and the scoring can be viewed by connecting the app to our Target device. Below in **Figure XX9** are the block diagram for the phone app design and its functionalities.

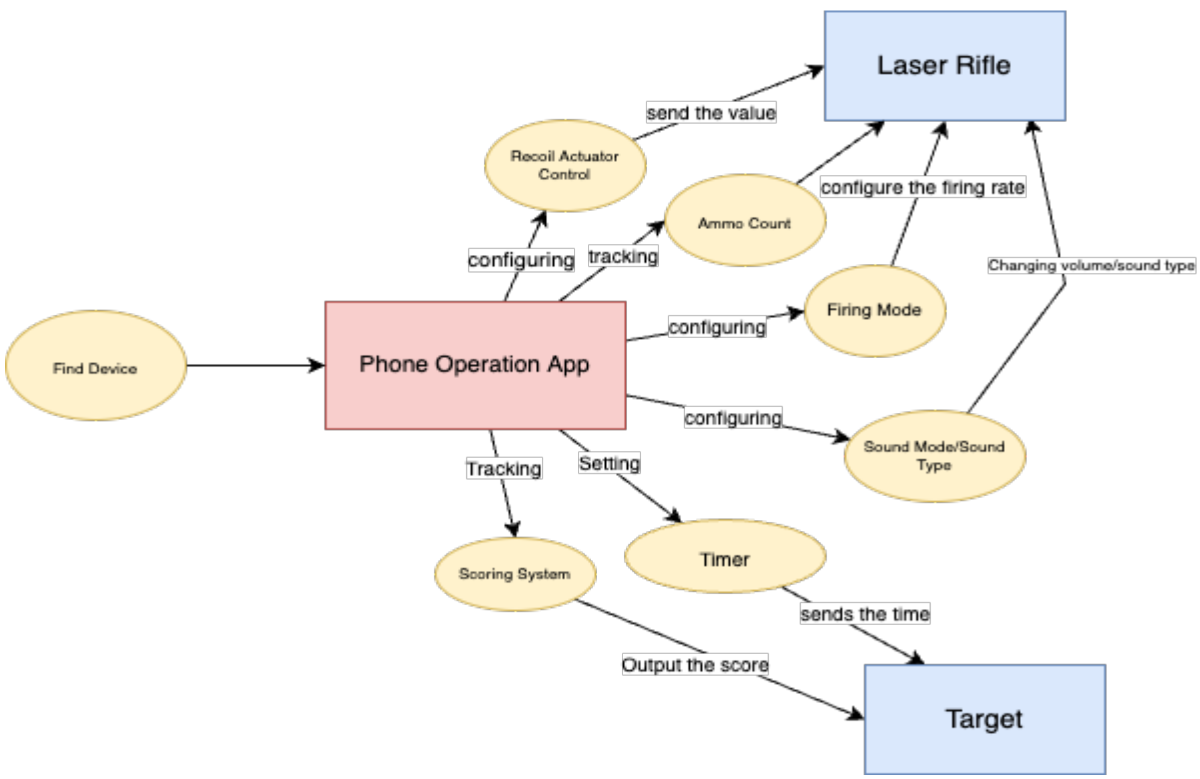


Figure X10 Mobile Phone Application Block Diagram

5.3.2 Software Design Tools

In order to complete the software development there are a few tools necessary. The main tools that are needed are the editor which can compile any language necessary, software libraries needed, and application for interface design tools.

React Native

We need a tool to develop one code base that will then transpile to be native apps in iOS and Android. Thus, we choose to use React Native to deploy to iOS and Android. Using React Native we can program using a special JavaScript language along with the help of React libraries to build our app. A brief description of React Native, it is an open-source mobile application framework created by Facebook. React Native knows how to talk to native platforms on Android and iOS and how to render native widgets. It gives us a bunch of these widgets as React components so that we can build a user interface with these components. React Native also gives us access to some native platform APIs. For example, we can access the Bluetooth system of the mobile device and pair it with our current project device. The tool also gives us more tools to connect JavaScript to Native Code. How React Native works, we use special components in JSX format like <*View*> and <*Text*>. These components are compiled in react Native and converted to native elements in native apps. For example, for Android, the <*android.view*> to structure the content. On iOS, that would be <*UIView*>. Then in React Native, we use <*View*> tag to compile into native widgets on Android and iOS.

The reason why we choose React Native because the tool lets us have the freedom to build apps for all platforms and we also can export from Expo CLI to the React Native CLI so that we can take control over the management of the project locally. You can create and run your applications.

Figma

For prototyping our current app without needing to code up, we use Figma as our user interface design. Figma is a collaborative web application for front end design. The feature set of Figma focuses on User Interface and User Experience design. The tool helps represent the concept of our mobile app design for everyone in the team. Figma allows us to make the tool our own. The ease of access allows us to have all we're needed to work as efficiently as possible. We also chose Figma because it lets us work on more iterations in a shorter time without the hassle. Version Control is also a very important feature in Figma. Since we have people work on the same file at the same time, it's so important to have the built in 'Version History' to go back to when something we did was wrong or looks bad and then everyone can continue work on the next prototype without worry about messing up the main prototype.

Integrated Development Environment (IDE)

We decided to use Visual Studio Code as the primary code editor for mobile app development. VS Code includes enriched built-in support for development applications that make extensive use of the ability to run Javascript both on a client as well as the server, and this is called Node.Js.

VS Code has great tooling for app technologies such as JSX/React Native because it has a public extensibility model that lets software engineers or developers build and use extensions that richly customize their edit-build-debug experience. Visual Studio Code also includes an interactive debugger that allows us to dive into our code and go through the code step-by-step. We dive this deeper in the Test plan section.

Arduino Integrated Development Environment is utilized to connect to the Arduino hardware to upload programs and communicate with them. Programs written in the software are called sketches. These sketches are written in the text editor. In the editor, we need to write in it with C++ language. Most libraries that provide extra functionality for use in sketches are C++ classes. The software also has the console that displays text output including complete error messages and other information. Another cool thing about Arduino Software is that there is a Serial Monitor that displays serial sent from the Arduino board over USB. It's an essential tool because it is used as a debugging tool, testing out concepts or to communicate directly with the Arduino board.

5.3.3 PCB Design Software

Autodesk EAGLE

Autodesk Eagle was the first PCB design program that came to mind since much of our group has experience with it from our Junior Design course. We all have access to the educational license for Autodesk Eagle since we are students at UCF. Unfortunately, when we took Junior Design, we were unable to actually send our designs to be printed due to the global part shortage issue with many electronics companies. For all of us, Eagle is our only experience with PCB design software, so this made Eagle our first choice for PCB design software.

Autodesk Eagle has many features including the schematic editor, PCB layout editor, PCB library content, as well as an online PCB community. The Eagle schematic editor includes the SPICE simulator, modular design blocks, and electronic rule checking. The SPICE simulator allows you to test and validate circuit design and performance. The modular design blocks have reusable design blocks that you can drag and drop between multiple projects, the modular design blocks also have schematic and PCB circuitry. The electronic rule checking is a way to validate your schematic designs and stay on track and make sure you have a functioning schematic design.

Another feature Autodesk Eagle has is the PCB layout editor which includes real-time design synchronization, intuitive alignment tools, push and shove routing, obstacle avoidance routing, new routing engine, and design rule checking. The Eagle real-time design synchronization keeps your changes between the schematic and layout in sync. The intuitive alignment tools arrange and order the PCB design objects. The push and shove routing are an adaptive tool meant to push and shove you PCB traces to ensure they abide by the design rules. Obstacle avoidance routing aids in ensuring traces get to the appropriate destination by maneuvering around the PCB design. New routing engine allows for quick PCB design. Tools within the new routing engine include loop removal and cornering. The design rule checking allows the user to control the flow of their design and abide by the PCB rules of design to avoid unwanted outcomes.

Furthermore, Autodesk Eagle includes PCB library content. Online libraries are useful for finding many different parts to place in your PCB circuit with a continuously growing library. The PCB library content also allows for 3D PCB models to help the user get an idea of what their PCB will look like when it is sent off for printing, and to make sure the PCB fits in the hardware you would like to implement it in. Complete components allows the user to search physical hardware components such as MCU, chips, op-amps, symbols, and footprints **[19]**.

Altium

5.3.4 Summary of Design

6.0 Prototype Construction and Operations

This section will detail the steps we plan on taking for building the prototype and will include Solidworks 3D models of our designs. We also include an “owner’s manual” providing instructions on how to use the prototype.

6.1 Laser Rifle Assembly

First, regarding the frame for the laser rifle, we have bought one rather than constructed it ourselves, so many of our designs will be working with the empty shell of the rifle. In our project, we heavily used heat-set threaded inserts for strong, reliable screw threads in 3D printed material. While you can print threaded holes using a 3D printer, these threads are not very strong nor accurate. Heat-set inserts on the other hand are threaded pieces of brass that are heated using a soldering iron and pressed into holes in a 3D printed part, causing the threads to melt the plastic around them. This creates a strong bond in the plastic while also allowing for screws to pass through the threads.

In **Figure X60** below, we provide a general layout of where each component will lie within the rifle. Due to the small space contained within the rifle frame, we moved the beam expander outside of the rifle with the idea that it would still have a fitting look for the rifle as a suppressor. The beam expander will be a simple 3D printed tube that will be fixed to the barrel of the rifle.

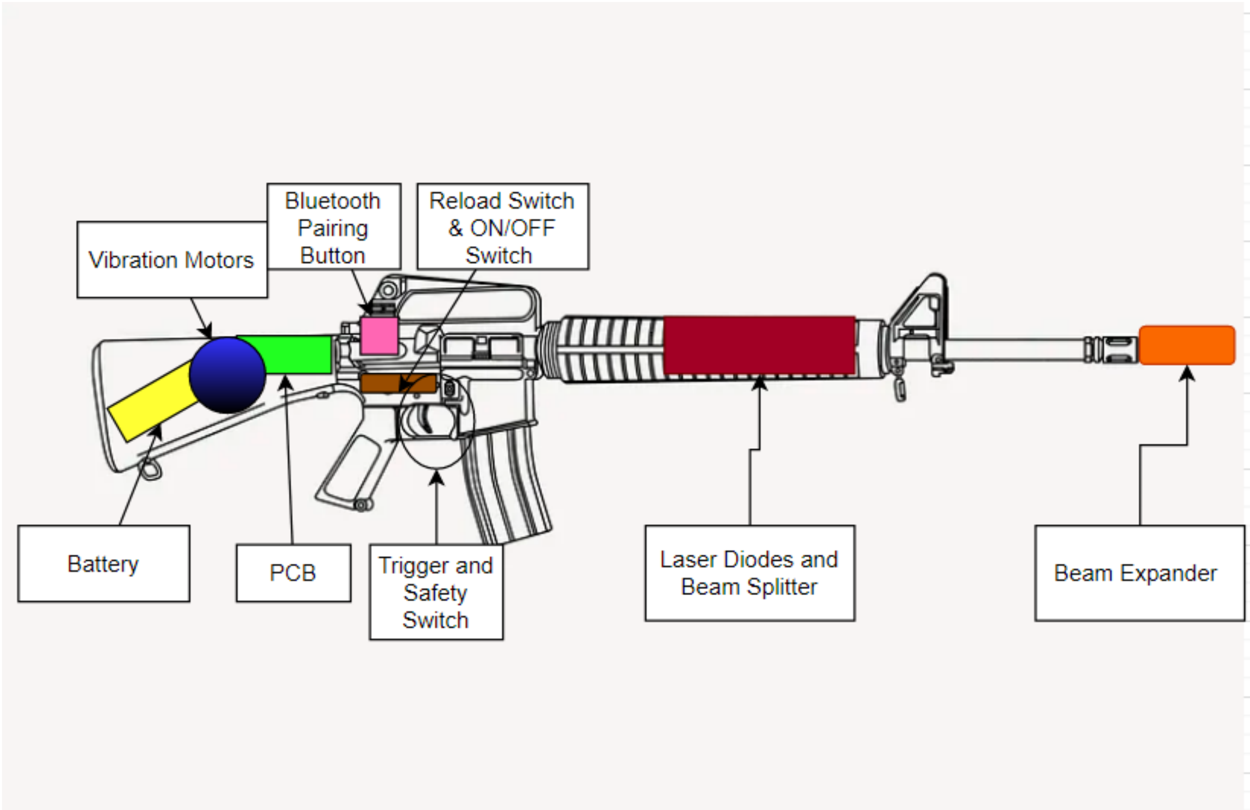


Figure X60. Component Placement in Rifle

6.1.1 Rifle Attachments

Since the frame of the rifle was purchased, we had to make all of the housings for the attachments for the rifle such as the optical sights and flashlight. These designs were made using Solidworks and plan on being made using a 3D printer. In **Figure X61** below, the preliminary design for the reflex sight is shown. Now, it does not contain a battery holder for the LED. The LED is mounted into the hole shown in the image. Both the holder for the concave mirror and hole for the LED are angled to decrease the total amount of vertical space taken up by the sight since the LED has to be at the focal length (103mm) of the mirror for the light to be collimated. Picatinny rails will be attached to the bottom of the sight for mounting to the rails of the rifle.

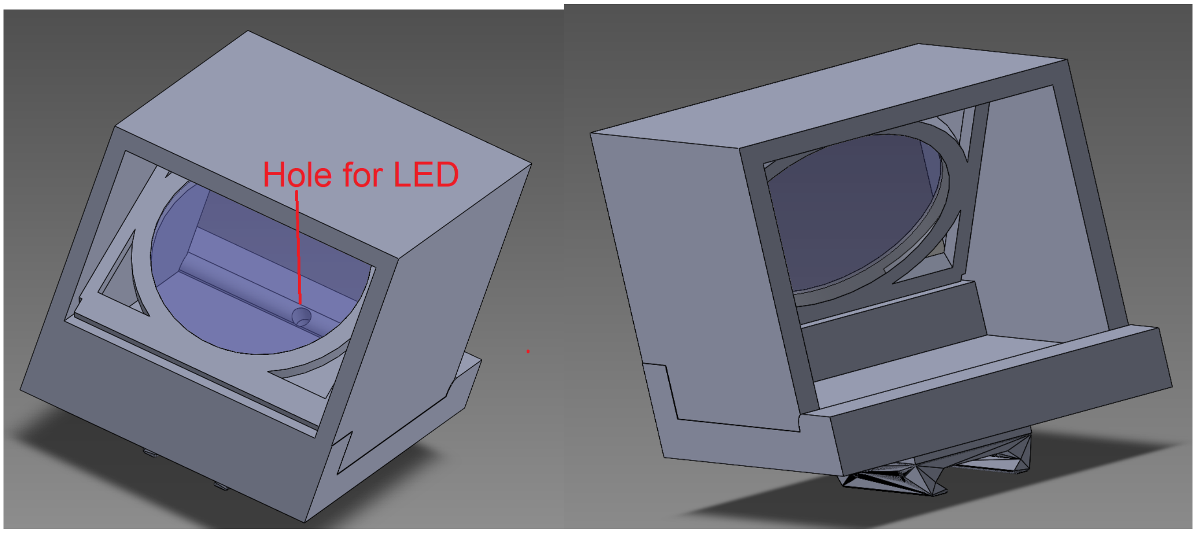
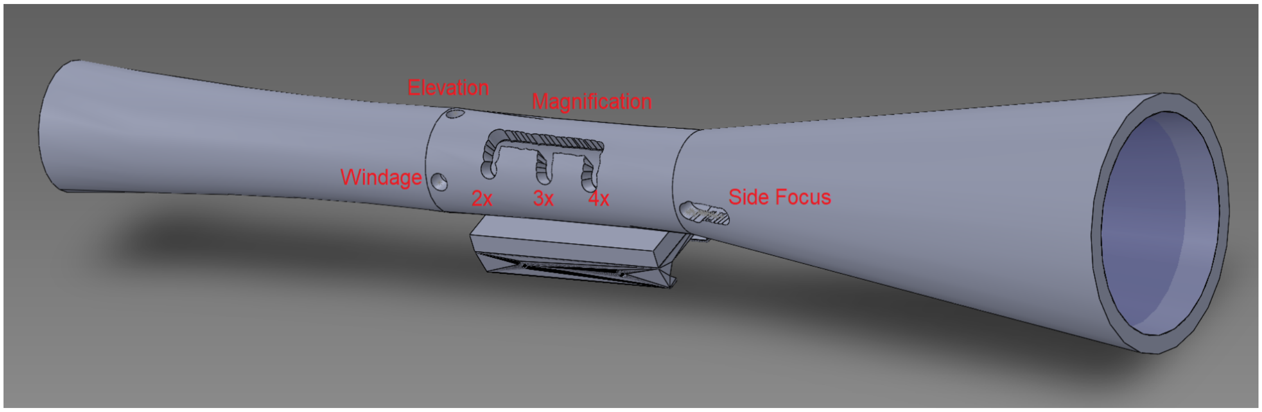


Figure X61. Reflex Sight 3D Model

The rifle scope will also be 3D printed. The erector assembly will be contained in a separate tube within the rifle scope that will be able to move to back and forward. As shown in **Figure X62**, there are several holes in the scope. The holes that are closer to the eyepiece of the scope are to control the elevation and windage of the scope. In a rifle scope, there is a spring inside of the scope that keeps the erector tube in position while the elevation and windage knobs are used to control the position of the erector tube in the vertical and horizontal directions respectively. These knobs are typically used for calibration of the scope to make sure that the position of the shots you take are aligned with the reticle inside of the scope. For our scope, we can either use a traditional knob system using a spring or use a pair of horizontal and a pair of vertical screws to adjust the position so that a spring is not needed.

The erector tube will also need to be movable along the axial direction in order for the variable power to take place. Magnification adjustment rings on variable power scopes are quite complex to make, so we will likely use a locking system similar to a slide bolt locking system used in doors by using a long screw that is connected to the erector tube. This method essentially locks the magnification to pre-set values, so it is imperative that we test the scope before finalizing the design to determine which positions result in which magnifications. A similar setup using a tube will be required for the side focus lens because it must also shift axially to correct parallax.

The CMOS camera will be installed directly into a camera tube with the FOV shrinking lens installed into it. This camera tube will mount directly onto the eyepiece section of the scope with the lens located at the exit pupil of the scope. The camera tube will be connected to the LCD display via RCA or BNC cables. A clamping ring will be made and installed onto the LCD display so that the display can be securely mounted to the scope.



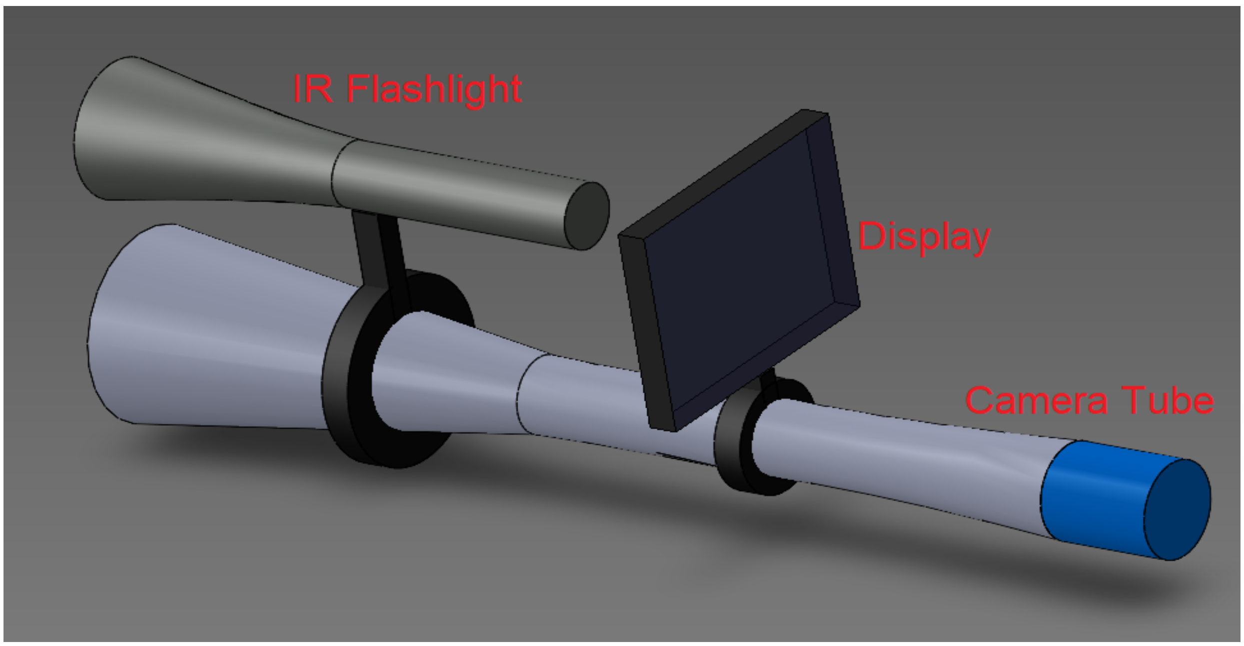


Figure X62. Rifle Scope With and Without Night Vision Setup

Construction wise, the IR flashlight will be a simple device to build. It will have a PCB with the 860 nm LEDs connected and a battery installed into the back end of the flashlight just like a standard flashlight you can buy on the market. Since the IR flashlight will need to have a variable focus, we will have a setup similar to the side focus lens of the scope. A similar clamping mount will be made for the IR flashlight. If we find that both the flashlight and display being mounted to the scope is too bulky, we could also mount it to the underbarrel of the rifle itself using the rifle's rail system.

6.2 Target Board Assembly

The target board will be mainly 3D printed into four large parts that will be combined after printing using screws. This is because the board is large at 12 in x 12 in, and there are two separate layers: the front surface and the back surface. The total thickness of the board not including lenses is planned to be around 50mm. Both the front surface and back surface layer will be 7.5mm thick. There will be a 35mm spacing between the front and back surface that allows space for the PCBs and internal components of the board to be mounted. The back surface will just be a simple flat board, while the front surface will have holes where the PETG lenses will be installed into. The PETG lenses must be printed in very strict conditions to produce a usable lens, so we will print them separate from the rest of the target board system. We will likely use some form of adhesive such as epoxy to hold the lenses in place after installation.

Additionally, we may apply a reflective coating using paint or polish on the front surface of the target board before installing the lenses. Aside from aesthetic reasons, this is to assist the CMOS camera for night vision operation since most of the light coming from the IR flashlight will need to be reflected off the board for a good image. Of course, this will also decrease the amount of electrical power consumed by the flashlight since less optical power will be needed for sufficient lighting.

Concerning the LEDs, we have had some ideas regarding how to deal with their installment. The issue with the original design model where all the LEDs are placed outside of each target circle is the installation of the LEDs. Since the LEDs will have to be installed onto PCBs, we would either get many small PCBs or install one giant PCB onto the target board. Both are simply unrealistic when it comes to implementation. Therefore, we mentioned using LED strip lights in the Part Selection because they would simplify the connections to the PCBs, but as we discussed, these strips are flawed due to their viewing angles. There are two ideas we have considered, and they are both illustrated and explained in **Figure X63**. Since the main goal is to concentrate the LEDs to smaller areas, the simplest way is to make the score number above each target area powered by LEDs. Upon hitting a target area, the associated score number will light up. This would still require separate PCBs for each score number. A more complex, but complete way is to make a large LED array that lights up LEDs to make the score number for the target you hit as shown in the figure. This would be more complex to program, but this would simplify the installation process since all of the LEDs would be connected to one PCB.

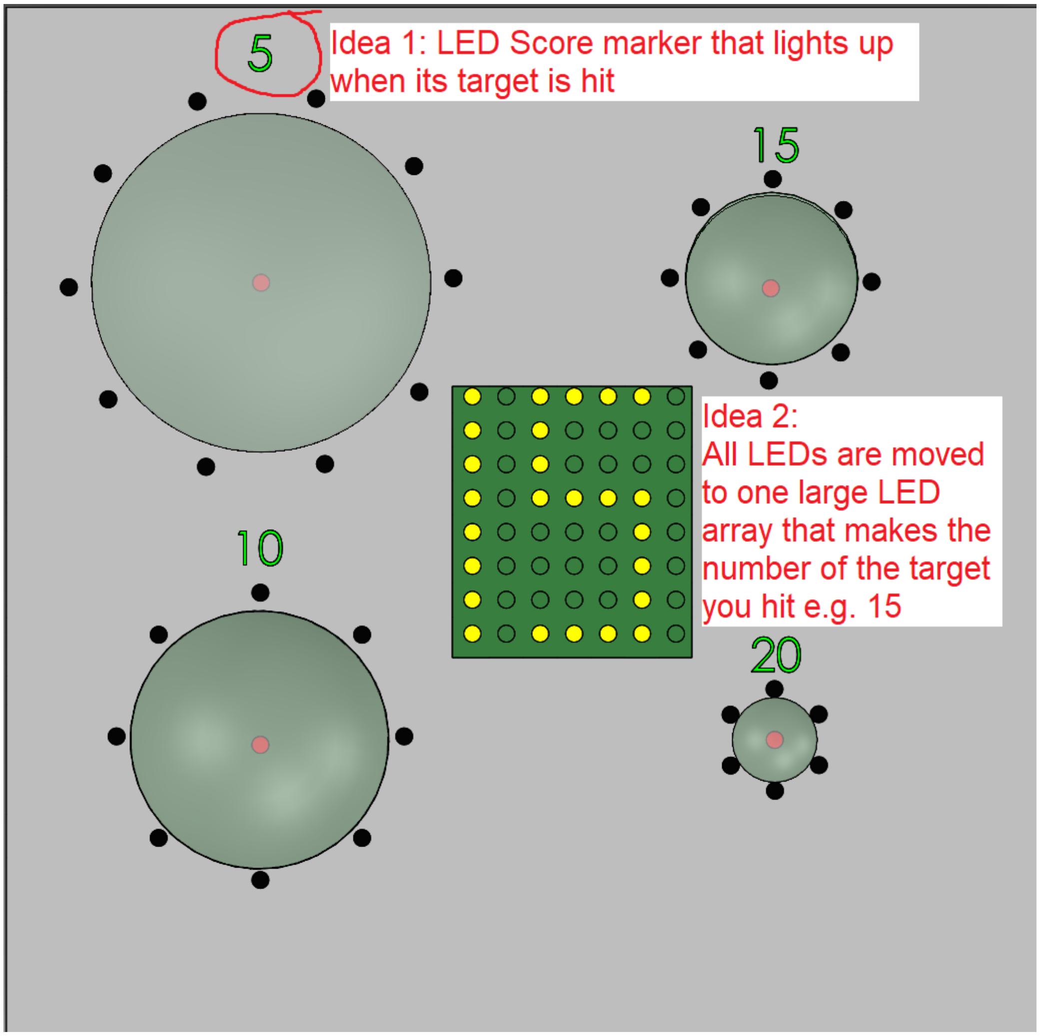


Figure X63. Target Board Potential LED Designs

6.3 User's Manual

In this section, we are presenting our project user's manual. The purpose of making this section is to present the project effectively. A major point of the user manual is educating people, and its importance for the user to be easily able to read, reference, and absorb the information clearer.

Instructions for Software Use:

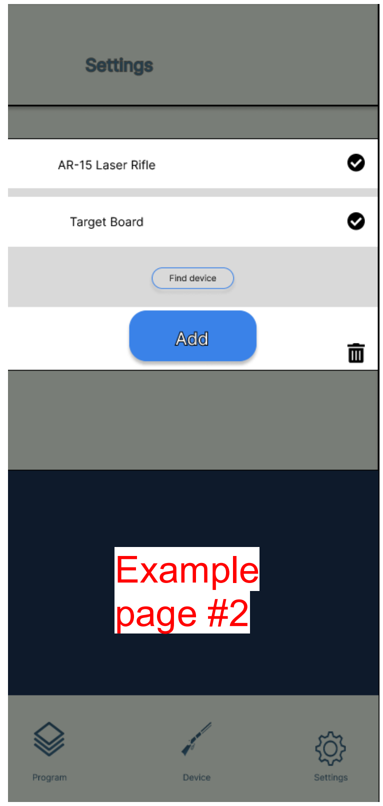
<u>First Time Setup:</u>

1. Click on the FIND DEVICES to start searching for Laser Rifle through Bluetooth.
2. Depending on the device OS, a SETTING screen will show up. Please find the device name "G6-LaserRifle" and click on it.

3. Switch back to the app. If the device is paired, the device name will show up in the app - **Example page #1**.

Example page #1 - Illustration of the Device Paired Page

4. Click the ADD button to add the device and we will configure the Laser Rifle device.
5. Click the FIND DEVICE to add another device and this time it will be the Target Board device.
6. Depending on the device OS, a SETTING screen will show up. Please find the device name “G6-TargetBoard” and click on it.
7. Switch back to the app. If the device is paired, the Target Board device name will show up in the app - **Example page #2**.



Example page #2. Illustration of Two Devices Paired Page

Configure devices:

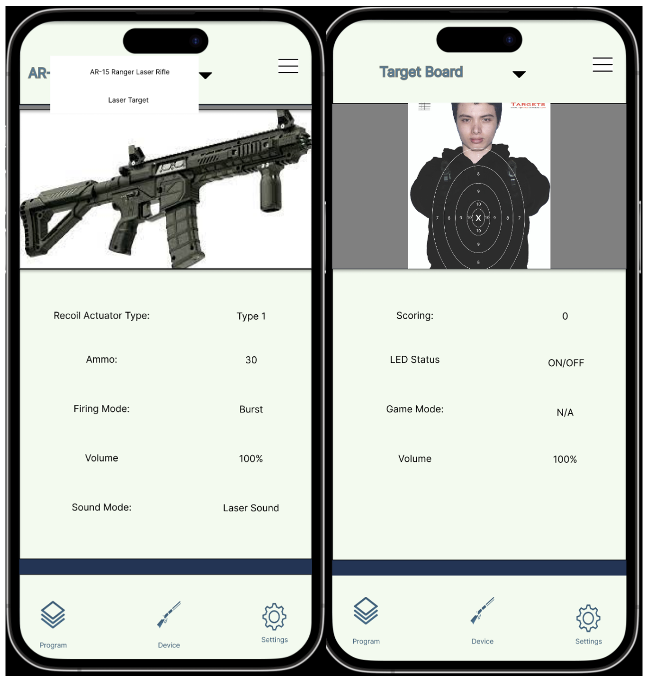
1. Once all devices are paired, you can now configure the device setting. You can tap on the ▼ to switch to different devices in the **Example Page #3.**
2. You can change values for each of these devices:
    a. **AR-15 Laser Rifle:**
        i. **Recoil Actuator Type**: Type 1: Short Buzz, Type 2: Long Buzz, Type 3: Rapid Buzz
        ii. **Ammo:** Ammo round counter. Press a button on the Rifle to RELOAD.
        iii. **Volume**: change the sound level of the AR-15 Laser Rifle in percentage.
        iv. **Sound**: change this to customize the Rifle sound effect.
    b. **Target Board**

i. **Scoring:** Gameplay score counter, the

ii. **LED status:** ON for LEDs light on, OFF for LEDs light off.

iii. **Game Mode**: Current Gameplay mode - Time Attack, Whack a Mole, Aim Trainer (accuracy),

iv. **Volume:** change the sound level of the Target Board in percentage.



Example Page #3. Illustration of the Two Devices information

Instructions for Laser Rifle Use:

1. Find the ON/OFF switch on the side of the Rifle. Switch it to ON.
2. The LED standby of the Rifle will light up and begin blinking BLUE, indicating it is in the PAIRING state.
3. If it is not blinking BLUE, press and hold the PAIRING button next to the ON/OFF switch for 5 secs.
4. Go to the mobile phone setting, and find the device named “G6-LaserRifle”, tap it to begin the pairing process.
5. Once paired, the Rifle is in a READY state.
6. To firing, press or hold the TRIGGER BUTTON on the Rifle. Release the TRIGGER to stop firing.

Instructions for Target Board Use:

1. Find the ON/OFF switch on the Target. Switch it to ON.
2. The LED standby of the Target will light up and start blinking BLUE, indicating it is in the PAIRING state.
3. If it is not blinking BLUE, press and hold the PAIRING button next to the ON/OFF switch for 5 secs.
4. Go to the mobile phone setting, and find the device named “G6-TargetBoard”, tap it to begin the pairing process.
5. Once paired, the Target is in a READY state.
6. The Target has a sensor and a receiver, so when the Rifle is firing at it, the LEDs on the Target will light up, showing visible feedback.
7. Properly aim the Rifle at the Target sensor to get the visible feedback.

7.0 Prototype Testing

In order to effectively evaluate various parts in our selection in both hardware and software components, we need to create testing scenarios for each particular section. In this section, we discuss the different ways we plan on testing our design. Some of the information included in this section are the testing environments, our developing test rigs, lens testing, IR receiver testing, optical scope testing, and unit test case for the software.

7.1 Hardware Testing Environment

The main buildings used for testing are CREOL’s Senior Design lab as well as the Engineering Building Senior Design lab. Within these facilities, basic electrical components such as resistors, capacitors, wires, etc are free to use. Additionally, testing equipment such as oscilloscopes, digital multimeters, power supplies, optical power meters, and function generators are available for use. Soldering equipment such as soldering irons as well as hot air soldering stations are available. 3D printers and computers are also available for use. Using these equipment, we performed various tests for not only making prototype designs, but testing their optical or electrical performance as we will describe later in this section.

7.2 Hardware Testing

7.2.1 PETG Lens Testing

One of our first tests was to test making transparent PETG filament and making high power lenses using this filament. To confirm that the lenses we made function as lenses are not simple diffusers, we made a convex lens capable of focusing light. A 40mm focal length Plano convex lens was designed and printed using a Prusa I3 MK3 3D printer. Using a layer height of 50 microns and 100% layer infill, a 2 inch diameter lens was printed over the span of 15 hours. Extensive post-processing involved sanding from 400 grit to 1500 grit in increments of 200 grit, and after sanding to a smooth finish, the lens was polished using Novus #2 fine scratch remover with a Dremel tool. After post-processing was finished, the lens went from being a translucent diffuser to a transparent lens that could focus light. **Figure X41** compares the planar surface of an unprocessed lens to that of the processed convex lens. It is not a surprise that the unprocessed lens acts like a diffuser based on the lack of uniformity in the surface.

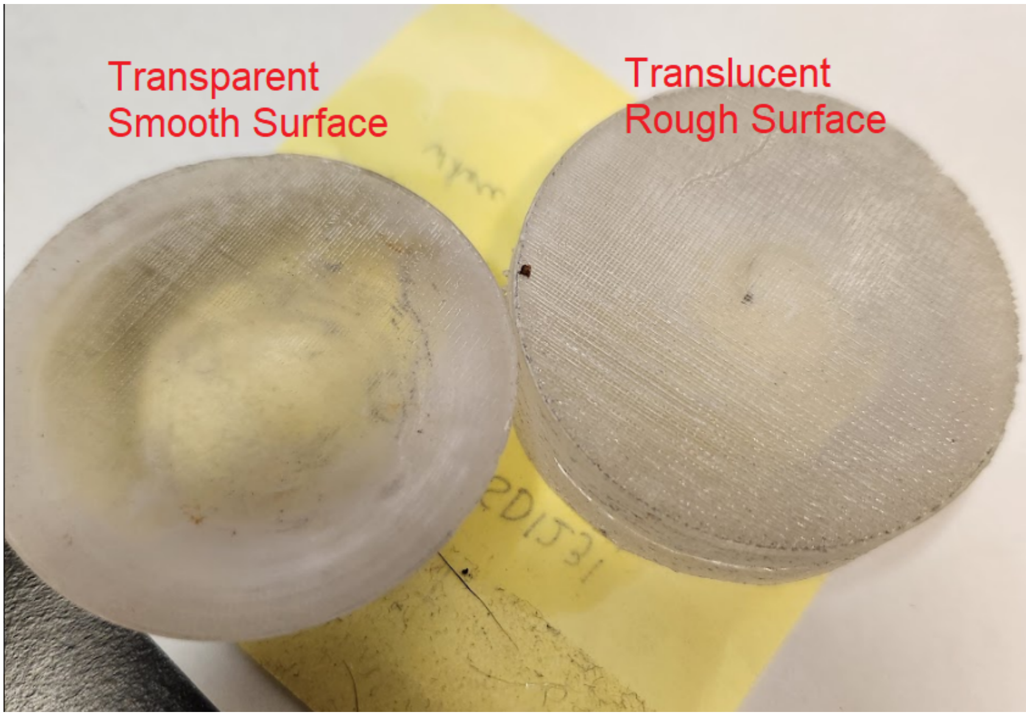


Figure X41. Surface of Unprocessed vs Processed Lens

In **Figure X42**, the performance tests for the lens are shown. As our goal with the lens was to prove that it actually functions as a lens and focuses light, we put the lens into the path of a laser to show the focusing capabilities of the lens. When tested using a power meter, the transmission through the lens was found to be around 50%. Since the post-processing was not perfect, light coming from positions far from the center of the lens suffered from moderate diffusion. With more thorough polishing and sanding, the transmission can be increased even further. With this test finished, we know for certain that it is possible to make functional high power lenses using the 3D printer.

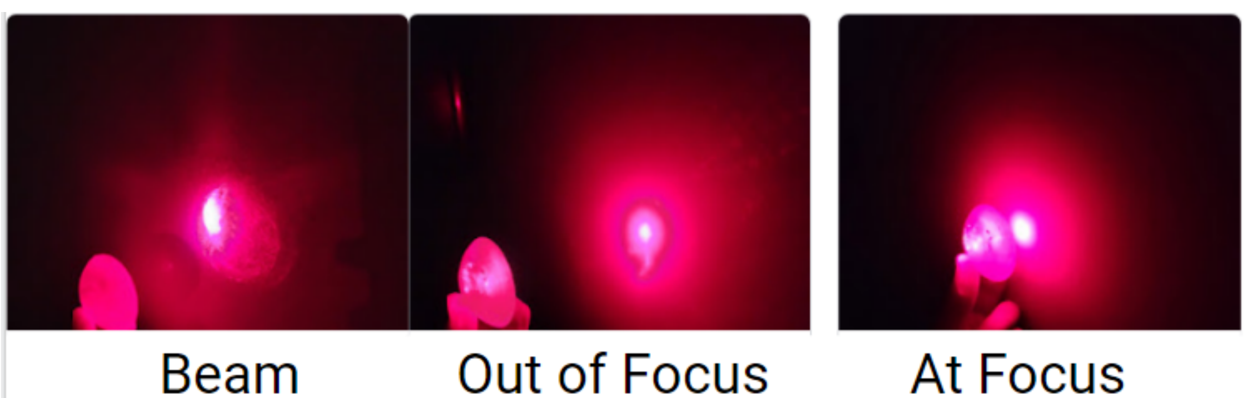
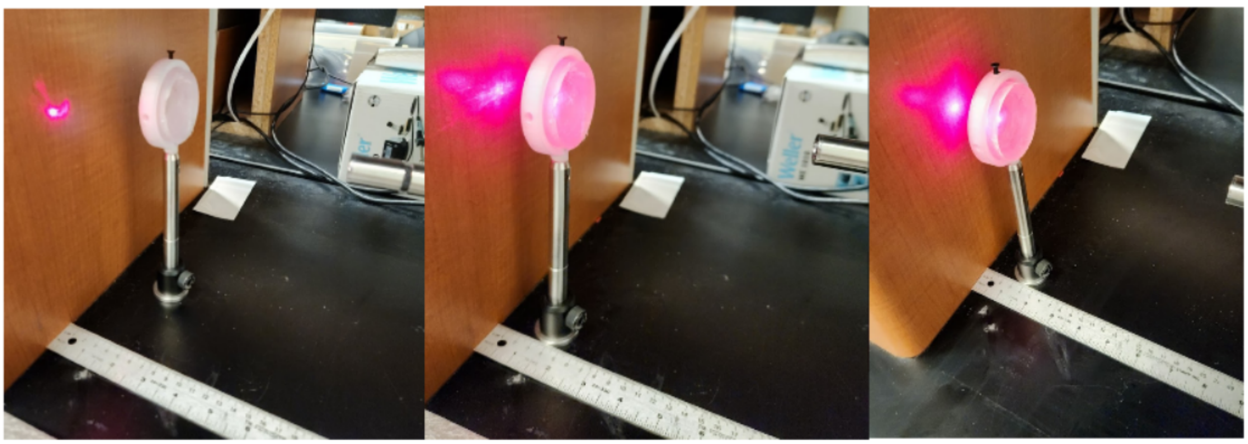


Figure X42. PETG 40mm EFL Plano Convex Lens Testing

With this knowledge, we made the 50 mm diameter plano concave lens with 60mm EFL that was displayed in the design section. We also made sure to measure the back focal distance from the wall to the planar side of the lens (35mm) to simulate how the beam will change size upon hitting the lens when actually installed into the target board. We also provide a comparison to how the lens fresh off of the 3D printer performs compared to the performance of the lens after being processed using the steps described above. The input beam was a laser pointer with a 4mm spot size. These results are shown in **Figure X43** with the processed lens clearly having a greater transmission, although there was still diffusion due to imperfections in the post processing process like in the case of the plano convex lens.



Beam Unprocessed Lens Processed Lens

Figure X43. PETG 60mm EFL Plano Concave Lens Testing

7.2.2 Laser Diode Testing

We have performed some initial tests on the IR laser diode, but further testing is required. As stated in the datasheet, this laser diode's performance is directly affected by the quality of the solder. This can affect optical power, efficiency, and even output beam angle. The datasheet explicitly mentions and heavily recommends the use of a reflow soldering machine, which unfortunately is not available to us in the Senior Design labs. Using a soldering iron, we hand soldered wires onto the base of the diode for breadboard testing. After some testing, we confirmed that the optical power output was correct at 8mW at 12mA, but the beam divergence was observed to be very poor. Despite having a built-in collimation lens, the output beam was observed to have a divergence of over 75 mrad. This means that our soldering was flawed and further testing is required to see if the diode truly offers a collimated <10 mrad beam without modification. Otherwise, the beam will need to be collimated using a separate lens in the system.

7.2.3 Visible LED Testing

For the LEDs, these will be tested for range and output power. Since our design plans to be used at at least 15m, this is an obvious test since the LEDs must emit enough light to be visible from quite far away. Since these LEDs are entirely for visible feedback, many of the optical properties listed in the datasheets such as optical spectrum are not very relevant and do not require testing for the purpose of our system. We can also test what angles or distances we can view from and still see a bright light emitted by the LED with respect to the input current to determine the limitations of our system.

7.2.4 IR Receiver Testing

Using 940 nm LEDs, we will perform tests on how to get the IR receiver to respond to the incoming modulated light. IR receivers typically respond to specific codes, or sequences, of modulated light that are pre-determined by the manufacturers of the receivers. For our system, we will need to test how we can encode one of these codes into the output of a 940 nm LED (or IR laser diode), and then see how we can get the digital signal output that the receivers should output according to the datasheet.

7.2.5 Optical Scope Testing

In this section, there are five tests we performed on the optical scope. These include light transmission, resolution, light gathering, field of view, and magnification tests. For the light transmission test, we simply put a 2mW 650nm laser through the system and measured the output power using a power meter. We observed that the light transmission through the system was 79.5% which is close to 80% like we had calculated beforehand.

The scope was tested for its angular resolution in different lighting conditions. The angular resolution is an important quality of the scope and determines how much detail can be discerned while using the scope to view an object. This is important since our target will be at least 15m away from the user. In the worst-case scenario, parts of the target board may not be clear while viewing with the scope if the angular resolution of the scope is too low. Note that we specify "angular" resolution rather than spatial resolution because the system is a focal and does not have a strict working distance like when using a microscope. The different lighting conditions are important to test because this gives us a better understanding of the light gathering capabilities of our system. Larger amounts of light coming into the system result in a higher resolution image, and some scopes may be better at performing in low light conditions compared to others depending on the design used.

For our testing, we printed a 1951 USAF Resolution Test Chart shown in **Figure X72**. Each set of lines has a different spatial resolution in line pairs/mm that can be converted into an angular resolution by using a simple trigonometric relation where the angular_resolution=2*arctan((2*line_pairs_per_mm*distance)$^{-1}$). In the test chart, the smaller the set of lines, the more line pairs/mm. The angular resolution of our scope is tested by looking for the smallest set of lines that can be clearly distinguished. Since we printed an image of the chart rather than buying a test chart, the line pairs/mm corresponding to each set of lines of our chart is not the same as a commercially produced test chart. We measured the width of each line using a microscope in order to calculate the amount of line pairs/mm for our angular resolution calculations. The chart was viewed using the scope at a 3m distance. The testing setup is shown in **Figure X73.**

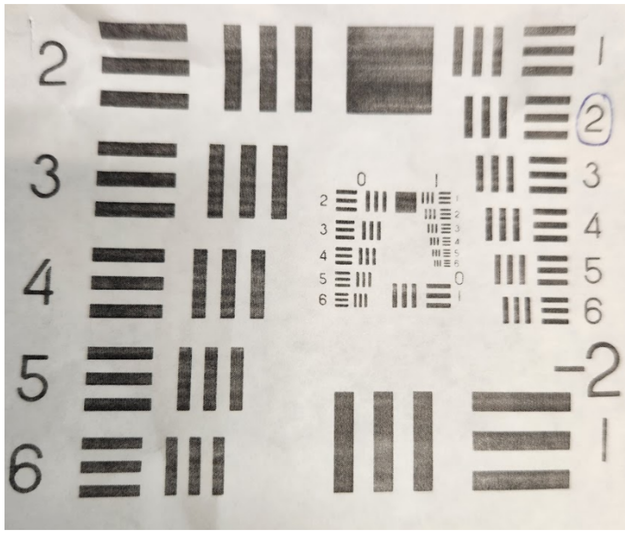


Figure X72. Printed 1951 USAF Resolution Test Chart

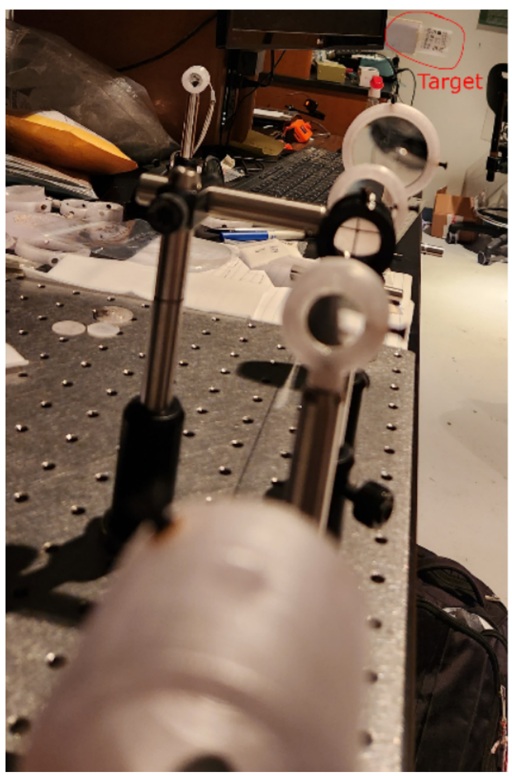


Figure X73. Scope Test Setup

For the testing, we looked through the scope and looked for the smallest target (highest line pairs/mm) that is clearly distinguishable. This was tested across three different lighting environments. For each test, we took images using a smartphone camera looking through the scope when placed at the exit pupil to show how the resolution changes with the light. We outlined the sets of lines where the resolution is limited in **Figure X74.** We looked through the scope beforehand to determine what was the most resolvable, so the camera pictures may not be perfectly clear. The large black lines intersecting on each image is the reticle of our scope that will be used for aiming when the prototype is finished.

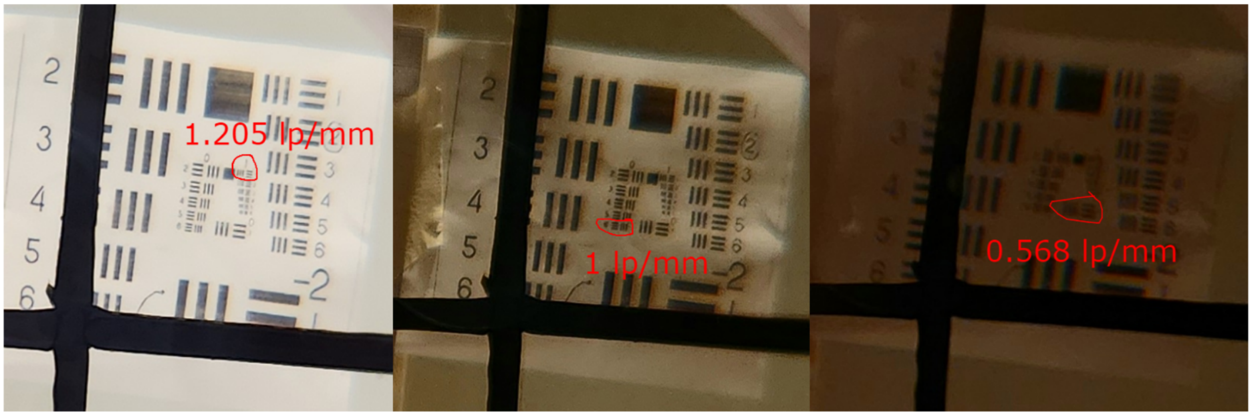


Figure X74. Scope Resolution vs. Lighting Test

For reference, the angular resolution limit of the human eye in peak condition is 1 arcminute, or 0.3 mrad. From our tests, we calculate that the angular resolution limit in these three different lighting conditions from brightest to dimmest are 0.277 mrad, 0.33 mrad, and 0.587 mrad. These results are quite bad and can be because of two major factors. One reason is because the target distance is only 3m away, so the light coming from the object is not as close to paraxial as a target at 15m would be. To test this, we performed two more tests at longer distances of 15m and 26m. We were able to resolve a 0.33 lp/mm line set at 15m and 0.192 lp/mm line set at 26m, which are both equivalent to a 0.2 mrad angular resolution. This shows that closer targets will have significantly worse resolution. Additionally, the next factor decreasing the resolution is the aperture stop size. This is due to the size of the lenses used in the system themselves, mainly the 18mm diameter achromats used in the erector lens assembly. System numerical aperture is directly proportional to the entrance pupil diameter, so using larger lenses would result in more light collection and potentially higher resolution if the aberrations introduced by a larger aperture stop are not large.

We then measured the field of view of the system. We replaced the resolution test chart with a ruler to measure how much we can see when looking through the scope. This was tested at the 3m target distance as shown in **Figure X75**. This image also gives a better view of what the image outputted by the scope will look like in the prototype and shows some chromatic aberration that was expected from the Zemax design. Using the ruler as a basis, the FOV of the scope can be calculated as 5.02 degrees. Commercial rifle scopes generally provide field of view in terms of feet per 100 yards, and research indicates that the FOV for a 4x rifle scope can range from 21 feet to 33 feet per 100 yards, or 4 degrees to 6.3 degrees. This means that our scope is quite average in terms of FOV.

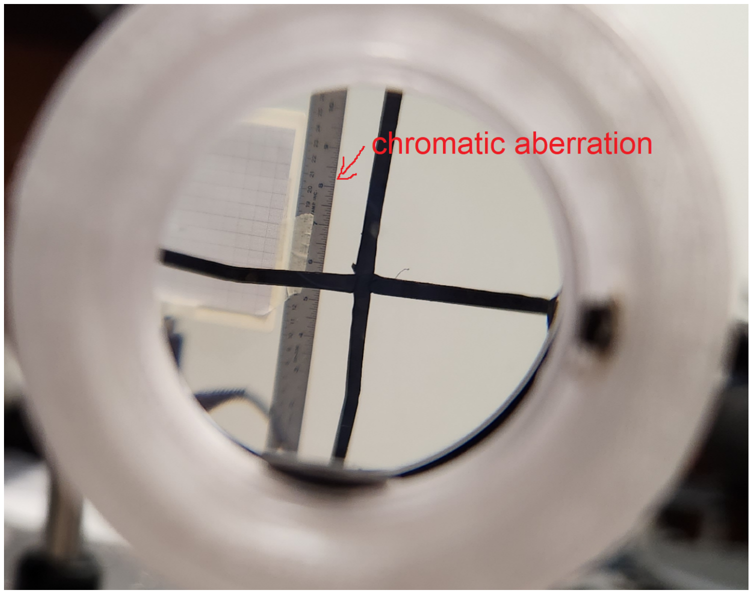


Figure X75. Scope FOV Testing with Ruler

Finally, we tested the variable magnification capabilities of the scope. It is important to perform this test to determine the range of movements that our scope will allow when we actually build it as explained in the Prototype Construction section. The variable magnification comes from the shift of the position of the erector lens assembly. As stated before, we designed our scope such that the maximum magnification is at 4x. Therefore, we can only move our erector assembly towards the eyepiece, decreasing the magnification. In this test, we moved the target back to a 15m distance and observed how the magnification of the system changed as we moved the erector assembly closer to the eyepiece. These results are shown in **Figure X76** with the aiming reticle removed.

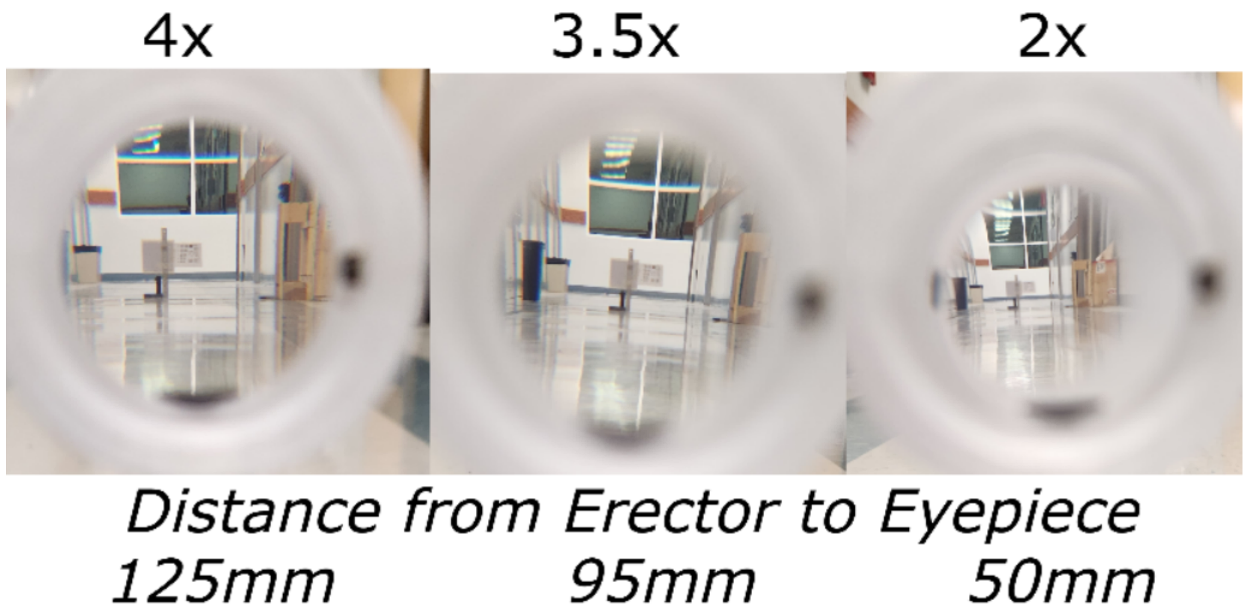


Figure X76. Magnification vs Erector Assembly Displacement

As seen in the 2x magnification image, the view through the scope becomes increasingly obstructed by the holders of the lenses although the overall FOV increases. We will likely restrict the movement of the erector assembly to a maximum of 75mm displacement which will result in the 2x magnification.

7.2.6 IR Flashlight and CMOS Camera Testing

The 860 nm LEDs tie into the functionality of the CMOS camera as a night vision system. There is really no way to determine the amount of optical power needed to achieve a bright picture while using the CMOS camera without extensive testing. This is because the camera, which already has low quantum efficiency for the target wavelength, is creating an image based on reflections from a target that is going to be at least 15m away. This is worsened further by Fresnel reflections and other losses when passing through the rifle scope. We can test by using different amounts of LEDs and input current into the flashlight, which can provide insight on how much optical power will be needed to properly use the CMOS camera for night vision. We can also try implementing reflective surfaces onto the target such as white spray paint or metallic paint to see if the camera will get a better picture. Additionally, the IR flashlight will use a telescoping lens to change the focus of the 860 nm light, so we will need to determine how the focus of the light will impact the image output by the camera.

7.2.7 Audio Testing

The objective for this test should be to ensure that there are no compatibility issues between our audio system which includes the microcontroller, audio amplifier, and choice of speaker. Specifically, we want to ensure that the playback of our chosen audio samples output with a high enough audio quality and timing precision so that when the laser rifle trigger is pulled the user can easily understand the sound effect being played under any condition.

The materials necessary for the test are pretty standard being that the entire audio system is only 3 components. The materials that will be used for the test will be the chosen microcontroller, ESP32, the Audio Breakout MAX98357A board, and both speakers that were discussed in the Audio Parts selection section, the one from Ada fruit and the MakerHawk from Amazon. These 3 major components in conjunction behavior will be an ample representation of how the final audio system will act in our prototype and possibly final design. Lastly it is important to have a computer to compile and flash the audio test software, and a breadboard to wire the circuit together.

In order to test the audio we will be using the necessary software that is compatible with the chosen microcontroller. We have found that the ESP8266 Audio library can produce and manage audio playback on our ESP32. The library is supposedly compatible with many microcontrollers that have similar processors including ours. We plan to use a provided example file to test functionality of our audio system.

7.2.8 Wireless Communication Testing

The purpose of this test is to ensure the stability of Bluetooth communication of both devices. We write a small code to turn on the LED connected on the Target Board, and the Laser Rifle. Then, we can try to test the range of the Bluetooth communication between the devices and the mobile phone to see how far they could still stay connected. We also test the range of the device by finding the max range so that we know what the transmitter power and if it’s necessary to raise the power to meet the necessary range or lowered if the range has already been met to lower power consumption.

Next, we test the quality of the data by going through a few several situations to find the limiting factors. We introduce a Microwave signal to see if that could affect the current Bluetooth communication. Then we test with the dry heat, rain, sunshine, and EMF submission and emissions, conjoined with altitude and pressure to stress the quality of the connection.

7.2.9 Unit Testing

The purpose of unit testing is to test the quality of our code during the software development and embedded system development. When programming them, we have to assume that the behaviors of ESP32 microcontrollers and Arduino libraries to be either correct or at least *consistently* incorrect. What this means is that when our tests produce output contrary to our expectations, then we likely have a flaw in our code that was tested. If our test output matches the expectations, but the program does not behave correctly when we upload it to the ESP32, then we know for sure that our tests were based on incorrect assumptions, and we likely have a flawed test. So that means the quality of our feedback has improved from "*something* is broken" to "this *specific code* is broken".

Based on our further research, the ESP32 provides integration with the Unity unit test framework, which we will use to streamline writing tests for our software **[15]**. They can be integrated into an ESP-IDF component by placing them in the component's "*test*" subdirectory. So, if we follow this cited document, we can test the abilities of both our Laser Rifle and Target board software components.

7.2.10 Pairing Testing

From the Ready state, our system should be able to successfully pair the Rifle. We will test our system by pairing two devices next, which are the Rifle and the Target board. Our targets should respond visually by turning green as they are paired. The controller screen should display the targets, indicating they have been successfully paired. If each target is successfully paired within 4 clicks, this test passes.

7.2.11 Energy Testing

7.2.12 Uptime Testing

To do the uptime test, we will leave the microcontroller of the Rifle to be idling in the READY state for at least 4 hours and the Target board be idling at least 5 hours. If these conditions are met, this test case passes.

7.3 Software Prototype

7.3.1 User Interfaces Design

The **Figure xx.1** is the home page when the program first started. In the picture, there is a "FIND DEVICES" button to pair the Rifle or the Target. The app gets the Bluetooth permission of the device and then only compatible devices will show up in the device list and populate in the app.

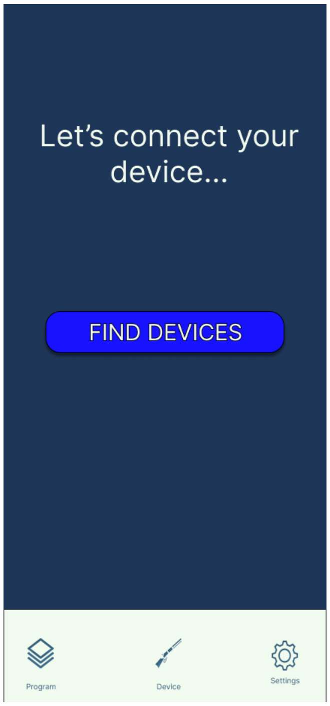


Figure xx.1 Find Device Page

After the pairing process is finished, **Figure xx.2** below shows the main page of the app. The current screen shows the information about the Laser Rifle: what is the type of the recoil actuator, the ammo count, the current firing mode, and the current volume percentage. Recoil Actuator 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. 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. The Laser Rifle will need to manually reload the round with a press of a button, and the counter will reset back to the original number, and in this case it will be 30. Sound Mode element is showing the current sound effect outputting from the Rifle speaker. The app can change this element and can be configured into another sound effect. This element will be a user customizable feature to the user's liking.

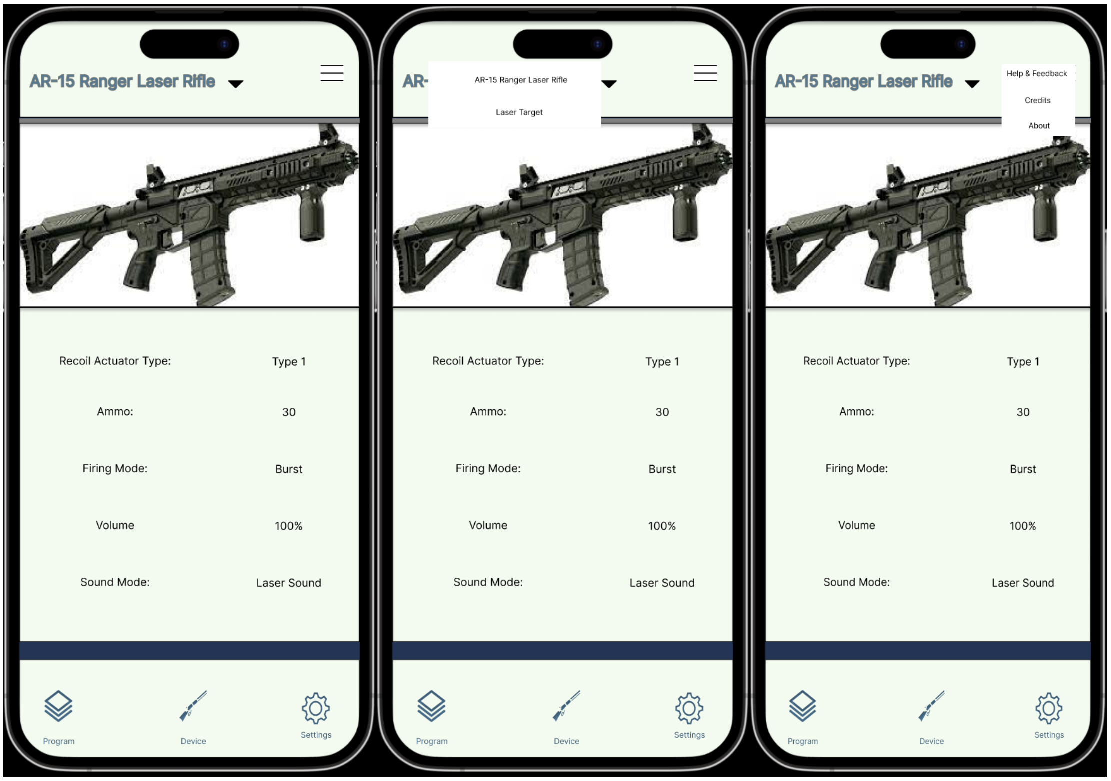


Figure xx.2 Gun Page Information (not final)

The **Figure xx.3** below shows the target board page after pairing it to the mobile app. Similar to the Laser Rifle information page, the page shows the information about the Target: the Scoring counter, the LED status state, the current Game Mode state, and the current volume percentage. The Target counts the Score when the built-in sensor receives the laser wave signal from the Rifle. The output result can be seen on the app itself. Next element is the LED status state of the Target board. This shows the current LED state of the board so it will either ON or OFF depending on the situation (this actually will be dive into more details and changed in the later stage). Next element is the current Game Mode state that prints the name of the current game that the user is playing. The final element is the Volume which states the current volume in percentage that controls the output sound of the Target speaker when the Target built-in sensor is triggered.

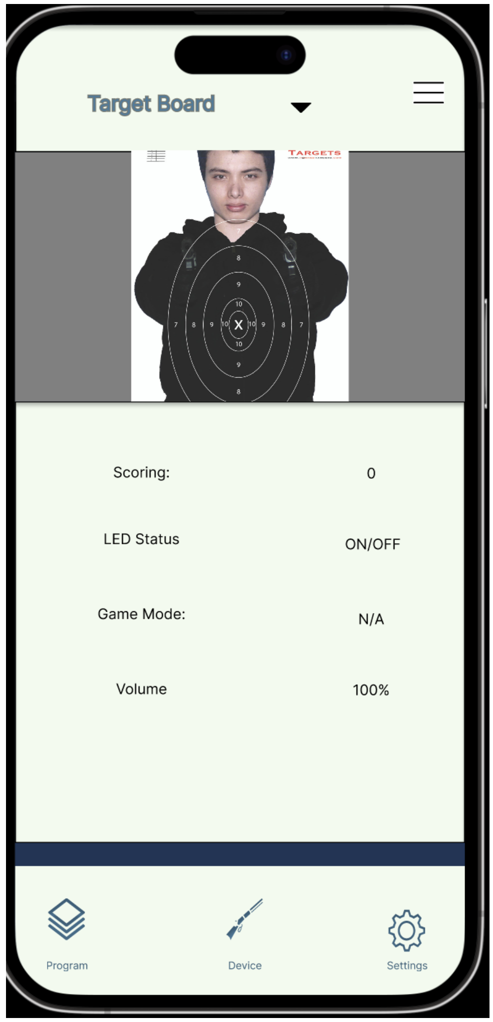


Figure xx.3 Target Board information (not final)

7.3.2 System Features Design

The **Figure xx.4** below shows every state of the entire system including during the gameplay that both Laser Rifle and Target Board would be in. The illustration is the finite state machine system that can very well explain the behavior of every state when the system shifts into states according to the user input or other environmental factors. In this example illustration, there are four states: PAIRING, READY, PLAY and END denoted by circles. Each state takes some type of input representing a transition arrow, and then outputs the result from one state to another followed by another transition arrow.

The PAIRING state is a start state where the Laser Rifle and the Target board begin the pairing request with the mobile application, connecting and communicating with each other. Once the pairing is established, it shifts its state to the READY state the system is waiting for user input or new instructions while maintaining consistent connections. On the mobile application, the user chooses the gameplay mode, and then the system will switch to the PLAY state indicating a game is currently running. If the game event has come to an end or is being interrupted somehow, then the system will switch to the END state which is also known as the accept state, denoted graphically by a double circle. For example, the input is “Game starts, game ends, game resets, game starts, game ends” then it would lead to the state sequence as READY, PLAY, END, READY, PLAY, END and is hence accepted.

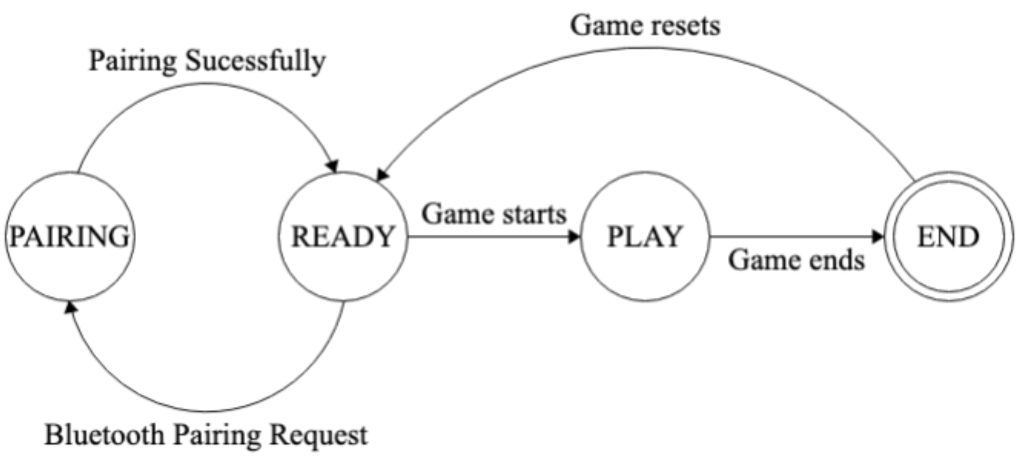


Figure xx.4 Laser Rifle and Target Board MCU State Machine Diagram

8.0 Administrative Content

This section deals with the managing aspects of our project. These mainly include our project deadlines, milestones, and associated budget.

8.1 Budget

This project will be self-funded by the group, with costs being split evenly among each group member. In **Table X54**, an estimated cost range for each item and an estimated minimum and maximum total cost is provided. We will buy extra parts for testing purposes and as backups. These prices will be reflected in the table. Additionally,

Part Description	**Price Range**

Rifle Frame	$50-75
Laser Diodes	$50-75
Lenses	$250-300
CMOS Sensor	$20-50
LCD Display	$10-30
LEDs	$20-40
3D Printer PETG	$100-150
IR Receivers	$20-40
Battery for Rifle	$15-30
Battery for Target Board	$15-30
Speaker	$5-10
Microcontroller Units (PCB)	$40-70
Vibration Motors	$10
Breadboard	$10
Misc Components	$40
Minimum	**$605**
Maximum	**$950**

Table X54. Estimated Budget

8.2 Scheduling and Milestones

Project deliverables and milestones for the Fall 2022 and Spring 2022 semester are shown in **Table X55**. The table will be updated as deliverables are completed.

Early Stage/Bootcamp			
Form Groups	**8/23/22**	**8/30/22**	**Complete**
Discuss Project Idea	**8/30/22**	**9/1/22**	**Complete**

Decide Meeting Schedule	**9/1/22**	**9/1/22**	**Complete**
Divide and Conquer 1.0 9/16			
Finalize Project Idea choice	**9/1/22**	**9/6/22**	**Complete**
Determine Budget	**9/6/22**	**9/12/22**	**Complete**
Hardware Diagram	**9/6/22**	**9/13/22**	**Complete**
Determine Objectives	**9/6/22**	**9/13/22**	**Complete**
Determine Standards	**9/6/22**	**9/13/22**	**Complete**
Determine Specifications	**9/6/22**	**9/12/22**	**Complete**
Divide and Conquer 2.0 9/30			
Group 6 DCV1 Meeting	**9/21/22**		**Complete**
Refine Goals, Constraints and Standards	**9/21/22**	**9/30/22**	**Complete**
Apply changes discussed in DCV1 Meeting	**9/21/22**	**9/30/22**	**Complete**
Create House of Quality	**9/21/22**	**9/30/22**	**Complete**
60 Page Draft Document 11/4			
Research and Document work	**9/30/22**	**11/4/22**	**Complete**
Refine Requirements, Constraints and Standards	**9/30/22**	**11/4/22**	**Complete**
Create Hardware Schematic	**9/30/22**	**11/4/22**	**To Do**
Create Hardware Testing Plan	**9/30/22**	**11/4/22**	**To Do**
Create Software Testing Plan	**9/30/22**	**11/4/22**	**To Do**
Design Mobile App	**9/30/22**	**11/4/22**	**To Do**
Wireless Considerations	**9/30/22**	**11/4/22**	**To Do**
Software to Hardware Integration Plan	**9/30/22**	**11/4/22**	**To Do**
Select Parts	**9/30/22**	**11/4/22**	**To Do**
Order Parts	**9/30/22**	**11/4/22**	**To Do**
100 Page Draft 11/18			
Parts Testing and documentation	**11/4/22**	**11/18/22**	**To Do**
Hardware Prototype Assembly Plan	**11/4/22**	**11/18/22**	**To Do**
Software Prototype Assembly Plan	**11/4/22**	**11/18/22**	**To Do**
Final Document 12/6			

Build and Test Hardware Prototype	**11/4/22**	**11/18/22**	**To Do**
Build and Test Software Prototype	**11/4/22**	**11/18/22**	**To Do**

Table X55. Fall 2022 Project Milestones

Appendices

Appendix A: References

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