

Shooting Gallery Simulator: Laser Based Shooting Gallery for Hunting Training

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Abstract — This project addresses the challenges associated with developing hunting skills in a safe and accessible environment. Traditional training methods often require expensive equipment, dedicated facilities, and the use of live ammunition, which can pose safety risks for beginners. Additionally, new hunters may lack opportunities to practice essential skills such as accuracy and reaction time without exposure to potentially dangerous situations. To overcome these limitations, the Shooting Gallery Simulator provides a safer alternative to traditional training methods. The system replaces conventional ammunition with a pulsed laser emitted from a rifle, which is detected by a target board composed of photodiodes. Interactive targets equipped with LEDs guide users on when and where to shoot, while a scoring system tracks performance and encourages skill development. To enhance realism and functionality, the simulator incorporates modular features such as a detachable rifle scope, a LiDAR-based rangefinder for distance measurement, and haptic and audio feedback to simulate firing. Designed for portability and usability in various environments, the system emphasizes safety, accessibility, and adaptability. Overall, this project aims to deliver a unique and effective training tool that improves hunting proficiency while minimizing risk and cost.

I. Introduction

Hunting demands a high level of awareness, precision, and ethical responsibility. Hunters must quickly identify targets and ensure that every shot is safe and deliberate. However, traditional training methods rely heavily on live firearms, which introduce safety risks and can limit opportunities for beginners to practice in a controlled environment. This creates a barrier for individuals seeking to develop fundamental hunting skills. The Shooting Gallery Simulator is designed to address these challenges by providing a safe and controlled training platform. Using a laser-based

rifle system and photodiode target detection, users can practice aiming accuracy and reaction time without the dangers associated with live ammunition. This approach allows beginners to build confidence while refining essential skills. Accuracy remains a cornerstone of ethical hunting, as precise shot placement is critical for both safety and effectiveness. To support this, the simulator integrates features such as haptic feedback, an adjustable scope, and a LiDAR-based rangefinder, creating a more realistic training experience. With the capability to simulate distances of at least 20 meters, the system prepares users for real-world hunting scenarios. Overall, the Shooting Gallery Simulator promotes responsible hunting practices while offering a practical and accessible method for skill development.

II. Features and Functionality

The main goal of the shooting gallery simulator project is to bring a variety of different components together into a cohesive package that has many modular components.

The main system is the main gun component and its reaction – the laser diode to photodetector system. Physically, this will take the shape of a type of actual rifle, with some clear changes to make it fit with our requirements. The rifle cannot be too big or bulky as to become uncomfortable or unwieldy, but it must be big and strong enough to carry all necessary components. Electrically, the laser diode and its corresponding driver are the main portion of the project. There will be a trigger the user can pull, which pulses the laser diode inside of the gun, which lets off a laser signal. This then leads to the second major portion of the project, the target boards, and target system.

The main board consists mostly of 3 individual target solo boards. These boards have their own photodetector and transimpedance amplifier (TIA) that are able to detect the laser pulse signal and output a current. The TIA then takes the small current that is outputted from the photodiode and increases the current and voltage significantly as to become easily readable from the software programmed on board the ESP32 on the main board. This will be the main basis of the project as the laser to detector system will be able to detect shots, and detect them as hits or misses.

On top of the main systems, there are a number of subsystems that are used in addition to the main systems as to create a full package.

The most important of these is the LiDAR ranging system that takes input range data from a LiDAR sensor that the system is able to use. There are other subcomponents too, such as a haptic feedback system, and many lenses. All of these assist in bringing the

project together, and our idea for a shooting gallery simulator to life.

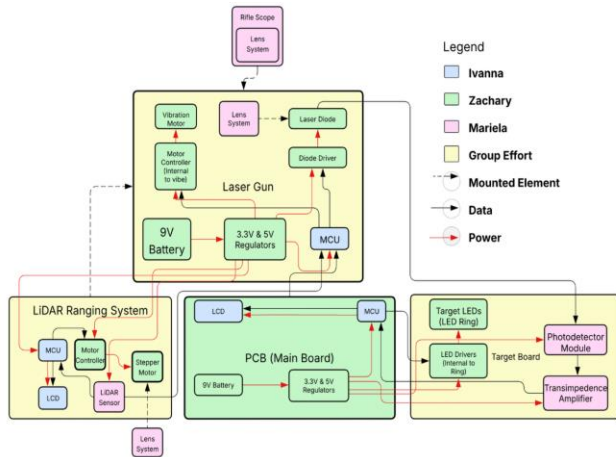


Fig. 1 Overall System Block Diagram

III. Systems and Subsystems

Given that our project is made up of one main system and several subsystems, there are many components that make up the project.

a. Laser Rifle

Our project is centered entirely around our laser rifle. Our ammunition is solely comprised from the pulses of a RLD65NZX2-00A laser diode, which has a wavelength of 658nm and an optical power of 7mW. The pulsing of the diode will be controlled by an ESP32, and one pulse will happen each time the trigger is pulled. It will also be able to hold modular attachments, which will be discussed further. In order to correct the divergence of the diode, there will be a beam expander system. It includes two cylindrical lenses perpendicular to each other in order to make the beam circular, and two plano convex lenses to expand the beam. Moreover, the gun will provide haptic feedback whenever a shot is fired to provide a more realistic training experience.

b. Target board

In order to detect a shot coming from the laser gun, we have made a target board that is comprised of several photodiode targets, specifically VBPW34S photodiodes. These photodiodes have a responsivity of 0.6 at a wavelength of 650nm which is very close to the wavelength of our laser diode. There will also be an optical filter placed in front of the targets to ensure that some ambient light is blocked out, and no false positives are detected by the photodiodes. Above these targets will be an LCD which will keep track of the user's accurate shots.

c. LiDAR Rangefinder

In order for the user to have a more realistic training experience, our project features a LiDAR rangefinder system for the user to know their distance from the target. This system will be completely modular so that the user is able to customize their experience in the way they please. Additionally, this system will have an automatic focusing feature to ensure the beam is always in focus when being detected by the LiDAR module. This autofocus system is comprised of one plano convex lens and one plano concave lens. These lenses will be positioned to provide the best focus according to the distances read on the LiDAR module.

d. Rifle Scope

Another main subsystem in our project is the rifle scope. It is completely modular, meaning it can be detached from the gun if the user wishes to do so. It also has a movable objective lens in order for there to be adjustable focus. The length of the scope is approximately 300 millimeters, and is comprised of four lenses, each with a different purpose. These lenses will be discussed further along.

e. Motor and Driver

The motor system is an addition to the LiDAR ranging system that will include an auto lens focus system. The motor is a 28BYJ-48 class motor, which is a cheap and simple system that uses 4 phases to control its pathing. The motor uses a ULN2003 driver, which is a simple constant current source that allows easy current control to the necessary 3 phases of the system. This will be controlled by the ESP32 software using LiDAR range and position data to determine where the motor has to move to meet necessary focusing requirements of the LiDAR lens system.

f. Feedback System

The vibration motor is a haptic feedback system that allows the user to clearly determine when the trigger has been pulled, and the system recognizes a shot has been fired. The system will provide slight audio feedback in terms of the buzzing of the unit, and there will be a haptic vibration within the gun whenever a shot is fired, similar to arcade games, and simulating bullet feedback.

IV. System Components

This section will go further into detail about what makes up each component in a more technical sense.

a. Rifle Scope Lens System

The rifle scope is comprised of four lenses. The first lens in the system is the eyepiece which is an achromatic doublet. Specifically, it is a Thorlabs AC254-030-A which has a focal length of 30 millimeters. This is the lens which will be closest to the user's eye. The following two lenses make up the erector system, which flips the image right side up so that the user does not see an upside-down image. Both of these lenses are Thorlabs LA1805-A, which are plano convex and AR coated. They have a focal length of 30 millimeters. The last lens in the system is the objective lens, which is the largest lens in the system in order to collect enough light to form a proper image. This is also an achromatic doublet, specifically a Thorlabs AC508-180-A with a focal length of 180 millimeters.

Two achromatic doublets were used in the system in order to reduce chromatic aberrations as much as possible. Although the erector system could have been comprised of achromatic doublets as well, they were ultimately too expensive to implement. Below is a Seidel Diagram which shows how the aberrations behave throughout each surface of the system. On the right of the diagram is the total aberrations of the system. It can be seen that they were greatly minimized with the lenses discussed previously.

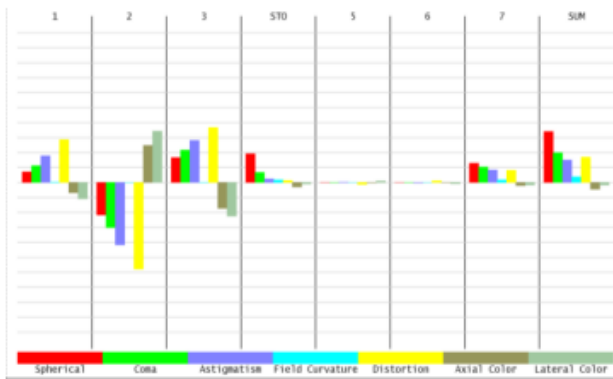


Fig. 2

b. Rifle Beam Expander

The beam expander system has two functions: to reshape the beam and to expand it. It is comprised of four different lenses. The first part of the system where the beam is reshaped includes two cylindrical lenses. These two lenses are placed perpendicular to each other in order to correct the divergence of the laser diode. Additionally the ratio of the lenses' focal length must equal the ratio of the slow and fast axis divergence. The first lens is a Thorlabs LJ1918L1-A, which has a focal length of 5.79 millimeters. The second cylindrical lens is a LJ1155L1-A with a focal length of 19.7 millimeters, making the ratio of these two focal lengths

approximately 3.4. The laser diode has a fast axis divergence of 28 degrees and a slow axis divergence of 8.5 degrees, making the ratio of the divergences approximately 3.3. Moreover, the distance between the laser diode and the first lens must be equal to that lens' focal length. This also applies to the second cylindrical lens in the system.

The following two lenses make up a Keplerian beam expander. The first lens that makes up this system is a Thorlabs LA1805-A, which is a plano convex AR coated lens with a focal length of 30 millimeters. The following lens is a Thorlabs LA1461-A which is also a plano convex AR coated lens, but has a focal length of 250 millimeters. With these focal lengths we are able to achieve a magnification of 8, proven below:

$$M = \frac{F_1}{F_2} = \frac{250}{30} \approx 8.33$$

In order to determine the distances required between the lenses to have the best focus, we had to look at geometric optics theory. For a Keplerian system, the distance between lenses is determined by the following equation:

$$d = f_1 + f_2 = 30mm + 250mm = 280mm$$

Using this equation and the focal lengths of the two plano convex lenses, we see that the distance needed is 280 millimeters.

c. LiDAR Autofocusing Lens System

The LiDAR autofocusing lens system is made up of two lenses. One is a Thorlabs LC1715-A, which is a plano concave lens with a focal length of -50 millimeters. The following lens is a Thorlabs LA1708-A, a plano convex lens with a focal length of 200 millimeters. These two lenses create a Galilean beam expander, even though our intention is not to expand the beam. This is why we have a relatively low magnification for this system. Below is the calculation for the magnification:

$$M = \frac{|f_1|}{|f_2|} = \frac{200mm}{50mm} = 4$$

The distances between the lenses in this case can be calculated the same way they were calculated for the laser diode beam expander. Below are the calculations for this distance:

$$f_1 + f_2 = d$$

$$200mm + (-50mm) = 150mm$$

d. Microcontroller

The simulator incorporates two Espressif ESP32-WROOM microcontrollers as the central processing units of the system responsible for coordinating all the systems operations. These operations include signal acquisition, game logic execution, user interface integration and feedback control logic. The ESP32 is a dual-core 32-bit microcontroller operating at up to 240MHz allowing for rapid handling of multiple concurrent tasks within the systems' real time restrictions.

The MCUs integrated peripherals, including analog-to-digital converters (ADC), general-purpose input/output (GPIO) pins and dedicated timing hardware, make it a good option for operations which require both digital control and analog signal processing within a single platform.

The firmware within the target board operates using a continuous control loop that monitors ADC inputs from three separate OPA2380 transimpedance amplifier circuits, evaluates hit conditions and updates the system outputs accordingly. Analog data acquisition is integrated through this same control loop where a low-level photocurrent is produced using OPA950 photodiodes and then converted into a usable voltage. The voltage readings are then sampled, filtered and compared against the threshold to determine whether a valid event has occurred. To improve detection accuracy and reduce the effects of noise of ambient light, signal averaging and validation logic are implemented into the software.

An LED feedback system is also controlled by the firmware within the target board. This feedback system requires precise timing for driving the addressable RGB LEDs, the ESP32 is required to generate reliable signals for the LED system without excessive processor overhead. The MCU also interfaces with an ILI9486 TFT touchscreen LCD via the serial peripheral interface (SPI), which allows for real-time rendering of the graphical user interface (GUI) and processing of user inputs.

The ESP32 on the rifle system operates independently from the target board and is responsible for handling trigger input, generating laser pulses, controlling haptic feedback, and interfacing with the detachable LiDAR rangefinder subsystem. Managing these functions separately from the target board allowed for minimal latency between user input and laser emission. This ensures that the timing of each shot closely reflects real-world behavior and improves the overall realism of the training experience.

The LiDAR subsystem, which is a detachable feature for the rifle, provides real-time distance measurements between the user and the target. When connected to the rifle, the ESP32 on the rifles

communicates with the LiDAR sensor, continuously acquiring distance data, through the inter-integrated circuit (I2C) on the MCU. The information is then displayed on the ST7735S TFT LCD on the rifle to allow for enhanced distance awareness, playing a critical role in the users' decision-making and accuracy.

The data from the LiDAR is processed locally on the rifle and eliminates the need to transmit raw sensor data to the target board, reducing communication overhead and ensuring quick response times. In addition, the modular nature of the LiDAR allows the rifle to operate independently of this feature, allowing users to customize their experience without affecting the core functionality.

e. Power Supply

The power system is a combination of two different systems on both sides. The power input and delivery is reliant upon two different batteries that supply different levels of input current and voltage. There is a 8.4V rechargeable battery with a higher possible current output (at 8.4V) of up to 2.5A of continuous current. This is more than enough for our higher current applications, such as the motor and its driver, and the laser and laser driver. The other is a standard 9V battery, capable of pushing 200mA at a constant level. This will be used for all other sources not requiring higher current, such as the target boards. These feed into two different LM2596, an LM2596-5 and LM2596-3.3. These will supply the needed voltage of 5V and 3.3V to the entire system.

f. Transimpedance Amplifier and Photodiode

The laser from the rifle gun will be detected on the target boards, which is how the system will be able to detect hits or misses. This will be done by photodiodes which will convert the incoming laser light into an electrical signal.

The OP950 photodiodes, that were chosen for this system, are sensitive to the wavelength of the laser source and are able to efficiently convert the optical power into a low-value photocurrent.

The photodiodes do come with some limiting factors that have to be considered, the photocurrents that are generated from the photodiode are usually in the microampere range or lower, making for a very small photocurrent. These measurements cannot be detected directly using the ESP32's ADC. For this reason, in order for the ESP32 microcontroller to detect a hit or miss, an OPA2380 transimpedance amplifier (TIA) was provided to each photodiode. The OPA2380 has a low maximum input bias current of 50pA and a low input voltage noise density of $5.8nV/\sqrt{Hz}$, making it an ideal

option for the OP950 photodiode. The TIA is able to convert the low-value photocurrent from the photodiode into a measurable voltage that is readable to the ESP32's ADC.

Implementing the TIA included the configuration of a feedback resistor to set the gain of the system and a 22pF ceramic parallel feedback capacitor to stabilize the amplifier and limit high-frequency noise. In addition, the amplifier is biased around the midpoint voltage (approximately 1.65V), which allows the output signal to remain within the ADC input range of the ESP32. The midpoint voltage of 1.65V is generated using a resistive voltage divider that is connected between the 3.3V supply and ground.

V. System Concepts

a. Feedback and Response Time

An important standard in our system is making the time between pulling the trigger and receiving appropriate feedback reasonable. Our engineering specifications require both the input to be read, and the output response on the photodiode to be acknowledged in the respective software within 1 second. This will require an understanding of the response times of both systems, the trigger pull, and the reaction time of the photodiode and the respective software. It can be described by the following equation:

$$T_r = T_t + T_{pd}$$

Where the total response time, T_r , is the combination of the response time of the trigger pull to pulse the laser diode (T_t), and the response time of the photodiode detection system (T_{pd}). Each of these individual systems provides feedback, and their addition is the final result. This result must be under 1 second in order for the game and simulator to feel correct and be accurate to the real world it is trying to emulate. There is also an important consideration – the software/electrical response time that will inevitably come from any input. This will also be considered, such as time for a trigger input to be recognized, and time for the software to read the input and send its response.

The first system can be considered as the response time of the entire software recognizing the trigger pull to the laser diode being pulsed to turn on. The most obvious calculation is the travel time for the laser. For example, at 20m, using the speed of light:

$$T_{flight} = \frac{d}{c} = \frac{20}{3 \times 10^8} \approx 66.7ns$$

Where d is the target distance in meters, and c is the speed of light in meters per second. The time calculated, around 66.7ns, is almost negligible.

The other factors are much more difficult to calculate and need to be estimated. Electricity will also essentially move at the speed of light, so the main factor will be the ESP32's processing speed. The ESP32's ADC supports up to a 2 Msps sample rate, which would leave the sample rate speed minimum at about 0.5 us.

$$T_{sample} = \frac{1}{2 \times 10^6} \approx 0.5\mu s$$

All of these put together would have a response time (even with both ESP32s) at less than 1 millisecond, of course well below the required threshold.

This leaves only the response time of the trigger and the photodetector. The trigger will use a contact bounce and debounce time, while the photodiode has a rise and fall time. These specifications can be found in the datasheets, and most components have a very similar time. Our trigger button has a bounce time specified of ≤ 1 ms, and the photodiode has a rise and fall time of 100ns. Combining all of these (while adding an extra 50ms as a buffer to account for potential errors).

$$T_r = 66.7ns + (0.5\mu s \times 2) + 1ms + 100ns + 50ms \approx 51ms$$

As can be seen, the vast majority of the time calculated is in the given 50ms to account for errors, and the other portions play only a tiny factor in the final result. Overall, there is more than 940ms of available time, even with a generous amount of time given for potential errors. Our system should be well defined within the engineering specification threshold.

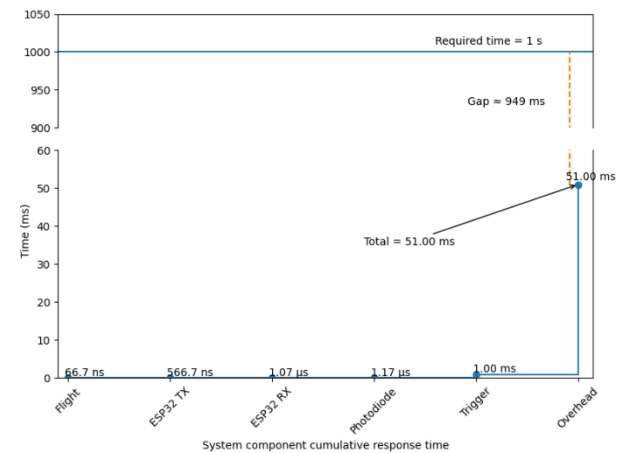


Fig 3. Time Response Graph

b. Transimpedance Amplifier and Photodiode Current

Another important consideration is how the laser will be detected on the target boards, and how this will be read throughout the system as a hit or miss. This will be done by photodetectors, but there are some limiting factors that have to be considered, such as small photocurrents. For this reason, and in order for the ESP32 microcontroller to detect a hit or miss, a TIA (transimpedance amplifier) was used to increase the current and voltage to a readable level.

In order to know what feedback resistor is needed for the TIA, some calculations were done. First, we needed to know how much photocurrent would be produced by our photodiode with our light source. Below is the calculation for this, where I_{ph} is the photocurrent, R is the responsivity of the diode, and P_{out} is the optical power of our light source:

$$I_{ph} = R \times P_{out} = 0.6 \text{ A/W} \times 7\text{mW} = 4.2\text{mA}$$

With this information, we can now use Ohm's Law to calculate the value of our feedback resistor. We have set our voltage value to be 1.65V since that will be the "swing point" on our TIA. Once this voltage is registered by the ESP, it will be registered as a shot hitting the target. Below is the calculation for the feedback resistor:

$$V_{out} = I_{ph} \times R_f$$

$$R_f = \frac{V_{out}}{I_{ph}} = \frac{1.65\text{V}}{4.2\text{mA}} = 392.86\Omega$$

c. System Detection Accuracy

Another key specification and part of our system is to be able to accurately detect a shot being hit or not, on top of the speed of that reaction and giving feedback.

The percentage accuracy can be simply measured by the number of expected hits and expected misses over the total number of shots fired, multiplied by 100 percent:

$$Accuracy = \frac{Misses_{Expected} + Hits_{Expected}}{Shots_{Total}} \times 100\%$$

Our system goal is an accuracy of least 95%, meaning this calculation should be higher than 95%. In our testing, we did find this accuracy to be consistently above this number, nearly never failing. So how did we accomplish this?

To achieve this level of accuracy, the system was specifically designed to be able to quickly and accurately distinguish between valid laser signals and ward off unwanted noise. Most of this is done from the chosen photodiode, but component placement also

matters. If two photodiodes are placed too close to each other, that could lead to false positive results. If LEDs are too close to the photodetector, it could also lead to weaker accuracy detection, and weaker response times.

Software-based validation also plays a crucial role in accurate detection. The ESP32 microcontroller interacts with the photodetector and TIA combination. The microcontroller will continuously monitor the incoming signal (which is an appropriately high voltage of 1.65V to be read by the ESP32) and based off that signal, decide to react if a shot was registered.

On top of the TIA and target system, the gun will have its own system to determine if a shot was fired, and to make sure it goes off at the proper time. There is communication between the two separate ESP32 microcontrollers that allow the target board to read when the trigger was pulled (allowing it to determine if it was a hit or a miss) and the gun board to read if the shot was a hit or miss (allowing for clearer feedback based on the result).

VI. Software Detail

a. MCU Programming

The software architecture of the full system was implemented using the C programming language within the ESP-IDF framework on ESP32-WROOM microcontrollers. The system is distributed across two MCUs, one which is located on the rifle subsystem and the other on the target board. The firmware within the rifle ESP32 manages trigger input, laser pulse generation, LiDAR sensing, and motor control. On the target board the firmware manages photodiode signal acquisition, LED feedback, graphical user interface (GUI) rendering, and gameplay logic.

The firmware is structured around continuous control loops and task-based execution using FreeRTOS. Each subsystem works as a modular component, allowing for independent operation and customized experience. The main goal was to maintain synchronization through the shared state variables and event-based communication.

The system utilizes multiple hardware peripherals, which include:

1. General-purpose input/output (GPIO): trigger detection, laser control, motor driving.
2. Analog-to-digital converter (ADC): photodiode signal acquisition.
3. Remote Control Peripheral (RMT): addressable LED control.
4. Serial Peripheral Interface (SPI): LCD and touchscreen communication

5. Inter-Integrated Circuit (I2C): LiDAR distance measurement

This architecture enabled efficient coordination of sensing, processing and feedback mechanisms within the unified system.

b. Laser Pulse Generation

The laser pulse is implemented within the rifle ESP32. To ensure consistent operation a finite state machine model is implemented into the program. The finite state machine approach helps guarantee that each trigger press results in exactly one laser pulse, preventing unintended multiple detections which could be a safety hazard for the user and their surrounding. The trigger input on the rifle is configured as an active-low GPIO, and each press generates a single laser pulse. The state machine model consists of five states:

1. Waiting for press
2. Debounce press
3. Firing pulse
4. Waiting for Release
5. Debounce release

A debounce delay was configured at 30ms to eliminate mechanical noise from the trigger input. The laser pulse duration was defined as 500ms to ensure that the emitted signal is long enough for reliable detection by the photodiode system while still avoiding continuous emission. The pulse for the laser is generated by setting the laser GPIO pin high, it is then delayed for the debounce time and once pulsed it is reset back to low.

c. Photodiode Signal Acquisition and Hit Detection

During an active session the target board ESP32 works with a sensing loop that continuously samples the output voltage provided by the TIA using the 12-bit ADC. The ADC has a maximum resolution of 4095 counts and operates with a reference voltage of 3.3V. To find the voltage measured from the ADC reading the following formula was used:

$$V_{out} = \frac{ADC_{raw}}{4095} \times 3.3V$$

To improve the measurement stability and reduce the effects of noise of ambient light, each reading is averaged over eight samples which is conducted periodically during the session setup, the following formula:

$$ADC_{avg} = \frac{1}{N} \sum_{i=1}^N ADC_i, \text{ where } N = 8$$

This process reduces the impact of random noise and small fluctuations in the analog signal. The voltage output from the TIA can be affected by electrical noise, ambient light changes and ADC quantization effects. By taking multiple samples and computing their average, the system effectively is able to smooth out high frequency noise components and prevent inconsistent hit detections.

A series of thresholds are put into place to work with the esp32 to detect a hit. A hit is detected when the measured voltage exceeds 2.9V which was determined after testing several laser hits to the photodiodes. It is cleared when the voltage drops below 2.7V. The detection condition can be expressed as:

$$|V_{out} - V_{ref}| > V_{threshold}, \text{ where } V_{ref} \approx 1.65V$$

d. LiDAR Measurement and Motor Control

The detachable LiDAR subsystem is interfaced with the rifle ESP32 using the I2C protocol and operates at 100kHz. Each measurement cycle consists of initiating a ranging command, polling the sensor until the measurement is complete, and retrieving both the distance and signal strength value.

To improve the measurement reliability, the system collects 20 samples at start up and computes the average distance, variance and a standard deviation. This helps prevent noise, reflection inconsistencies and any environmental interference. The average is calculated using:

$$D_{avg} = \frac{1}{N} \sum_{i=1}^N D_i$$

The variance and the standard deviation are then calculated to evaluate the measurement quality:

$$\sigma^2 = \frac{\sum D_i^2}{N} - (D_{avg})^2 \text{ and } \sigma = \sqrt{\sigma^2}$$

The standard deviation is gathered to calculate how many individual measurements deviate from the average. If the standard deviation is low this can indicate that the measurements are consistent and reliable, a high standard deviation suggests instability or noise in the reading and reports an error to the user through the LCD display on the rifle.

The LiDAR sensor also provides a strength value to represent the intensity of the returned signal. A stronger strength signals that the measurements are

more reliable while a weaker strength communicates to the auto-focusing lens system to move the motors and realign the lenses.

When the system determines the strength to be too low the motor is activated. The motor system is controlled using GPIO outputs connected to a stepper motor. The motor follows a predefined stepping sequence where the position is determined by the number of steps using the following formula:

$$\theta = \frac{\text{steps}}{\text{steps}_{\text{per revolution}}} \times 360^\circ$$

e. Game Logic and Results Processing

The gameplay system on the target board uses state-driven architecture that can be switched through using the GUI. The system supports two game modes: Reaction based and Freestyle Mode.

When a reaction-based game is chosen, the performance is evaluated by the number of rounds the user chooses to play. Each round records correct hits, incorrect hits, and the rounds accuracy. The overall accuracy is calculated in two formats, the shot-based accuracy is weighed by all the shots regardless of the round and then round success rate which calculates accuracy by finding the average of all the individual round accuracy. Each round calculates a score which is added to the total score for the full session. Below shows the equation for a rounds score:

$$\text{round_score}_i = (100 \times \text{correct_hits}) - (20 \times \text{incorrect_hits})$$

During a freestyle game, the score is calculated based on the number of shots the player hits. Each hit is counted as 100 points. The user also has the chance to win multipliers if hits are calculated with certain time ranges.

VII. Conclusion

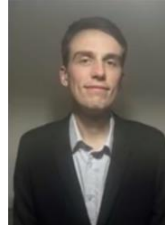
The Shooting Gallery Simulator successfully demonstrates a safe and cost effective alternative to traditional hunting training methods. By replacing live ammunition with a pulsed laser diode system and utilizing photodiode-based target detection, the design eliminates many of the risks associated with conventional firearms while still providing a realistic experience. The integration of modular attachments and user feedback enhances both the functionality and engagement of the project. From an engineering perspective, the system meets its core performance goals. The response time is well within the required

threshold and detection accuracy consistently exceeds 95%. Additionally, the use of ESP32 microcontrollers enables efficient coordination of sensing, processing, and feedback across distributed subsystems. The Shooting Gallery Simulator not only meets its initial objectives but also represents a meaningful step toward safer and more accessible training technologies in the field of hunting and marksmanship.

VIII. About the Engineers



Mariela Montanez is a graduating Optics and Photonics Student. She will be taking a job at Nova Photonics as an optical engineer, and will participate in several projects throughout her time there.



Zachary Romanoff will be graduating Spring of 2026 with a degree in electrical engineering. He hopes to continue his current career in test engineering with his offer from Lockheed Martin.



Ivanna Socarras is graduating with a degree in Computer Engineering. She is currently in the process of applying to a Masters program.

We would like to give a special thanks to our project reviewers Dr. Yannick Salamin, Professor Mark Maddox, Dr. Wei Sun for their help throughout this process, as well as our project advisors Dr. Chun Yong Chan and Dr. Aravinda Kar for their guidance.