

Projectile Tracking Chronograph (PTC)

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1 Executive Summary

The Projectile Tracking Chronograph (PTC) is a senior design project developed by Group 5 at the University of Central Florida for the 2026 Spring/Summer semesters. The interdisciplinary team consists of students from Optical Engineering, Electrical Engineering, and Computer Engineering. The PTC is an integrated ballistic measurement system that combines precise velocity measurement with optical trajectory estimation in a single, affordable platform.

Traditional commercial chronographs provide only muzzle velocity and offer limited or no information about the projectile's flight path. The PTC addresses this limitation by using a laser-based optical gate to accurately measure velocity while simultaneously capturing synchronized high-speed images of the projectile in flight. These images are processed in real time to extract spatial position data, enabling the system to reconstruct and visualize the projectile's trajectory, launch angle, and predicted impact point. The system will operate reliably in both indoor and outdoor environments by employing modulated laser detection and synchronized strobe illumination to minimize the effects of ambient light.

The PTC is designed to be user-friendly and suitable for hobbyists and educational use. It features an intuitive graphical interface that displays both numerical results and a graphical trajectory visualization after each shot. By integrating optical sensing, embedded processing, and real-time image analysis, the PTC provides a complete picture of projectile performance that is better than conventional chronographs at a significantly lower cost.

This document presents the complete design and development process of the PTC. It begins with the project background and motivation, followed by a detailed review of the current technologies. Subsequent chapters cover the research and component selection for all major subsystems, engineering standards and design constraints, hardware and software implementation, system fabrication, testing and evaluation, and administrative content.

The PTC represents a practical and innovative advancement in ballistic instrumentation, demonstrating how optical, electrical, and computer engineering can be combined to create an accessible measurement tool for modern shooting sports and research applications.

2 Project Description

2.1 Background and Motivation

The ability to accurately measure projectile velocity has long been fundamental to the study of ballistics and the advancement of shooting sports. Early methods relied on manual observation and empirical estimation, which were often inconsistent and dependent on environmental conditions. The development of mechanical ballistic chronographs in

the late nineteenth century introduced a scientific approach by measuring velocity from distance over time, laying the groundwork for modern ballistic instrumentation.

In contemporary applications, ballistic chronographs have become essential tools for competitive shooters, hunters, and militaries as they provide quantitative data about projectile performance. Even small variations in muzzle velocity can significantly impact a projectile's trajectory and bullet drop, specifically at long ranges. Competitive shooters depend on accurate velocity measurements to refine ballistics and ensure the target is consistently hit. Other measurements of extreme spread and standard deviation are of interest, where lower variability in these metrics directly correlates with tighter shot grouping and improved accuracy.

Modern commercial chronographs further enhance usability by performing real-time calculations of muzzle energy, allowing users to simply gather projectile data rather than manual processing. However, many advanced chronograph systems rely on technology that can be expensive for hobbyists. Additionally, the commercially available systems focus primarily on velocity measurement and provide limited insight about the projectile's trajectory without the use of specialized or high-cost radar technology.

The PTC project is motivated by the need for an accessible and transparent ballistic measurement system that goes beyond the basic velocity calculation. By leveraging optical sensing, precise timing, and embedded computation, PTC aims to provide accurate projectile velocity measurements while enabling trajectory estimation through angular and spatial analysis. Beyond its technical objectives, PTC serves as an interdisciplinary senior design experience; this effort brings together optical engineering expertise focused on laser optics and beam deflection, electrical engineering contributions centered on analog sensing and signal processing, and computer engineering responsibilities of embedded firmware, timing analysis, and user interface implementation. Through collaboration, the team aims to develop a ballistic measurement system while fostering teamwork and problem-solving skills essential for professional engineering practice.

2.2 Current Technologies and Relevant Projects

2.2.1 The First Patented Ballistic Chronograph

Early projectile velocity measurement can be traced back to the late nineteenth century through purely mechanical systems such as the Le Boulenger ballistic chronograph, which was patented in 1874. This device relied on electromagnetic release mechanisms to drop two metal rods at different times as a projectile passed through two spaced wire screens. Knowing the acceleration due to gravity and the fixed spacing between the screens allowed the projectile's velocity and flight time to be calculated. Although entirely mechanical, this approach established the fundamental concept of velocity measurement through precise timing, a principle that remains central to modern electronic and optical chronographs. [1]

2.2.2 Optical Chronograph

These devices operate by detecting the passage of a projectile across two optical sensors spaced at an identified distance. As the projectile passes over each sensor, the light received through the sensor is interrupted, generating electrical signals that are time-stamped to compute the projectile's velocity. [2]

While optical chronographs are relatively affordable and straightforward to operate, they are sensitive to environmental conditions. Measurement errors are introduced when there are changes in sunlight intensity, shadows, or improper projectile positioning. These commercial chronographs only display the velocity data. PTC builds upon the fundamental principle of measurement used by optical chronographs, but seeks to mitigate environmental sensitivity by designing laser-based detection and precise electronic timing, enabling improved consistency and expanded trajectory analysis beyond simple velocity measurement.

2.2.3 Magnetic Chronographs

Magnetic chronographs measure projectile velocity by detecting disturbances in a magnetic field caused by a projectile passing near a sensor array. These systems are typically mounted directly to the firearm barrel and do not rely on external lighting conditions. [2]

Magnetic chronographs introduce certain limitations despite their reliability. The attachment of the device to the barrel can slightly alter the harmonics of the barrel, affecting where the projectile impacts. Magnetic chronographs are not suited for spatial position movement since their purpose is to measure velocity close to the muzzle. In contrast, PTC is designed as a non-contact measurement system, allowing projectile velocity and angular trajectory to be determined without physical interaction with the firing mechanism, preserving ballistic integrity.

2.2.4 Doppler Radar Chronographs

Doppler radar chronographs represent the most advanced of the commercially available projectile measurement systems. These devices transmit radar signals that reflect off the projectile during flight, allowing the system to continuously track velocity based on Doppler frequency shifts. [2]

While radar-based chronographs offer excellent accuracy and ease of use, they are costly and rely on complex signal processing hardware, limiting user access to customization of raw data. PTC aims to explore an alternative approach by leveraging optical scanning techniques and real-time signal processing to achieve comparable spatial resolution at a lower cost. By using laser interruption timing and angular position mapping, PTC seeks to bridge the gap between basic optical chronographs and high-end radar systems.

2.3 Goals and Objectives

The PTC project is designed to extend traditional ballistic chronograph functionality by combining optical sensing, embedded computation, and user-friendly data presentation into a single system. The goals define the overall vision of the system and its intended capabilities, while the objectives describe measurable outcomes that guide implementation. The stretch goals are identified to encourage innovation beyond the minimum functional scope of the project.

2.3.1 Goals

Basic Goals:

- Develop an optical-based system capable of detecting a projectile as it passes through a defined measurement region.
- Accurately measure projectile velocity using precise timing and optical sensing techniques.
- Ensure the system operates reliably in indoor environments without dependence on ambient lighting conditions.
- Provide calculated results, including projectile velocity, to the user within 10 seconds of projectile detection.
- Present projectile-related information in an intuitive manner suitable for novice users.

Advanced Goals:

- Extend the system's measurement capabilities beyond velocity to include trajectory-related information, such as the direction of projectile travel.
- Display processed data on an integrated screen, enabling standalone operation without the need for external devices.
- Reconstruct and visualize a 3-dimensional representation of the projectile's trajectory.

Stretch Goals:

- Determine whether a projectile's trajectory would intersect a target with a one-meter diameter at a distance of ten meters.
- Integrate environmental sensing (such as temperature and humidity) to support improved ballistic analysis in outdoor environments.
- Incorporate atmospheric effects such as wind, temperature, humidity, and pressure into trajectory and offset calculations based on user-input target distance.
- Support a wide range of projectile velocities, from as low as 5 m/s to as high as 100 m/s.
- Determine and report the compass direction of projectile travel using onboard orientation and navigation sensors.

2.3.2 Objectives

Basic Objectives:

- Implement an optical detection system that does not require precise alignment by the end user.
- Capture projectile event data using optical sensors, cameras, or laser-based detection methods.
- Present results to the user via an integrated display with minimal user interaction required.
- Utilize a microcontroller such as a Raspberry Pi-based platform to coordinate sensing, timing, computation, and user interface tasks.

Advanced Objectives:

- Develop a calibration procedure that is intuitive, such as using known reference objects with the camera's field of view.
- Synchronize optical detection events with strobe lighting and camera/image acquisition to capture multiple images of the projectile in flight.
- Implement image processing and mathematical analysis to extract spatial information from captured images.

Stretch Objectives:

- Integrate a magnetometer to determine the compass orientation of the device and infer the compass direction of the projectile motion.
- Use an accelerometer to determine the vertical orientation of the system and calculate the projection elevation angle.
- Combine orientation, environmental, and optical data to improve trajectory estimation accuracy.

2.3.3 Projectile Tracking Chronograph: Features/Functionalities

The PTC is designed to provide a comprehensive set of features that extend beyond the traditional ballistic chronograph by incorporating various subsystems such as optical sensing, embedded computation, and spatial analysis. PTC implements an optical light detection system (light gate) that identifies a projectile as it enters the sensing region. By interrupting a modulated beam from a light source, the system generates high-speed timing events that are captured using hardware interrupts on the microcontroller. These events can be used to enable accurate time-of-flight measurements across a known distance, allowing for precise velocity calculations. The use of a modulated carrier frequency along with photodetector(s) that have a sufficient bandwidth will allow the system to operate in indoor and ambient lighting conditions. Additionally, PTC uses an optical chamber with synchronized strobe light illumination and camera imaging to capture multiple instances of the projectile as it is moving through the chamber. Once the initial velocity is obtained from the light gate, the microcontroller activates the strobe flashes and camera exposures. This in turn produces a single image containing multiple shadows of the projectile, each corresponding to a known interval of time. Image processing algorithms can then be executed on a Raspberry Pi to extract the spatial position data from the shadows of these images, allowing for the direction of the

projectile and its angular trajectory to be approximated.

This system also supports embedded ballistic and trajectory computation, combining the previous timing data and spatial measurements to calculate the projectile velocity, angular deviation, and estimated trajectory path through the measurement region. In our advanced and stretch goals, we would like to further enhance these calculations by incorporating other environmental data from other types of sensors. Integrating information from temperature, humidity, and pressure sensors can be used to further refine the ballistic calculations to increase the overall accuracy of the system by accounting for atmospheric effects. Furthermore, combining other sensors such as an accelerometer and magnetometer would allow the system to determine its own orientation. This capability would support other advanced features, like determining the compass heading of the projectile's travel path.

To enhance the usability of PTC, a user interface consisting of simple input controls and a display has been incorporated into the system. Processed ballistic results are to be presented to the user within seconds of the detection of the projectile. This interface is designed to be user-friendly while still providing meaningful data to the user. Collectively, these features make the PTC a powerful tool for projectile measurement and analysis.

2.4 Required Specifications

2.4.1 System Specifications

General System Specifications:

TABLE 2.1: Specification of System Components

Parameter	Description	Specification
Speed Measurement Error	The error of the speed detected of the projectile	$< 20\%$
System Response Time	The time from a projectile traveling through the system until information is displayed to the user	$< 5 \text{ s}$
Detectable Projectile Size	The diameter of a spherical projectile that can be detected and characterized	15 mm to 50 mm
Detectable speeds	The speed of a projectile that can be detected and characterized	10 m/s to 50 m/s
Angular Resolution Error	The error of the angle detected of the path of the projectile	$< \frac{1}{5} \text{ radian}$

Power Requirements	The power the system will draw on average over the course of 10 seconds	$< 300 \text{ W}$
Sensing Area	The area of the system that will be able to sense projectiles through it	$> 10 \text{ cm} \times 10 \text{ cm}$
System Size	Total size of the system	$< 3 \text{ m} \times 3 \text{ m} \times 3 \text{ m}$
System Weight	Total weight of the system	$< 50 \text{ pounds}$
Ambient Light Tolerance	The amount of ambient light the system can tolerate	$< 20 \text{ lumens per square foot}$
Cost	The total cost to make the system	$< \$1000$

2.4.2 Component Specifications

Specific Component Specifications:

TABLE 2.2: Specification of Project Components

Component(s)	Description	Specification
Camera(s)	The sensor area, the quantum efficiency of detecting the photons in the wavelength of the strobe, and the resolution of the sensor	$\geq 6 \text{ mm}$ sensor width; 600–700 nm spectral sensitivity; 50–70% quantum efficiency @ 650 nm; 1600×1200 – 1920×1200 pixel target resolution; 200–500 fps target frame rate; $\geq 60 \text{ dB}$ dynamic range
Photodetector(s)	The responsivity of the photodiode in the wavelength of the emitting laser or LED wavelength, the noise floor of the photodiode, and the bandwidth of the photodiode	$> 100 \text{ kHz}$ bandwidth; 0.3–0.6 A/W @ 650 nm; 5–10 mm width; $\geq 20 \text{ dB}$ SNR during beam interruption
Gate light source(s)	The light source for the initial light gate for detecting the projectile entering into the system	635–670 nm; $\leq 1 \mu\text{s}$ rise/fall time; 10–100 kHz carrier frequency; $\geq 80\%$ modulation depth; $\geq 100 \text{ mm}$ line length

Environmental Sensor(s)	Accuracy of the humidity, temperature, and pressure sensors	$< \pm 10 \text{ hPa}$ at 1000 hPa ; $< \pm 5\%$ humidity at $30\text{--}80\%$; $< \pm 5^\circ\text{C}$ at $10^\circ\text{C}\text{--}50^\circ\text{C}$
Power Supply	Provides a regulated voltage and current to power the electronic devices	$\geq 50 \text{ A}$ continuous current; $12\text{--}48 \text{ V}$ output; $\leq 2\%$ ripple; $\leq 5 \text{ ms}$ transient response recovery
Strobe Light Mechanism	Capabilities of the subsystem that creates the strobe flashes	$< 200 \mu\text{s}$ flash time; $< 100 \mu\text{s}$ turn-on time; $< 100 \mu\text{s}$ turn-off time; $> 1000 \text{ lm}$ output
Physical System Structure	Physical layout of the system	$> 10 \text{ cm}$ sensing width/height; $< 2 \text{ m}$ sensing length; $< 3 \text{ m}$ height; $< 2 \text{ m}$ width; $< 3 \text{ m}$ length
User Interface	User interface specifications	$> 2 \text{ cm}$ screen size; $< 1 \text{ m}$ screen size
Microcontrollers and Computers	Microcontroller and computer specifications	$> 1 \text{ MHz}$ MCU clock speed; image processing capability for computer

2.4.3 House of Quality

In this section is a House of Quality showing the relationships (main body) between various customer and engineering requirements, as well as the correlations between those engineering specifications (roof). The relationships in the main body between customer and engineer have different weights depending on how closely one affects the other, with the strongest relationship having a weight of 7 and the weakest having a weight of 1. Each requirement also has a polarity, denoted by an up or down arrow, that displays the desirability said requirement. For example, "Affordability" would have a positive polarity because a cheaper product is a more desirable trait. In the roof of the House, the correlations between engineering tradeoffs can be seen. A positive correlation means that improving one engineering requirement also benefits another, while a negative correlation means that improving one engineering requirement comes at the detriment of another.

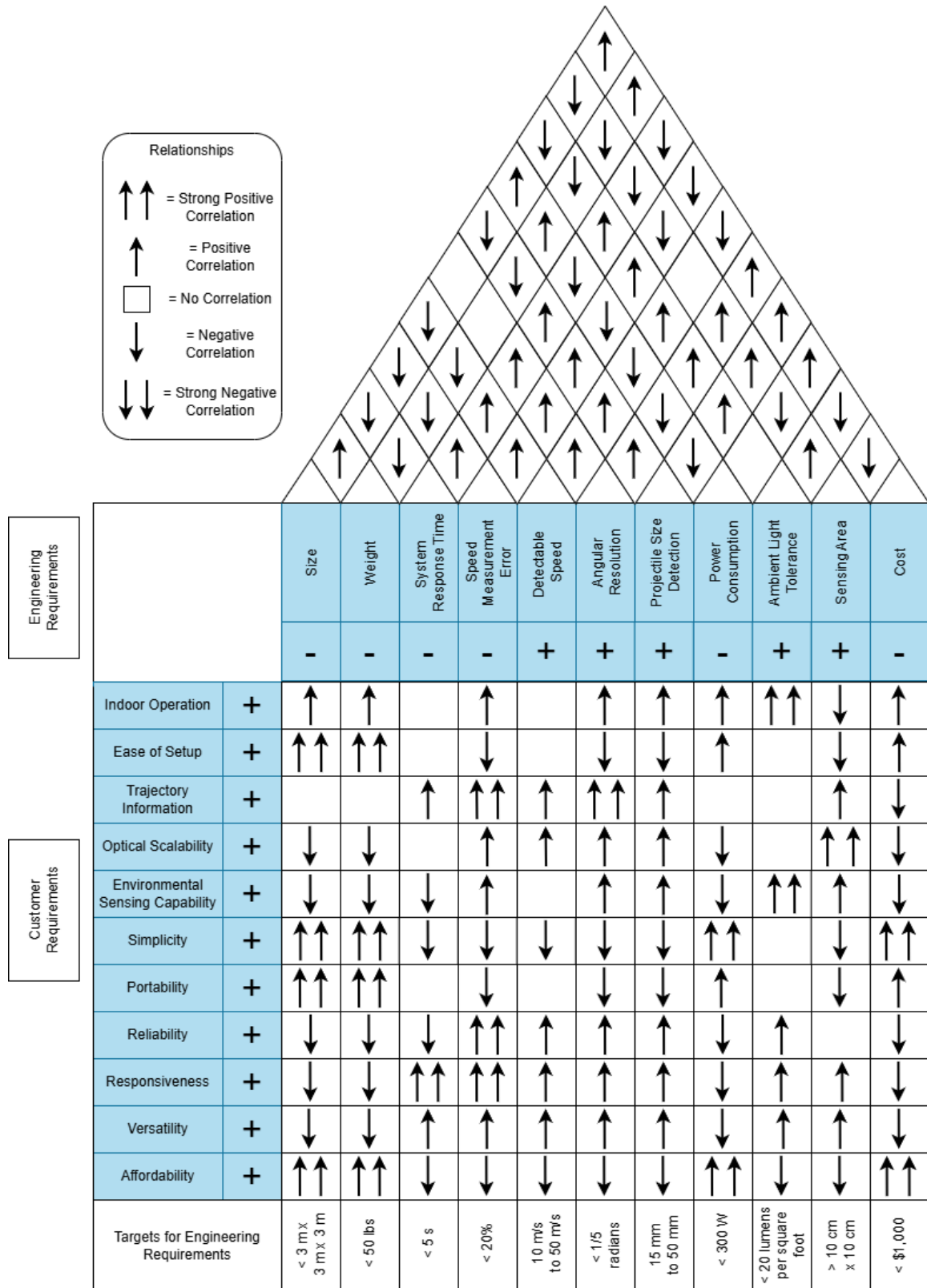


Fig. 2.1: House of Quality diagram that shows the tradeoffs between the engineering and customer requirements of the project. The customer requirements (left-most column) depict the features that are more important to the user, while the engineering requirements (top row) show the features that are considered for various engineering aspects of the project

2.5 Optical Hardware

The system will consist of a light gate (or sensor gates) and an area for strobe photography of the projectile (optical chamber). The initial light gate will get a projectile speed that will determine the timing of the strobe flashes. The camera(s) will take one photo that contains multiple shadows of the projectile at the points in time where the strobe is triggered.

The cameras, lenses, and strobe LEDs depend on each other. The LEDs must be bright enough to drown out the ambient light leaking into the box in order to provide a good signal to the cameras. The lens system must be designed to capture enough light to provide a sufficient signal to show the projectile on the cameras. The LEDs will need to flash for a short enough time to avoid too much blurring of the projectile in the chamber; however, they should flash for a long enough time to provide sufficient light to activate the camera sensor enough to get an acceptable picture. A rough estimate of a camera that operates at 30 fps can comfortably film at typical bedroom levels of illumination, which is about 10 lumens/square foot. Given an approximate strobe area of 2 square feet, and about 20% illumination efficiency, that would be 100 lumens for the 1/30 s or 33 ms that a camera frame lasts. With a 100 microsecond strobe time, that's 330 times the brightness needed for an equivalent amount of light to hit the camera sensor during the 100 microsecond strobe, which gives at least 3000 lumens required from the strobe for a simple camera.

The initial light gate will be used to detect the projectile entering the system and its approximate speed. The photodiode must be of sufficient bandwidth to detect a fast-moving projectile (a paintball is about 17mm and travels at 90 m/s, which gives 180 microseconds of signal time) would require at least 5 kHz of bandwidth. A projectile that is 1/4 inch long and traveling at 1000 feet/s would require a 50 kHz bandwidth sensor to detect the projectile. In order to filter ambient light, a carrier wave of sufficiently higher bandwidth would be required, so 100 kHz would be the minimum for detecting a bullet.

In the following, the diagram elaborates on the design of the sensor gates and optical chamber responsible for detecting a projectile and taking a picture of the projectile as it moves through the enclosure. By interrupting the line of sight of the light source to its corresponding photosensor, a projectile can be detected for initial calculations to be made. As the projectile moves through the optical chamber, multiple cameras can be used to make further calculations that estimate position and trajectory.

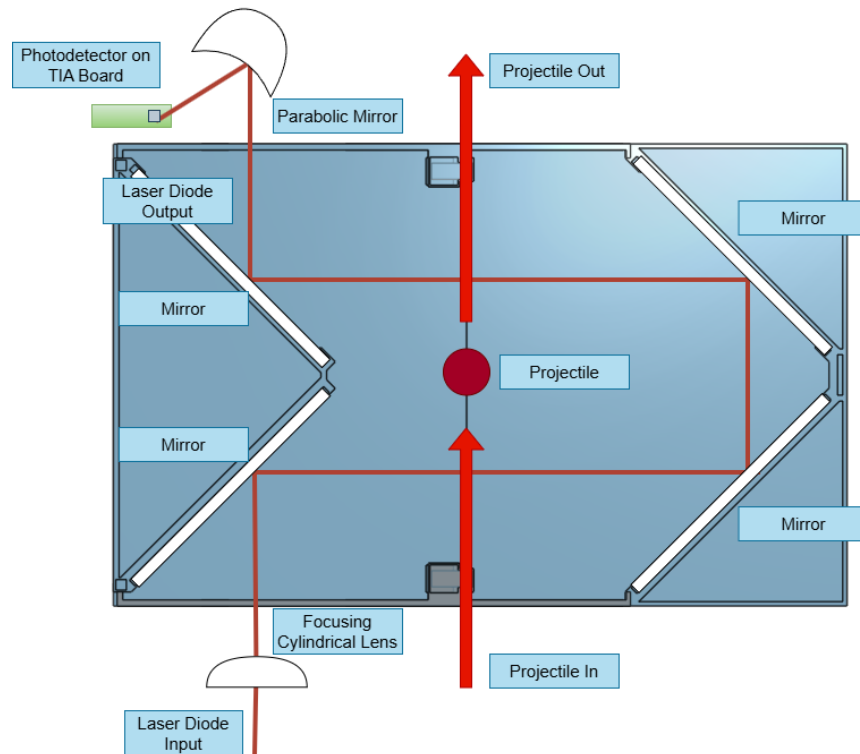


Fig. 2.2: Diagram of the movement of a projectile through the sensor gate subsystem

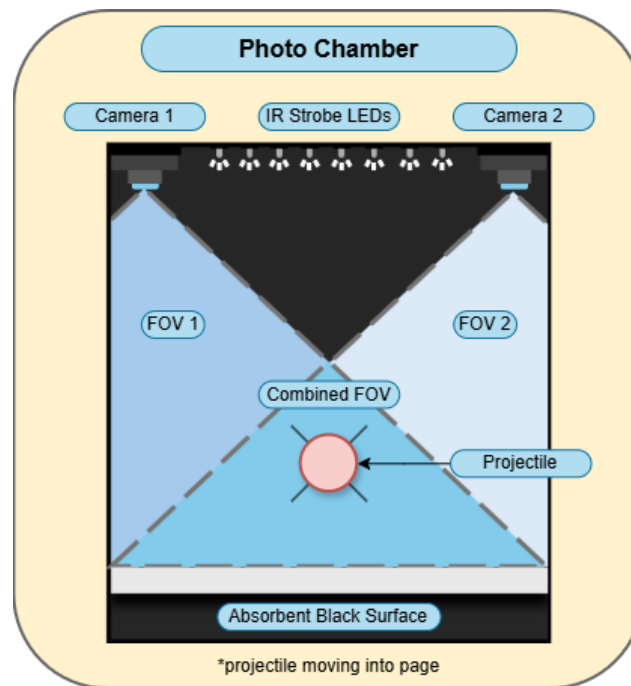


Fig. 2.3: Diagram of the movement of a projectile through the imaging subsystem

2.6 Electronics and Software

The hardware block diagram illustrates the necessary hardware and connections to facilitate our goals and objectives, as well as their current status at the time of this writing. Each block in the diagram is color-coded to indicate which team member will be primarily responsible for its research, design, and operation. The RP2350 MCU will be primarily responsible for handling sensor information and hardware-level interactions, whereas the Raspberry PI computer will be used for image processing of the projectile and to control the user interface. An optical sensor and chamber will be used to detect a projectile and take pictures, and these signals will be used by the RP2350 and the Raspberry PI to make calculations.

Projectile Tracking Chronograph

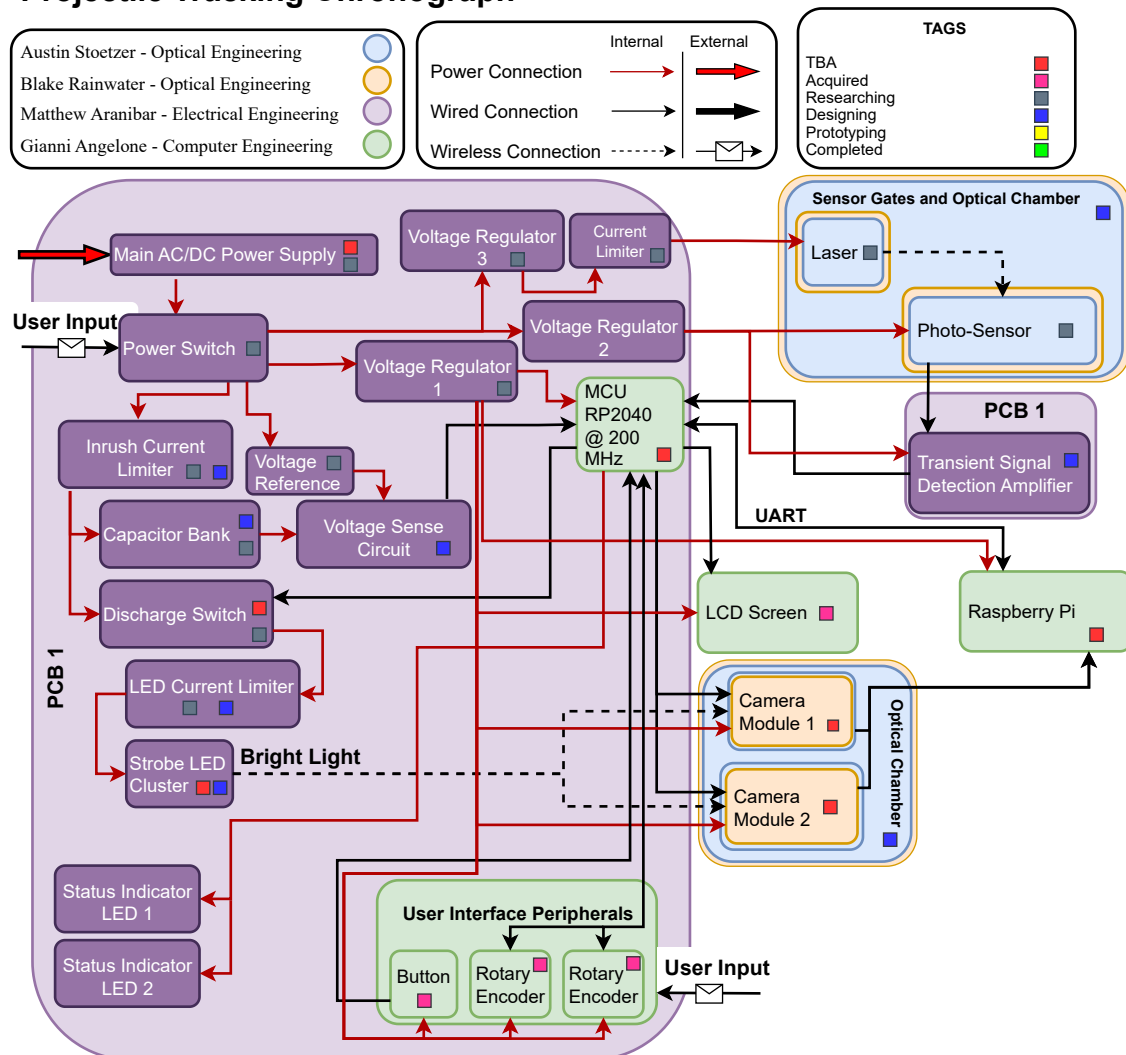


Fig. 2.4: Hardware Diagram of the PTC system that illustrates component connections, status, and division of workload

The software flowchart begins with the system power-on and initialization of the Rasp-

berry Pi subsystems. After loading the configuration settings and performing the necessary calibrations, the system enters a charging state to prepare the capacitors for the strobe LED cluster. Once the capacitors are fully charged, the software transitions into an armed "idle" mode that continuously monitors for a projectile detection signal from the sensor gate. Once a projectile is detected, the system will trigger synchronized strobe pulses and camera captures, followed by image processing to extract positional data from the projectile. The ballistic and trajectory calculations are then performed, with the results being displayed through the user interface.

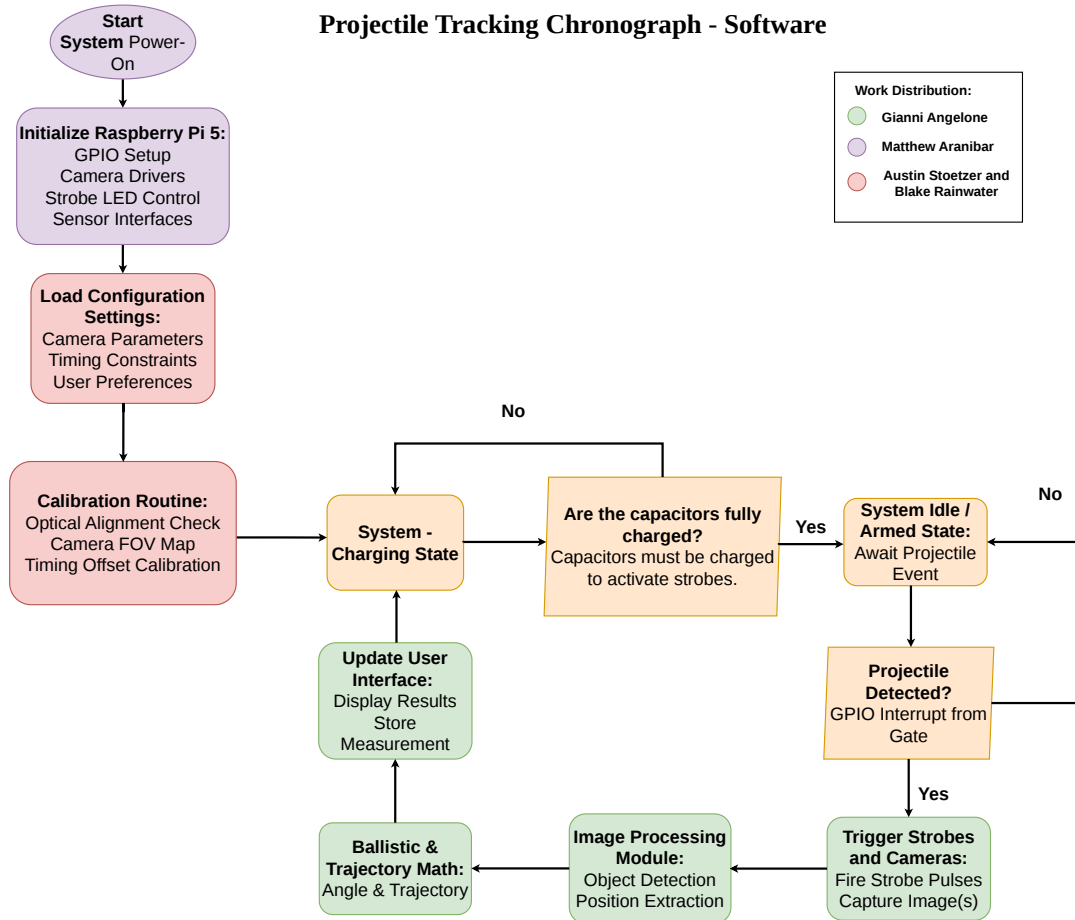


Fig. 2.5: The software flow of the Projectile Tracking Chronograph, detailing system initialization, projectile detection, data acquisition, processing, and reset to an idle state

The data flowchart of the PTC system, details the flow of data from initial projectile detection to final system output. The diagram outlines how optical interruptions at the gates trigger hardware interrupts that prompts the MCU to synchronize the cameras and LED strobes, enabling the capture of multiple images of the projectile as it moves through the system. These images are then processed using computer vision techniques to extract positional data, allowing for the velocity and trajectory to be calculated in the ballistic and trajectory engine. The resulting data from these subsystems is then communicated to the user interface, where the results are displayed.

Projectile Tracking Chronograph - Data Flow Diagram

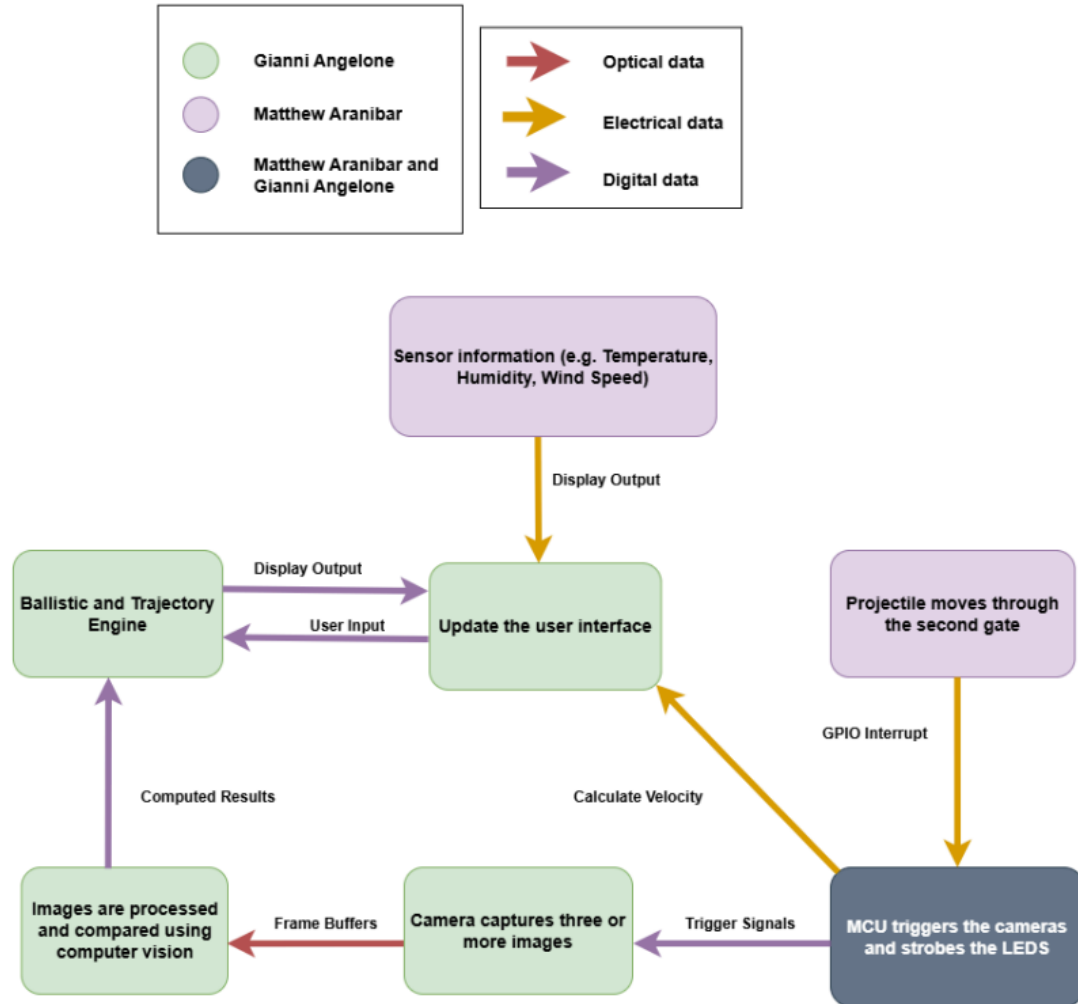


Fig. 2.6: Flowchart of the PTC system that illustrates the end-to-end data flow from optical event detection and hardware interfacing through synchronized strobe and cameras, image processing, and ballistic computation, outputting to the user via the user interface

The illustrations below present the current prototype configurations developed for the PTC. These figures provide visual context for the mechanical layout of the various system components described in the previous sections. These sketches are intended to provide a clear framework for system functionality during development and testing.

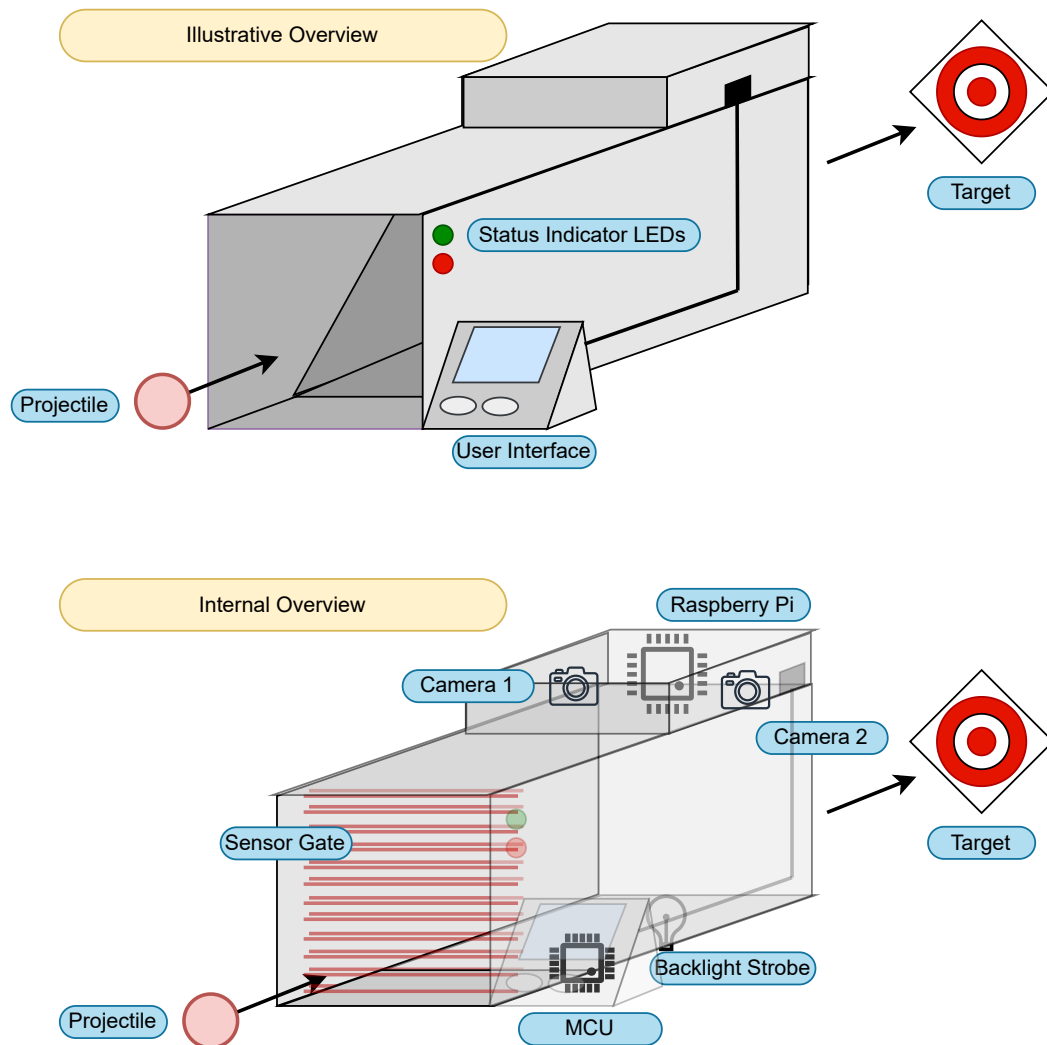


Fig. 2.7: Prototype Illustrations

3 Research and Investigation

3.1 Illuminative Technology - Light Gate

3.1.1 Light Sources

3.1.1.1 LEDs

LEDs are semiconductor devices that are capable of emitting light through a process called electroluminescence. This happens when charge carriers (electrons and holes) recombine within a semiconductor junction and produce photons. In an LED, this type of emission

is mostly driven by spontaneous emission, which means that the emitted photons have a random direction, phase, and polarization upon emission. These types of light emitter lack an optical cavity as well, leading to an incoherent light source that has a broad spectral distribution. [3], [4]

Due to their broad emission angle, LEDs are useful for many applications that require wide or diffuse illumination. Examples of this include general lighting, displays, and indicators. LEDs generally operate with low to moderate efficiency and can achieve long operating lifetimes as well. These light sources typically have lower optical power density and broader spectral output compared to laser diodes, making them less suited for high-precision optical measurements. [3], [4]

3.1.1.2 Laser Diodes

Laser diodes, like LEDs, are semiconductor light emitters that make use of carrier recombination to produce photons. Unlike LEDs, however, laser diodes utilize stimulated emission within an optical resonant cavity to produce monochromatic light that is coherent and highly directional. In stimulated emission, an incoming photon causes the release of an identical photon in phase and direction. Since the optical cavities operate as a positive feedback loop, these photon interactions get amplified, leading to a narrow beam of light that is concentrated at a single wavelength. [3]

Due to these properties, laser diodes can generate significantly higher optical power, maintain a narrow spectral linewidth, and support fast modulation at timescales much shorter than LEDs. These characteristics make laser diodes ideal for applications such as communications, sensing, and high-speed measurement systems. Drawbacks of these components are that they typically tend to be much more complex, have higher costs, and require better thermal management techniques. [3]

3.1.1.3 Technology Comparison - Light Sources

For the PTC project, we want modulated illumination across the sensing region, enabling reliable projectile detection when the gate is disturbed by a passing object. This light source must maintain sufficient intensity and uniformity to ensure consistent triggering while also being resistant to variations in ambient lighting. Due to these conditions, the light source chosen for this subsystem was the laser diode.

The coherent and greatly directional output of laser diodes enables the design to illuminate specified detection zones with minimal spreading and high intensity. Additionally, the advantages of laser diodes will improve timing accuracy and reduce the susceptibility of the sensor gate to ambient lighting variations. In contrast, LEDs produce broad light that would require large optics or complex lens systems to achieve a similar power density, increasing overall system complexity without delivering equivalent precision to the laser diode.

TABLE 3.1: Illuminative Technology Comparison

Feature	LED	Laser Diode
---------	-----	-------------

Emission Type	Spontaneous	Stimulated
Coherence	Incoherent	Coherent
Spectral Width	Broad	Narrow
Beam Directionality	Broad	Very Directional
Optical Power Density	Lower	High
Modulation Capability	Lower	Higher
Thermal Sensitivity	Low	Higher
Cost	Low	Higher

3.1.2 Wavelengths (Light Gate)

3.1.2.1 Ultraviolet

Ultraviolet (UV) light occupies the portion of the electromagnetic spectrum with wavelengths between 100 and 400 nm. Due to its relatively short wavelength, UV light carries higher photon energy compared to visible and infrared radiation. This higher energy enables strong interactions with biological compounds and photosensitive materials, making it very useful in applications for fluorescence analysis, photolithography, and sterilization. UV light can be divided into three main sub-categories: UV-A (315-400 nm), UV-B (280-315 nm), and UV-C (200-280 nm). [5], [6]

Although UV light is very useful, there are several challenges associated with using this light for optical sensing systems. For instance, many common optical materials and protective coatings absorb UV radiation, reducing the amount of light that can be sensed on photodetectors. Additionally, common silicon photodiodes have low sensitivity in the UV region because much of the incident light is absorbed by the protective window materials or the surface of the detector itself before photoelectric conversion can take place. These limitations can significantly increase the difficulty of trying to use ultraviolet detection for optical sensing without the use of specialized optical components. [7], [8]

3.1.2.2 Infrared

Infrared (IR) light consists of wavelengths longer than visible light, ranging from 700 nm all the way to 1 mm. In optical sensing systems, the near-IR region (700-1000 nm) is most commonly used because it can be easily generated by semiconductor emitters and efficiently detected by silicon photodiodes. Infrared emitters are used for a wide range of applications, such as remote control, night-vision imaging, and proximity sensors. [9]

One advantage of IR illumination is its ability to penetrate materials and scattering media more effectively than shorter wavelengths. Silicon photodiodes are able to maintain high responsivity throughout much of the near-IR region, often reaching peak sensitivity between 800 nm and 900 nm. This makes infrared illumination particularly viable for optical sensing systems that use photodiode detection. However, one drawback of IR light is that it is invisible to the human eye, making beam alignment and system testing particularly difficult. [8]

3.1.2.3 Visible (Red)

Visible light spans wavelengths from approximately 400 to 700 nm, corresponding to colors that are perceptible to the human eye. The red portion of the spectrum (about 620-700 nm) is particularly useful for optical sensing systems due to its compatibility with silicon photodetectors. Red light sources are frequently used in optical sensors, alignment tools, and various measurement systems because they provide a good balance between practical usability and detector sensitivity. [5]

Silicon photodetectors exhibit strong responsivity across the visible spectrum, especially the red region, allowing efficient conversion of photons into electrical signals. Furthermore, visible red light offers practical advantages during system development and operation, since the light can be easily observed by users. This visibility simplifies beam alignment and calibration, making troubleshooting processes much simpler compared to infrared systems. For these reasons, red wavelengths are commonly selected for optical sensing applications that require reliable detection and simpler system setups. However, one limitation of visible light is its sensitivity to ambient light. Since many common indoor lighting sources also emit strongly within the visible spectrum, background light can introduce noise and reduce the signal-to-noise ratio of optical detectors. [8]

3.1.2.4 Technology Comparison - Wavelengths (Light Gate)

Several factors are to be considered when choosing the wavelength for our light source, such as detector sensitivity, ambient light susceptibility, alignment convenience, and overall system complexity. UV light offers high photon energy and strong material interactions, but often requires specialized optical components due to factors such as reduced detector sensitivity and material absorption. IR light provides strong compatibility with many photodetectors and is widely used in sensing systems, but its invisibility to the human eye can make system alignment more difficult. [7], [9]

Visible red light provides many of the advantages of infrared illumination and adds more as well. Silicon photodiodes maintain high responsivity in this region, and the emitted light is visible, allowing simple system alignment and calibration. Due to these factors, the visible red wavelength was chosen as the primary wavelength for the sensor gate subsystem.

TABLE 3.2: Wavelength Technology Comparison

Feature	UV	Infrared	Visible (Red)
Typical Wavelength Range	100–400 nm	700 nm – 1 mm	620–700 nm
Photon Energy	High	Low	Moderate
Detector Compatibility	Lower for standard Si detectors	High for Si detectors	High for Si detectors
Visibility to Human Eye	No	No	Yes

Common Applications	Sterilization, fluorescence, photolithography	Remote sensing, night vision, proximity sensors	Optical sensing, alignment systems
Alignment Convenience	Difficult	Difficult	Easy
System Complexity	Higher	Moderate	Lower

3.1.3 Types of Lasers

3.1.3.1 Point Laser

A point laser is a light source that emits a highly focused, collimated beam concentrated into a small spot. This type of laser typically produces a Gaussian beam profile, where the intensity is highest at the center of beam and decreases radially outward. Due to its high optical power density and narrow beam divergence, a point laser is useful in applications requiring precise alignment, localized illumination, or high-accuracy targeting. Examples of this can be found in systems such as interferometers, laser cutting tools, and laser-targeting technologies. [10]

The high coherence nature of a point laser allows for extremely accurate spatial resolution, making it particularly useful in systems where only a single point in space being disturbed is desired. However, it is this same property that limits the point laser in applications that require coverage over a large sensing region. For applications like this, additional optical components will be required to expand the effective detection area, increasing overall system complexity and costs. [10]

3.1.3.2 Line Laser

A line laser is a laser source that has been modified to project the laser beam in a line rather than a point. This is typically achieved through the use of optical components, such as cylindrical lenses or other diffractive elements. These optics spread the beam in one dimension while maintaining collimation in the perpendicular direction. Due to this modification, the emitted light forms a continuous line across a surface, providing a much larger area of illumination than that of a point laser. [11]

These types of laser are commonly used in applications such as alignment systems, dimensional measurement systems, and machine vision technologies. Line lasers are particularly beneficial in systems where you want to illuminate an entire cross-sectional region simultaneously. However, since the optical power is distributed over a larger area, the intensity at any given point across the line is lower than that of a point laser, which can increase the need for more robust sensing in some systems. [11]

3.1.3.3 Technology Comparison - Types of Lasers

When selecting between point and line lasers, the primary consideration for the PTC project is the tradeoff between spatial coverage and optical intensity. The sensing system

benefits from illumination across a defined detection region rather than a single point. A line laser enables the creation of an optical "gate" that can be interrupted by a passing projectile. While the reduced intensity of a line laser compared to a point laser is a consideration, the benefits provided by the increased coverage of a line laser outweigh the drawbacks.

TABLE 3.3: Laser Type Comparison

Feature	Point Laser	Line Laser
Beam Shape	Focused point	Expanded line
Optical Power Density	High	Lower (distributed)
Coverage Area	Small	Large (1D spread)
Alignment Sensitivity	High	Lower
Need for Scanning	Often required for coverage	Not required
System Complexity	Higher (for large coverage)	Lower (built-in coverage)

3.1.4 Component Selection - Laser Diodes

3.1.4.1 Adafruit 1057 Laser Diode

The Adafruit 1057 laser diode module is a compact red line laser designed for low-power optical applications. This device operates at a wavelength of approximately 650 nm and provides an optical output power of up to 5 mW. It is designed to operate over an input voltage range of 2.8-5.2 V, with a maximum current draw of 25 mA. This is a Class IIIR laser that is made to have direct compatibility with low-voltage embedded systems without the need for complex driver circuitry. This module incorporates an integrated cylindrical lens that converts the emitted beam into a line pattern with a wide fan angle of approximately 120°, allowing for broad area coverage. The physical dimensions of this device are 10 mm in diameter and 32.8 mm in length, with wire length of 100 mm. This makes the module very easy to mount and integrate into compact systems. While this module provides low power consumption and overall simplicity, its performance is primarily suited for general-purpose sensing tasks. The datasheet for this particular device is limited in optical specifications, indicating that it is not optimized for high-precision measurement applications. [12]

3.1.4.2 Quarton Inc. VLM-650-23 LPO

The VLM-650-23 LPO is a miniaturized red line laser diode designed for precision alignment and sensing applications. This device operates in a wavelength range of about 640-655 nm and produces a line-shaped beam using a cylindrical lens system. It is designed to operate at an input voltage of 3-6 V with a maximum operating current of 50 mA. The module produces a total optical power of less than 5 mW, while the accessible laser output is limited to less than 1 mW, classifying this diode as a Class 1 laser device. The optical system consists of a collimating glass lens and a cylindrical quartz line lens, producing a line beam with a fan angle of $50^\circ \pm 5^\circ$. The resulting line has a width of less

than 1.5 mm at a distance of 2.5 meters and a line accuracy of approximately 4/1000, which is a deviation of less than 1.6 mm at 400 mm. Mechanically, this device has a cylindrical diameter of 5 mm and a length of 22.8 mm, with an approximate mass of 6 g. It operates in a temperature range of -20°C to $+65^{\circ}\text{C}$ and includes various safety features such as surge protection and reverse polarity features. This device has suitable characteristics for sensing applications, but can be a little restricted due to its smaller fan angle. [13]

3.1.4.3 Quarton Inc. VLM-650-27 LPT-10

The VLM-650-27 LPT-10 is an industrial red line laser module designed for applications requiring higher optical output and a large coverage area. This device operates in a wavelength range of 645-655 nm and requires an input voltage of 2.6-6 V. The VLM-650-27 LPT-10 is able to support two output regimens, with the first being a low-power configuration with an optical output of less than 2 mW and the second being a higher-power configuration producing 12-15 mW. These two modes have operating currents of below 35 mA and below 100 mA respectively. For this project, the low-power configuration was considered as this is a safer laser being categorized as a Class 1 laser device. The optical system consists of an aspherical plastic collimating lens and a quartz cylindrical lens, producing a line-shaped beam with a fan angle of 90° . The projected line has a width of 3 ± 0.5 mm at 5 m with an accuracy of approximately ± 1 mm at 5 m. Physically, this device has a cylindrical brass housing with a diameter of 12.5 mm and a length of 30 mm and operates in a temperature range of $+10^{\circ}$ to $+40^{\circ}\text{C}$. This device is intended for general industrial alignment applications, with a recommended working distance of more than 2 meters on average. This device has a fairly moderate fan angle, making it better suited for more compact systems. [14]

3.1.4.4 Quarton Inc. VLM-635-55 LPO

The VLM-635-55 LPO is an industrial-grade red line laser module that is optimized for precision alignment and high visibility. This device operates in a wavelength range of 630-645 nm and requires an input voltage of 3-6 V, with a maximum operating current of less than 80 mA. This module produces a total optical output power of 4-5 mW, while the accessible laser output is limited to less than 0.39 mW, making this a Class 1M laser device. The optical system uses both a glass collimating lens and a glass line lens to produce a uniform, line-shaped beam. Similar to the VLM-650-27 LPT-10, the VLM-635-55 LPO generates a line that has a width of 3 ± 0.5 mm at 5 m with an accuracy of approximately ± 1 mm at 5 m. This laser has a fan angle of 60° , which is less than that of the VLM-650-27 LPT-10. This laser module features an aluminum housing with a diameter of 10 mm and a length of 38 mm, with a mass of about 6 g. It operates in a wide range of temperatures, from -20°C to $+65^{\circ}\text{C}$ and can be stored in temperatures up to $+85^{\circ}\text{C}$. This laser was designed for precision alignment applications as well, but with a bigger working distance of up to 20 meters. Like the VLM-650-23 LPO, the fan angle is a limiting factor due to its smaller beam spread over short distances. [15]

3.1.4.5 Component Comparison - Laser Diodes

The Adafruit 1057 module emphasizes simplicity, low power consumption, and a very wide fan angle, but offers limited optical precision characterization compared to the industrial-grade alternatives. The VLM-650-23 LPO provides a balanced combination of compactness, low power operation, and a well-defined line being generated, making it well-suited for applications requiring greater optical control. The VLM-650-27 LPT-10, on the other hand, delivers higher optical power and wider coverage, improving performance in more compact systems and in environments with greater amounts of ambient light. One drawback of these improvements though is the increased cost and power demand required by this laser. The VLM-635-55 LPO offers enhanced visibility due to its shorter operating wavelength and higher brightness, but also has the same disadvantages as the VLM-650-27.

Cost further differentiates these laser diodes. Listed on the DigiKey website, the Adafruit 1057 is the cheapest, being priced at \$8.95, whereas the Quarton Inc. VLM-650-23 LPO, VLM-650-27 LPT-10, and VLM-635-55 LPO are significantly more expensive at \$79.40, \$75.16, and \$83.22, respectively. Although the Quarton Inc. modules provide improved optical performance, the increased cost is not justifiable for a system focused on reliable projectile detection rather than high-precision measurements. For the PTC project, the primary objective of the sensor gate is to achieve consistent detection across a defined sensing region while maintaining a compact, low-power design while also being cost-effective. The Adafruit 1057 meets our requirements by providing a very wide fan angle (120°) for sufficient coverage in a compact system, while also having adequate optical output power.

TABLE 3.4: Laser Diode Component Comparison

Characteristic	Adafruit 1057	VLM-650- 23 LPO	VLM-650- 27 LPT-10	VLM-635- 55 LPO
Wavelength (nm)	~650	640–655	645–655	630–645
Optical Output Power (mW)	≤ 5	< 5 (total), < 1 (accessible)	< 2 (low power), 12–15 (high power)	4–5 (total), < 0.39 (accessible)
Laser Class	Class IIIR	Class I	Class I (low power mode)	Class 1M
Operating Voltage (V)	2.8–5.2	3–6	2.6–6	3–6
Operating Current (mA)	≤ 25	≤ 50	< 35 (low) < 100 (high)	< 80
Beam Shape	Line	Line	Line	Line
Fan Angle (°)	~ 120	50 ± 5	~ 90	60
Line Width	N/A	< 1.5 mm @ 2.5 m	3 ± 0.5 mm @ 5 m	3 ± 0.5 mm @ 5 m

Line Accuracy	N/A	$\sim 4/1000$ (< 1.6 mm @ 400 mm)	± 1 mm @ 5 m	± 1 mm @ 5 m
Dimensions (mm)	$\phi 10 \times 32.8$	$\phi 5 \times 22.8$	$\phi 12.5 \times 30$	$\phi 10 \times 38$
Mass (g)	N/A	~ 6	N/A	~ 6
Operating Temperature (°C)	N/A	-20 to +65	+10 to +40	-20 to +65
ESD Protection	N/A	Yes	30 kV	30 kV
Recommended Distance	N/A	N/A	> 2 m	1–20 m
Cost (\$)	8.95	79.40	75.16	83.22

3.2 Internal Sensor Technology

3.2.1 Photodetectors (Internal)

3.2.1.1 Photodiodes

Photodiodes are semiconductor devices that convert incident light into an electrical current through the generation of electron-hole pairs within a p-n (or p-i-n) junction. Photodiodes are commonly operated in a reverse-bias mode, meaning that the diode provides a high resistive path to the flow of current. When photons are absorbed in the depletion region, charge carriers are generated and flow across the junction under a reverse-bias, thus producing a photocurrent proportional to the incident optical power. Operation in this mode allows for improved response speed and reduced junction capacitance, making them suitable for high-speed detection tasks.

Silicon photodiodes have strong responsivity across the visible red and near-IR spectrum, with peak responsivities typically occurring between 600-900 nm. At wavelengths near our desired wavelength of 650 nm, responsivity values typically range from 0.4 to 0.6 A/W. These devices are very desirable to precision timing applications due to their very fast response times, often in the nano- to microsecond range. They are able to respond this quickly due to their low capacitance and lack of internal gain mechanisms, however, this also results in a naturally small photocurrent being generated from the device. This necessitates the inclusion of transimpedance amplifiers (TIA) or other gain amplification circuits in order to generate a usable signal. [7]

3.2.1.2 Phototransistors

Phototransistors are another light-sensitive semiconductor device like the photodiode. However, these photodetectors operate more similarly to a bipolar junction transistor, with the incident light acting as the base current. When photons are absorbed in the base-collector junction, a small photocurrent is generated and then amplified by the current gain of the transistor. This internal gain results in significantly higher output current

compared to photodiodes, often reaching micro- to milliampere ranges under similar lighting conditions. [16]

The increased sensitivity of phototransistors allows for the detection of much lower light levels without the need of additional amplification circuitry. One drawback of this, however, is that the internal amplification often leads to slower response times due to the charge storage effects within the device. Additionally, phototransistors tend to exhibit reduced linearity, greater sensitivity to thermal fluctuations, and have increased noise compared to photodiodes. As a result, phototransistors are commonly used in applications where sensitivity in low-light situations are more important than speed and precision. [16]

3.2.1.3 Technology Comparison - Photodetectors

When comparing photodiodes and phototransistors, several key tradeoffs are evident, including response speed, sensitivity, and circuit complexity. Photodiodes provide a much higher response speed and low noise, with the drawback being the necessity for additional amplification circuitry. The phototransistor offers much larger output signals compared to photodiodes, at the cost of increased noise and lower response speeds. For the PTC project, the primary requirement for the photodetector subsystem is to detect rapid interruptions of the optical signal as a projectile passes through the sensing region. Therefore, we believe that photodiodes are the more suitable choice for this system as they provide the necessary speed and precision required to meet our goals for projectile detection.

TABLE 3.5: Photodetector Technology Comparison

Characteristic	Photodiode	Phototransistor
Operating Principle	Photon-generated carriers in reverse-biased junction	Photon-generated base current amplified by transistor gain
Internal Gain	None	High ($\beta \approx 50\text{--}300$)
Output Current Range	nA to μA	μA to mA
Responsivity @ 650 nm	$\sim 0.4\text{--}0.6$ A/W	Gain-dependent
Response Time	ns to μs	μs to ms
Bandwidth	High (MHz range)	Low (kHz range)
Linearity	High	Nonlinear
Noise	Low	Higher
Sensitivity	Moderate	High
Saturation Behavior	Minimal	Susceptible at high illumination
Temperature Sensitivity	Lower	Higher
Circuit Complexity	Requires amplifier	Simple
Power Consumption	Low	Moderate

3.2.2 Component Selection - Photodiodes

3.2.2.1 PDB-C142

The PDB-C142 is a silicon PIN photodiode designed for general visible and near-IR light detection applications. This device operates over a wavelength range of approximately 400-1100 nm, with a responsivity around of $\approx 0.53 \frac{A}{W}$ at 650 nm. This photodiode exhibits a relatively fast response time of around 50 ns under a 10 V reverse bias with a 1 k Ω load, making suitable for moderate-to-high speed sensing applications. This device supports a maximum reverse voltage of up to 100 V and exhibits a low dark current that is on the order of nanoamperes (5-30 nA), with a junction capacitance in the range of 18-25 pF. Additionally, this device exhibits a shunt resistance of approximately 100-500 M Ω , indicating low leakage characteristics. Under standard illumination conditions, this photodiode produces a short-circuit current of approximately 100-150 μA and has a noise equivalent power (NEP) of $2 \times 10^{-14} \frac{W}{\sqrt{Hz}}$ at the 650 nm wavelength. [17]

This photodiode is packaged in a 5 mm (T1 $\frac{3}{4}$) through-hole package with a clear lens. The active area of this device is approximately 4.12 mm² with a viewing angle of about 40°. Larger active areas allow for improved light collection efficiency, which allows for the alignment tolerances of the application to be less strict, but the small viewing angle can increase difficulty in alignment. The device operates over a temperature range of -40°C to +80°C, making well suited for applications both indoors and outdoors. While this photodiode offers a good balance between speed and sensitivity, but its relatively higher capacitance, compared to smaller surface-mount devices, limits its performance in high frequency applications. [17]

3.2.2.2 PDB-C171SM

The PDB-C171SM is silicon PIN diode designed for surface-mount optical sensing applications in compact systems. This device operates over a spectral range of approximately 350-1100 nm, with a stronger sensitivity in the red and near-IR regions. Specifically, this photodiode has a peak responsivity of 0.68 $\frac{A}{W}$ at 940 nm, with responsivities of 0.4 $\frac{A}{W}$ and 0.3 $\frac{A}{W}$ at 650 nm and 1050 nm respectively. This diode exhibits a typical rise time of 100 ns with a junction capacitance of 25 pF at a 3 V bias, supporting moderate-to-high speed detection. The PDB-C171SM produces a short-circuit current of 50 μA and NEP of $4 \times 10^{-14} \frac{W}{\sqrt{Hz}}$ at the 950 nm wavelength. The dark current was characterized to be 2-30 nA with a maximum reverse voltage of 60 V. [18]

This photodiode features a ceramic surface-mount package with an active area of about 7.5 mm² and a wide viewing angle of approximately 130°. Similar to the PDB-C142, this device operates over a temperature range of -40°C to +80°C. Compared to through-hole alternatives, this photodiode has a strong optical sensitivity with reduced parasitic effects. Overall, this device has a good balance between a large active area, good sensitivity, and reliable system integration, making it a good fit for compact sensing systems that require reliable detection like the PTC. [18]

3.2.2.3 PDB-C152SM

Like the PDB-C171SM, the PDB-C152SM is another silicon PIN photodiode designed for compact surface-mount applications needing reliable optical detection. This device operates over a wavelength range of about 400-1100 nm, with a peak responsivity of $\approx 0.52 \frac{A}{W}$ at 900 nm. At the wavelength of our selected laser diode (650 nm), the responsivity of the photodiode is $\approx 0.33 \frac{A}{W}$, which is not that great compared to other photodiodes at this wavelength. This photodiode has a typical response time of 50 ns with a junction capacitance of 15-20 pF at a 10 V bias, which supports moderate speed operation. The short-circuit current of this device is in the range of 8-10 μA and the NEP is $1.5 \times 10^{-13} \frac{W}{\sqrt{Hz}}$ at the peak responsivity. The PDB-C152SM has a typical dark current of 2 nA, with a maximum of 10 nA and a breakdown voltage in the range of 50-100 V. [19]

The device is packaged in a compact surface-mount form factor (1206) with an active area of approximately 1.66 mm² and a viewing angle of 120°. This photodiode has a very small active area, greatly reducing the light collecting capabilities compared to larger photodiodes. This device, like the others before, can be operated in the temperature range of approximately -40°C to +80°C. While this device offers fast response times and compactness, the reduced active area of this device makes it more suitable for applications that require wide-area sensing as opposed to a focused point. [19]

3.2.2.4 SFH 2713

The SFH 2713 is a high-speed silicon PIN photodiode designed for precise optical detection specifically in the visible spectral range. Specifically, the SFH 2713 operates at a wavelength range of 400-660 nm, with a peak sensitivity at 635 nm. This device exhibits very fast response characteristics, with a rise time of 22 ns and fall time of 31 ns (at a measured wavelength of 530 nm). The junction capacitance is approximately 50 pF and supports a maximum reverse voltage of 16 V. At a forward voltage of 5 V, the generated photocurrent of this device is 0.95 μA . The dark current is very low (around 100 pA), making the SNR of this device very high in low-light environments. [20]

This photodiode is packaged in a 2-SMD compact surface-mount configuration with a moderate sensing area of 3.27 mm². The SFH 2713 has a viewing angle of approximately 126°, which allows for a higher light collection yield despite the smaller active area compared to the other photodiodes listed above. This device operates at the temperature range of about -40°C to +85°C, allowing this device to be operated in slightly higher temperature conditions. While the SFH 2713 offers the fastest speed and reduced noise characteristics, the reduced active area makes it slightly harder to align. Ultimately, this photodiode is still usable for this project due to its high speed sensing in the visible wavelength range. [20]

3.2.2.5 Component Comparison - Photodiodes

The PDB-C142 photodiode has a moderate active area with a through-hole package, making it more suited for applications where the alignment tolerance can be more lax.

However, the larger junction capacitance limits its performance in higher-speed detection circuits. Both the PDB-C171SM and PDB-C152SM provide improved integration capabilities through their surface mount designs, enabling them to be easier to use in compact system layouts. Between the two, the PDB-C171SM offers a favorable combination of sensitivity and large sensing area, making it the more versatile choice in general detection applications. The SFH 2713 stands out in terms of speed and overall performance, with very low junction capacitance and fast response characteristics. However, one major issue with this photodiode is the very small viewing angle, making alignment especially difficult. The cost of the photodiodes is another factor that has great consideration. On the DigiKey website, the costs of one for these photodiodes are as follows:

- **PDB-C142:** \$3.32
- **PDB-C171SM:** \$4.49
- **PDB-C152SM:** \$1.96
- **SFH 2713:** \$1.86

For the PTC project, the primary objective of the sensor system is to achieve reliable and repeatable detection. Overall, we have decided that the PDB-171SM provides the best compromise between size and performance. Its surface-mount packaging allows for decent PCB integration, while still maintaining sufficient sensitivity. We decided that one of the most important factors for consideration was sensing area, as it greatly increases the light collection capabilities of our system. Additionally, the moderate junction capacitance and low dark current are able to support stable and repeatable detection measurements without complex amplification circuits. Even though this was the most expensive photodiode, the PDB-171SM was selected as the optimal photodiode for the PTC project.

TABLE 3.6: Photodiode Component Comparison

Characteristic	PDB-C142	PDB-C171SM	PDB-C152SM	SFH 2713
Spectral Range (nm)	400–1100	350–1100	400–1100	400–660
Peak Wavelength (nm)	~ 650–660	940	900	635
Responsivity (A/W)	~ 0.53 @ 650 nm	0.68 @ 940 nm; 0.4 @ 650 nm	~ 0.52 @ 900 nm; 0.33 @ 650 nm	N/A
Active Area (mm ²)	4.12	~ 7.5	1.66	3.27
Response Time (ns)	~ 50	~ 100	~ 50	22 (rise), 31 (fall)
Junction Capacitance (pF)	18–25 @ 10 V	25 @ 3 V	15–20 @ 10 V	~ 50
Dark Current (nA)	5–30	2–30	2–10	0.1–5

Max Reverse Voltage (V)	100	60	50–100	16
Breakdown Voltage (V)	15–25	N/A	50–100	N/A
Shunt Resistance ($M\Omega$)	100–500	N/A	N/A	N/A
Short-Circuit Current (μA)	100–150	~ 50	8–10	0.95
NEP ($W/\sqrt{Hz}$)	2×10^{-14}	4×10^{-14}	1.5×10^{-13}	N/A
Viewing Angle ($^{\circ}$)	~ 40	~ 130	~ 120	~ 126
Operating Temperature ($^{\circ}C$)	-40 to $+80$	-40 to $+80$	-40 to $+80$	-40 to $+85$
Cost (\$)	3.32	4.49	1.96	1.86
Light Collection Efficiency	High	High	Low	Moderate

3.3 Reflector Technology

3.3.1 Types of Reflectors

3.3.1.1 Flat Mirrors

Flat mirrors are reflective surfaces where, for an incoming beam, the angle of incidence equals the angle of reflection. These mirrors produce virtual images that appear to be located behind the reflective surface at a distance of equal length to the object in front of them. Flat mirrors maintain the size and orientation of the reflected images, making them useful for applications requiring very accurate undistorted reflections. However, these types of reflectors provide little to no focusing capability, which limits their utility for applications requiring beam collimation or focusing. [21]

3.3.1.2 Diffuse Reflectors

Diffuse reflectors scatter incident light in many directions. This scattering occurs due to the microscopic irregularities on the reflector's surface, causing the light rays to reflect at various angles. These types of reflectors are useful in applications requiring uniform illumination such as display backlighting or photography lighting. These types of reflectors are unable to concentrate optical energy onto a focal point due to their scattering nature, making them unsuitable for applications where beam collimation or focusing is important. [21]

3.3.1.3 Retroreflectors

Retroreflectors are optical devices that are designed to reflect incident light from an oncoming beam directly back toward the source, regardless of the angle of incidence. Devices such as corner cubes or arrays of glass beads that make use of the laws of

internal reflection and refraction are used to achieve this effect. These types of reflectors are commonly found in technologies where you want to spot the reflector, such as bicycle reflectors and road signs. While these reflectors are very effective at returning light to its origin, they do not focus light onto a separate focal point, limiting its use in application requiring light collimation or focusing. [21]

3.3.1.4 Parabolic Reflectors

Parabolic reflectors are surfaces that use a parabolic shape to ensure that all of the wave traces in a reflected beam light runs parallel to each other. This means that the parabolic reflector is able to transform an incoming plane wave traveling parallel to the optical axis into a spherical wave converging at the focal point. Conversely, this also means that a point source placed at the focus produces a collimated parallel beam upon reflection. This makes this type of reflector very useful in technologies such as the receiving dishes of radio telescopes or car headlights. [22], [23]

These types of reflectors can be configured in both on-axis and off-axis configurations. On-axis mirrors have the focal point located along the axis of symmetry, while off-axis parabolic mirrors are sections from a larger paraboloid. These off-axis configurations are able to position the focal point away from the incoming beam path, eliminating obstruction of the incident light by detector hardware placed at the focus. These types of reflectors are very useful for applications where the collimation and de-collimation of light is important. [21]

3.3.1.5 Ellipsoidal Reflectors

Ellipsoidal reflectors are surfaces shaped as an ellipsoid of revolution. These reflectors are characterized by their unique property of having two focal points instead of just one. Light originating from one focal point is reflected by the reflector, and this reflected light then converges at the second focal point. This property makes this reflector useful in application requiring the transfer of light from one point to another, such as medical illumination systems. However, these types of reflectors cannot collimate light into a parallel beam, requiring external optical components to achieve this effect. [21]

3.3.1.6 Technology Comparison - Types of Reflectors

When comparing these different reflector types for the PTC system, the primary requirements are the ability to reflect a sufficient amount of light and concentrate it efficiently onto a photodetector. Flat mirrors, diffuse reflectors, and retroreflectors lack the focusing capability that is required for the design of the system. Ellipsoidal reflectors are able to transfer the light between two points, but ultimately fails at collimating or focusing parallel rays from extended sources. Parabolic reflectors uniquely combine the ability to both collimate light from a point source into a parallel beam while also being able to focus that same light back down to a single focal point. This bidirectional focusing property makes parabolic reflectors the optimal choice for the PTC system.

TABLE 3.7: Reflector Technology Comparison

Characteristic	Flat Mirror	Diffuse Reflector	Retroreflector	Parabolic Reflector	Ellipsoidal Reflector
Focusing Capability	None	None	None	Single focal point	Two focal points
Collimation Capability	None	None	None	Yes	No
Spherical Aberration	N/A	N/A	N/A	None	None
Light Concentration	None	None	None	High	Moderate
Reflection Pattern	Specular (single angle)	Diffuse (scattered)	Back toward source	Converging to focus	Point-to-point transfer
Alignment Sensitivity	Low	Very Low	Low	Moderate	High
Suitability for Light Collection	Poor	Poor	Poor	Excellent	Limited

3.3.2 Reflective Materials

3.3.2.1 Glass

Glass mirrors consist of a glass substrate with a metallic coating applied to one surface. This substrate provides great flatness and stability for the reflective coating. Front-surface glass mirrors place the metallic coating on the side incident to the oncoming beam, eliminating double reflections that occur in rear-surface mirrors where the light passes through the glass before and after reflection. These mirrors can have varying reflectivities based on the applied coatings, but aluminum-coated glass mirrors can have reflectivities in the range of 85-90% in the visible spectrum. One drawback of these mirrors though is that for the PTC system, a mirror that fits the exact sizing requirements for our sensing region can be significantly more expensive due to the large sensing area. [21]

3.3.2.2 Aluminum

Aluminum is a reflective metal that is commonly used in optical applications due to its high reflectivity in the visible spectrum. Polished aluminum surfaces can achieve reflectivity values of approximately 88-92%, with stronger performances falling in the red and near-IR regions. Aluminum maintains a relatively consistent reflectivity across a broad wavelength range of wavelengths though, from UV to IR. Other advantages of aluminum include low cost and good corrosion resistance. This material also has a good thermal conductivity, which helps dissipate heat in high-power applications. These factors make aluminum a preferred choice for many different applications. One drawback of aluminum is its relative difficulty to polish to an optical grade performance that allows for a collimated beam to remain collimated after reflection. [21], [24]

3.3.2.3 Silver

Silver has the highest reflectivity of any metal across most of the visible spectrum, achieving reflectivities of 95% at wavelengths above 450 nm and nearly 99% in the IR region. This makes silver an extremely useful coating material for applications where maximum optical efficiency is required, such as precision optical instruments or telescope mirrors. One drawback of silver, however, is that silver tarnishes over time due to reactions with sulfur compounds in the atmosphere, significantly degrading reflectivity. This can make the use of silver in applications that are outdoors cost ineffective due to this tarnishing effect. Protective overcoatings can be used to extend the life of silver mirrors, but these additional coatings add cost and complexity to the system while potentially reducing peak reflectivity as well. Ultimately, the higher cost of silver compared to aluminum, combined with its maintenance requirements, make this material unsuitable for a project where maximum optical efficiency is not the primary focus. [21], [24]

3.3.2.4 Stainless Steel

Stainless steel is a metal that has exceptional durability and corrosion resistance, making it a good material for reflectors operating in harsh environments. However, this material has a significantly lower reflectivity in the visible spectrum compared to silver or aluminum, with values in the range of 60-70%. The primary advantages of this material are its mechanical robustness, resistance to scratches, and ability to withstand rough environments with the need to additional protective coatings. These properties make stainless steel suitable for industrial applications where durability outweighs optical performance. For applications like the PTC, however, the significantly lower reflectivity offered by this material represents a great disadvantage in terms of light collection efficiency. [21]

3.3.2.5 Acrylic

Acrylic mirrors are lightweight reflective plastic materials that offers high shatter resistance, making them practical alternatives to glass in settings where high optical performance isn't a necessity. Acrylic mirrors also boast high bend tolerances, making them suitable for applications that require more than just a flat mirror. These mirrors have reflectivities of about 85-90% in the visible light spectrum. These properties make acrylic mirrors a highly suitable choice for the PTC, as these mirrors can be molded to the shape of the required parabolic mirrors quite easily compared to the other reflective materials. [25]

3.3.2.6 Technology Comparison - Reflective Materials

For our project, the reflective material must balance the reflectivity at the wavelength of our laser diode (650 nm), durability, cost, and ease of integration into the system. Silver offers the highest reflectivity, but requires additional protective coatings to prevent tarnishing and can be costly. Stainless steel offers great durability at the cost of significantly lower reflectivity, reducing the overall efficiency of this material to collect the light. Glass mirrors provide good optical performance, but can be hard to integrate due to sizing constraints. Aluminum provides a good balance between all of these factors, being fairly

durable with good reflectivity in the visible range. Like aluminum, acrylic mirrors provide good durability and high reflectivity in the visible range. Unlike aluminum, however, acrylic mirrors provide a higher optical quality that is able to maintain a beams shape after reflection. For the PTC, a combination of glass and acrylic mirrors have been chosen for the creation of the horizontal laser sheets as well as the focusing mirror, with aluminum being considered as a backup option.

TABLE 3.8: Reflective Material Comparison

Characteristic	Glass	Aluminum	Silver	Stainless Steel	Acrylic
Reflectivity @ 650 nm	85–90%	85–92%	>95%	60–70%	85–90%
Spectral Range	Visible Spectrum	Broad	Visible to IR	Visible to IR	Visible Spectrum
Corrosion Resistance	Good	Good	Poor	Excellent	Good
Durability	Good	Good	Requires protection	Excellent	Good
Surface Quality Achievable	High	High	Very High	Moderate	High
Cost	Moderate	Low	High	Moderate	Low
Thermal Conductivity	Low	High	High	Low	Low
Maintenance Requirements	Low	Low	High	Low	Low

3.3.3 Component Selection - Reflectors

3.3.3.1 Romeda Aluminum Foil Tape

The Romeda Foil Tape is a reflective material designed for insulation, sealing, and light reflecting applications. Depending on the surface finish, aluminum surfaces can exhibit reflectance values around 88-92%. This flexible tape consists of a thin aluminum foil layer with an acrylic adhesive backing. This backing allows for straightforward installation without the need for additional mounting hardware. The physical dimensions of this tape is typically 2-3 inches with a thickness on the order of 0.05-0.1 mm. One drawback of this product is that the reflective surface is relatively soft and can develop wrinkles during application, which can introduce unwanted diffuse scattering. Additionally, the long-term durability of the adhesive may degrade under environmental exposure, making the lifetime of this reflector somewhat short. While this material provides a low-cost and easily deployable solution, its optical performance is less consistent due to application difficulties. [26]

3.3.3.2 Plymor Non-Beveled Glass Mirror

The Plymor Glass Mirror is a rigid, polished reflective surface intended for general-purpose reflecting applications. The mirror consists of a glass substrate with a metallic (silvered) reflective coating on the rear face. This gives the mirror a smooth, distortion-free finish with highly consistent (90-95%) specular reflection. Its physical dimensions are 8 x 4 inches with a thickness of approximately 1.6 mm and a weight of about 4.96 ounces. The rigid construction of the glass mirror provides strong mechanical stability that ensures long time reliability. One drawback of this mirror is that this glass substrate is more susceptible to shattering or scratching, making it far more likely to break under higher mechanical pressures. The cost of this mirror \$4.90 per mirror, which is very low-cost compared to other glass mirrors of this size. The stable, uniform reflective surface along with its low-cost make this mirror a suitable choice for the project. [27]

3.3.3.3 Yuntop Self Adhesive Acrylic Mirror (8 x 8 Inches)

The Yuntop Acrylic Mirror is a flexible, self-adhesive reflective sheet designed for portable and lightweight applications. This mirror is made from a polystyrene plastic with a mirrored surface. The mirror finish gives this mirror an approximate reflectance of 80-90% in the visible spectrum. Each sheet measures to be 8 x 8 inches, with the material being very lightweight at about 0.14 kg for both sheets. The cost of both of these mirrors is \$5.90, making this a very cheap option. The flexible plastic makes this mirror more resistant to shattering than glass, which allows this mirror to be far more suitable for applications where the material needs to be bent. One downside of this mirror is that the plastic substrate can flex over time, causing it to be harder to keep the material at desired bends for long periods of time. Additionally, acrylic mirrors are very susceptible to scratching, which can degrade the optical performance of the mirror over time as well. While the optical consistency falls between that of the glass and aluminum mirror surfaces, the Yuntop acrylic mirrors offer a favorable balance between ease of integration and mechanical durability. [28]

3.3.3.4 Component Comparison - Reflectors

For our system, the primary objective of the reflector is to maximize the return signal of the laser to the photodiode while maintaining consistent performance. This means that when selecting a reflector, several key factors such as reflectivity, ease of integration, and cost are to be considered. The aluminum foil, while being easy to integrate and low-cost (\$6.98), has only moderate consistency in maintaining a good reflective surface due to the potential wrinkling that may occur during the application of this material. These qualities made the foil tape a good choice at the time for selection during Senior Design 1. However, after testing and prototyping with this material, it was found to be too difficult to implement due to the massive amount of diffraction that would occur when the laser light hit the material.

For Senior Design 2, the Plymor glass mirror, although more complex to integrate due to its rigid construction and large size, provides a stable and uniform reflective surface that is well-suited for the creation of the flat laser sheets for the sensor gate. This mirror also

has a relatively moderate at \$4.90 per mirror. The Yuntop acrylic mirror offers a flexible plastic substrate with higher mechanical durability and shatter resistance, making it far easier to use for the creation of a parabolic mirror while also being low-cost at \$5.90 for two mirrors. This mirror also has good optical performance that is on par with the glass mirror, however, this performance can degrade drastically due to the ease of scratching for this surface. Considering all of these factors, the Plymor and Yuntop mirrors were chosen as the optimal reflectors for this project, as they boast the high reflectivities and ease of integration/mechanical robustness that is necessary to create the sensor gate subsystem.

TABLE 3.9: Reflector Component Comparison

Characteristic	Aluminum Foil Tape	Plymor Beveled Mirror	Non-Glass	Yuntop Self Adhesive Acrylic Mirror
Reflectivity	85–92%	85–90%		80–90%
Surface Type	Thin foil	Rigid glass	silvered	Flexible plastic
Thickness	0.05-0.1 mm	1.6 mm		2 mm
Size	Variable	4 x 8 inches		8 x 8 inches
Surface Quality	Variable	Uniform		Uniform
Reflection Type	Mostly specular	Specular		Mostly specular
Mechanical Stability	Low	High		Moderate
Durability	Moderate	High		Moderate
Cost	\$6.98	\$4.90		\$5.90

3.4 Camera Technology

3.4.1 Camera Outcome

The cameras are primarily responsible for capturing an image of the projectile in flight within the strobe imaging chamber. Due to the potential speed of the projectile, these images need to be taken quickly, which is possible with a larger amount of incoming light.

3.4.2 Color vs Monochrome

Monochrome cameras are simpler, and are capable of higher resolutions than color cameras. Monochrome cameras do not provide color information, and therefore do not provide as beautiful of images compared to color cameras. For the goals of this project, a monochrome camera is advantageous for a number of reasons.

First, the camera lens design is significantly simpler due to the elimination of chromatic dispersion, so elements such as doublets and triplets are unnecessary to correct for this. Chromatic dispersion is the difference in effective refractive index of a material for

different wavelengths (or colors) of light. This difference in refractive index causes a change in the focal length of simple lenses for different colors of light, so a lens system set up perfectly for yellow light images will blur the blue and red light, causing chromatic aberration. Chromatic aberration can be compensated for by using doublets or triplets, which are lenses with different materials, which have different chromatic dispersions, and are arranged in such a way as to have nearly identical focal lengths for multiple colors of light across the visible spectrum.

Second, monochrome imaging would allow for a bandpass color filter which would greatly reduce the effect of ambient light on the system. With a narrow bandwidth strobe illumination, a bandpass color filter would not significantly reduce the light into the cameras from the strobe system, but would reduce light from outside, such as sunlight reflecting into the strobe imaging chamber during outdoor usage. Sunlight reflecting into the chamber would cause the imaging of the projectile to include times other than when the strobe is illuminated, which would cause a blurry streak that could interfere with the processing of the image.

Third, monochrome imaging allows for higher resolution. Color cameras use a grid color filter in front of a monochrome 2d sensor array in order to get color information. A process of demosaicing is used to recover the color information for the full resolution of the camera sensor; however, information or resolution is lost in the process. Monochrome imaging does not require a color filter grid for retrieving color information, which allows a higher resolution image to be produced. The higher resolution of a monochrome camera would allow more precise projectile tracking, giving higher accuracy on the position, angle, and speed of the projectile from the strobe photography stage of the system. [29]

3.4.2.1 Technology Comparison - Camera Color

While color imaging would allow us to produce more striking strobe photographic images to include with our presentation, the advantages of monochromatic imaging outweigh those of color imaging.

TABLE 3.10: Camera Color Technology Comparison

Feature	Color	Monochrome
Lens Design Complexity	High	Low
Ambient Light Sensitivity	High	Low
Resolution	Lower	Higher
Aesthetics	Better	Worse

3.4.3 NoIR vs Standard

Camera sensors are sensitive to IR wavelengths that are invisible to humans, and therefore many cameras have a filter that blocks those IR wavelengths in order to better replicate human vision. Sometimes it is valuable to be able to detect those IR wavelengths, such as when debugging a TV remote it can be advantageous to point your cell phone camera

at the remote to see if it is transmitting. Additionally, since we are using IR LEDs for lighting, ambient white light will have less of an affect on our camera's resolution.

3.4.3.1 Technology Comparison - Camera Filter

The selection of NoIR vs standard is not of great importance, except for the showcase high-speed strobe photographic images. Since we have decided to use IR LEDs as the strobing mechanism, the NoIR choice is the one we are proceeding with for the PTC.

TABLE 3.11: Camera NoIR vs Standard

Feature	NoIR	Standard
IR Sensitive	Yes	No
Color Fidelity	Worse	Better

3.4.4 Global Shutter vs Rolling Shutter

Global Shutter cameras have a shutter that changes from transparent to opaque or from opaque to transparent all at the same time, and samples all of the pixels at the same time. Rolling Shutter cameras use a technique that either samples the lines of pixels or blocks the light of the lines of pixels one line at a time, which causes a slight time delay between the top of the image being taken and the bottom of the image. Rolling Shutter is a less expensive technique, it allows for higher resolutions at a lower price, but there are significant issues for high speed photography.

3.4.4.1 Technology Comparison - Shutter Type

For early system integration, the low cost and high resolution offered by the rolling shutter type make this a desirable choice for the PTC. However, we would like to produce high quality images by using the high-speed photography capabilities provided by the global shutter type. Therefore, we have chosen the global shutter type for this project.

TABLE 3.12: Camera Shutter Technology Comparison

Feature	Global Shutter	Rolling Shutter
High-Speed Photography	Better	Worse
Cost	Higher	Lower
Resolution	Lower	Higher

3.4.5 Component Selection - Cameras

3.4.5.1 Raspberry Pi Camera Module 2

A low cost option, the camera module 2 is the camera we will use for integration testing while the proper cameras are designed and created. There may be problems with the rolling shutter in the high speed photography, which can be seen for example in the bend of moving propellers when imaging with a cell phone camera. The Raspberry Pi Camera

Module v2 is based on the Sony IMX219 sensor, which is an 8 megapixel sensor. The maximum image resolution is 3280×2464 pixels, but the video it can take is 1640×1232 at 41 frames per second. Pixel size is on the small side, at $1.12[\mu\text{m}] \times 1.12[\mu\text{m}]$. It does not have an interchangeable lens, so we would be unable to change out the lens for a custom one. There are versions with and without an IR filter which could be used for IR imaging. [30]

3.4.5.2 Raspberry Pi High Quality Camera

The high quality camera has a higher resolution than the global shutter camera, but has rolling shutter distortion that would interfere with proper capture of the high speed projectiles in the system. The Raspberry Pi High Quality Camera is based on the Sony IMX477 sensor with a resolution of 4056×3040 pixels. The module has an external trigger, which allows the capture of images to be synchronized and controlled by a simple electrical signal. It comes with either a M12 or a C/CS mount for the lens, allowing for custom interchangeable lenses. The IR filter can be removed, which will allow sensitivity to IR light. Video can be captured at a maximum resolution of 2028×1080 at 50 frames per second. The pixel size is $1.55[\mu\text{m}] \times 1.55[\mu\text{m}]$, allowing moderate low-light performance. [30]

3.4.5.3 Raspberry Pi Global Shutter Camera

The Raspberry Pi Global Shutter Camera is based on the Sony IMX 296 sensor. It has a resolution of 1456×1088 pixels. The key defining feature of this camera is the global shutter, which allows the entire frame to be exposed simultaneously, significantly enhancing photography of high-speed objects. The pixels size is $3.45[\mu\text{m}] \times 3.45[\mu\text{m}]$, allowing for excellent low-light performance. It has a C/CS lens mount, allowing for custom interchangeable lenses. The IR filter can be removed, allowing for IR imaging. The resolution is significantly lower at 1.58 megapixels. [30]

The global shutter camera is specialized for high-speed photography. While it has a lower resolution than the High Quality camera, the global shutter camera is capable of taking photographs over 500 times per second (at low resolution), or a single photograph as short as $30 \mu\text{s}$ using an external trigger. The advantages and rather low cost of the Raspberry Pi Global Shutter camera an ideal choice for the system. [31]

3.4.5.4 e-CAM21_CURB - 2MP OV2311

The e-CAM21_CURB is a global shutter monochrome camera compatible with the Raspberry Pi computer. It uses the OmniVision OV2311 image sensor. It uses a M12 lens mount, so any lenses would need to be made compatible with an M12 thread. 2MP resolution video can be streamed at 60 fps over the 2-lane MIPI connector. The image sensor has $3[\mu\text{m}] \times 3[\mu\text{m}]$ pixels. The field of view (FOV) is 58.6° by 48.77° . [32]

3.4.5.5 ArduCam OV9281 Global Shutter NoIR Mono Camera

The Arducam OV9281 is a 1 megapixel global shutter NoIR monochrome camera. It has a 130 degree field of view (FOV), and uses a M12 lens mount. Though it has an M12

lens mount, it claims that the lens is not interchangeable. Compatible with the Raspberry Pi ecosystem. It is sensitive to IR light due to a lack of an IR filter. [33]

3.4.5.6 Component Comparison - Cameras

For the PTC, the Raspberry Pi Global Shutter Camera provides the best overall balance between performance, system compatibility, and cost. Its global shutter mechanism eliminates motion distortion by exposing the entire frame at once. Additionally, its relatively large pixel size of $3.45\ \mu\text{m}$ improves its performance in low-light environments, which is beneficial for detecting fast-moving objects with short exposure times. While the resolution is lower than some of the alternatives listed, it is sufficient for the spatial requirements of the PTC system.

TABLE 3.13: Camera Selection Comparison

Name	Price	Resolution	Shutter	External Trigger	Color
Raspberry Pi Global Shutter Camera	\$50	1456 × 1088	Global	Yes	Color
Raspberry Pi Hi Quality Camera	\$55	4056 × 3040	Rolling	Yes	Color
Raspberry Pi Camera Module 2	\$15	3280 × 2464	Rolling	No	Color
e-CAM21_CURB	\$90	1600 × 1300	Global	Yes	Monochrome
ArduCam OV9281 Global Shutter NoIR Mono Camera	\$42	1280 × 800	Global	No	Monochrome

3.5 Illuminative Technology - Strobe Imaging

Strobe Imaging uses short bright flashes of light in order to image things faster than the framerate of the camera. The two most common technologies for strobe illumination is LED and gas discharge. LEDs, or light emitting diodes, are a common technology for lighting, and often have a rise time in the realm of 10 to 100 nanoseconds. This makes LEDs more than fast enough for strobe illumination. Gas discharge strobe illumination can be much brighter, but require high voltage and other considerations. A third alternative technology to investigate could be a Q-switched laser, however that is not common in practice and would therefore be too close to a research task for our senior design project.

3.5.1 LED vs Gas Discharge

LEDs as a light source for strobe photography is a cheap and inexpensive light source. The major challenge for LEDs is to provide a large current in a short period of time. Discharge flash lamps are a good way to create short flashes of light, however they

are broadband, expensive, and require high voltages. Different gasses can be used for different wavelengths of light, e.g. Xenon often produces a white light. There are details about the high voltage electric spark discharge triggering that make for a complex use case. Gas discharge lamps are often used to pump lasers. [34]

3.5.1.1 Technology Comparison - Strobe Illumination Source

Due to the low cost and simplicity of using LEDs, as well as the wider range of wavelengths available, we have selected to use LED lights for the PTC. Gas discharge lamps are too expensive and broadband to be used for a reliable illumination source.

TABLE 3.14: Strobe Illumination Technology

Feature	Gas Discharge	LED
Wavelength selectivity	High	Low
Cost	High	Low
Voltage Requirements	High (> 1 kV)	Low (2–20 V)
Intensity	High	Lower

3.5.2 Wavelengths (Strobe Imaging)

There are advantages and disadvantages to using different wavelengths, or colors, of light.

3.5.2.1 UV

UV leds are typically more expensive due to the exotic high-bandgap materials required. They require a higher forward voltage than other LEDs due to the higher energy of UV photons. The UV light will breakdown materials, causing lower operating lifespans for UV LEDs. However, UV LEDs have the shortest wavelength, which allows for higher resolution imaging than other wavelengths, but the sizes and distances we are working with do not get anywhere near the diffraction limits imposed by the wavelength of light. Cameras are less sensitive to UV light due to a few effects, including the higher energy per photon creating a lower response per unit power, and the absorption of UV light from the optics.

3.5.2.2 Blue

Blue LEDs are inexpensive due to their common use in white LEDs. White LEDs are typically made with a blue LED coated with a phosphor that converts the blue light into a wide range of wavelengths. Cameras are moderately sensitive to Blue light. While blue LEDs require gallium nitride (GaN), a slightly exotic material, with high temperature requirements for fabrication. Due to the high volume of manufacturing for use in white LED lights, the economies of scale have significantly decreased the costs for high power blue LEDs.

3.5.2.3 Red

Red LEDs are ubiquitous, but are often low powered. There are very few high-power red LEDs available, and those that are are quite expensive. Red light is often used for night time and camping due to it not ruining the night vision and low-light vision of humans. Cameras are often very sensitive to red light.

3.5.2.4 IR

IR LEDs in the 850 nm - 960 nm range are some of the cheapest LEDs due to the fact the bandgap of Silicon is in the energy range of IR photons. One of the advantages of IR is the invisible nature, so that it wouldn't interfere with vision nor would it alert enemies in military applications. Cameras are moderately sensitive to IR light in the 700 nm - 800 nm range, however they have a low sensitivity to the light in the 850 nm and up range, with about 0.4 responsivity to 850 nm light. [35]

3.5.2.5 Technology Comparison - Wavelengths (Strobe Imaging)

Each of these wavelengths have their own strengths and weaknesses, but for the PTC there are several factors that are more important than others. For our system, we want the LEDs to be cheap because we plan on ordering a lot of them, and we want the wavelength to have moderate amount of sensitivity for the cameras. Therefore, we have chosen the IR LEDs for the PTC project.

TABLE 3.15: Strobe Illumination Wavelength

Feature	UV	Blue	Red	IR
Cost per lumen	Moderate	Moderate	High	Low
Longevity	Low	Moderate	High	High
Diffraction-limited Resolution	High	Moderate	Low	Low
High Power Common	Yes	Yes	No	Yes
Visible	No	Yes	Yes	No
IMX296 Responsivity	Low (< 0.5)	Moderate (0.5–0.8)	High (0.9-1)	Moderate (0.5–0.9)

3.5.3 Component Selection - Strobe LEDs

3.5.3.1 Component Comparison - Strobe LEDs

The Solidlite IR LEDs of AG3535C, AC3535B, AC3535L, AC3535A are the IR LEDs that showed up as the lowest price per watt of generated light on Digikey. They are all 1.5 amp rated LEDs, and the manufacturer characterized the LEDs at 1 amp. They have radiant flux at 1000 mA between 1250 and 1550 mW. The rise and fall times are 10 ns and 15 ns respectively, which is more than enough for our purposes. Forward voltage for each is between 2.7 V and 3.6 V, with manufacturing or usage variation being the biggest driver of the differences (each gives a range of voltages with a $\Delta V \approx 0.6 V$). Spectral bandwidth

is $\Delta\lambda = 40$ [nm], with the peak wavelength at 850-855 [nm]. The biggest difference is the viewing angles, ranging between 60° to 150° . For a more uniform illumination, the AG3535C with its 120° viewing angle would be good. For more concentrated light and requiring fewer LEDs, the AC3535A with a 90° viewing angle would be better. One of the advantages of these LEDs compared to some of the others is that the IV curve flattens out around 3.5 V, which allows for a simpler driving circuit due to a more linear current relationship to voltage. The selected LED is the AC3535A since the FOV is compatible with that of the cameras. After building the camera lenses with only an FOV of about 42° , the smaller angle LEDs of 60° (AC3535B-YRR1000-mA-H1) would have been better in order to get more light onto the target (900 mW/sr versus 550 mW/sr).

TABLE 3.16: Comparison of IR LEDs

Parameter	AG3535C-YRR-1000mA-H1	AC3535B-YRR1000-mA-H1	AC3535L-YRR-1000MA	AC3535A-YRR-1000MA
Manufacturer	Solidlite	Solidlite	Solidlite	Solidlite
Price (\$)	1.1	1	1	1
Current - DC Forward (If) (Max)	1.5 A	1.5 A	1.5 A	1.5 A
Radiant Intensity (Min @ If)	430 mW/sr @ 1 A	900 mW/sr @ 1.5 A	175mW/sr @ 1 A	550 mW/sr @ 1 A
Viewing Angle	120°	60°	150°	90°
mW/\$	1228.08	757.61	814.97	1012.17
mW/\$ (wall-plug)	2454.55	4650	4650	4950
Total Radiant Flux @ 1000mA [mW]	1550	1350	1250	1350

3.6 Computational Technology - MCU

3.6.1 Microcontrollers

Sensing fast moving projectiles and measuring their physical characteristics is inherently a challenge that absolutely requires high speed processing. Therefore, it is essential that the processor we select is capable of receiving inputs and running calculations much faster than the projectile is moving. Our stretch goals list the PTC as possibly being capable of tracking projectiles moving as fast as 100 m/s. Given a projectile that is 1 cm long moving at 100 m/s, the time to detect the projectile moving past a fixed point is 0.1 milliseconds. To be able to detect a projectile in less than 0.1 milliseconds, that corresponds to a sampling rate of at least 10 kHz, which means that if the microcontroller can detect a projectile within 1 clock cycle, the minimum clock speed would be 10 kHz. The processor would likely need to have multiple clock cycles within one detection cycle, so a clock speed of 100 kHz or above is more reasonable. In order to detect the projectile

and to minimize error in doing so, our processor must be running as fast as possible while remaining reasonable in price, accessibility, and complexity. Even if we decide to use an external component for the detection of projectiles, these criteria still hold true as we would want to minimize the amount of time spent running calculations, potentially throwing off the accuracy of triggered flashes and image captures. Luckily, there are a wide variety of microprocessors available to both industry and consumers that operate at significantly higher speeds than 10 kHz while remaining extremely cheap, particularly in the hobbyist space with brands such as Arduino, Raspberry Pi, Espressif, and Adafruit. We prefer microcontroller architectures in the hobbyist space because they are guaranteed to have development boards that will be easy to develop and debug our programs on.

3.6.1.1 Arduino

Arduino is a brand of development boards with a wide range of products available to consumers, at widely varying price points. The most expensive Arduino product at 77.90 euros (about \$89.69) is the Arduino GIGA R1, with Wifi capability and a dual core architecture, running at 480 and 240 MHz with the STM32H747XI MCU. This is quite expensive, and does not include the cost of a separate MCU by itself. The only option in stock for the STM32H747XI MCU costs \$19.56. Among the cheapest of Arduino products is the Arduino Nano Every at 14.50 euros (about \$16.69), with an ATmega4809 MCU. The ATmega4809 has a maximum frequency of 20 MHz. In the middle of the pack lies the Arduino UNO family, with the UNO R4 Minima sporting a maximum clock frequency of 48 MHz at a price of 22.00 euros (\$25.33). At the time of writing, the cheapest option in stock for the ATMEGA4809 itself costs \$1.74 on DigiKey, and the cheapest option in stock of the RA4M1 MCU costs \$5.36. [36], [37], [38]

3.6.1.2 Raspberry Pi Pico

Raspberry Pi mostly specializes in Single Board Computers, however, they do have a series of development boards with their Pico line, the Pico 1 at \$4.00 and the Pico 2 at \$5.00. The Pico family consists of 2 MCU architectures, the Pico 1's RP2040, and the Pico 2's RP2350 family. The RP2040 can run up to 133 MHz, and the RP2350 series can run up to 150 MHz. The RP2040 and RP2350 chips themselves can each be found on Digikey at prices of \$0.70 and \$1.00, respectively. However, the RP2040 is not in stock, but the RP235X MCUs are. [39], [40]

3.6.1.3 Espressif

Espressif, like Arduino, hosts a wide variety of products, many of which include features like Wifi and Bluetooth. But with a far wider variety of products than Arduino, Espressif's website hosts a 'Product Selector' that can help narrow down choices based on a customer's needs. Since Espressif's product list still includes products that are Not Recommended for New Designs (NRND) or are only available as sample products, it is important to filter for only products under a Mass Produced status, meaning they are available and not too complex or specialized for new designs. Doing this reveals that nearly all Espressif microcontrollers available have processing speeds exceeding 100 MHz and that about 90 have processor clock speeds of 240 MHz, allowing a broad selection

of MCUs suitable for the PTC. Among the simpler and more common options are the ESP32-C6-DEVKITM, a general purpose development board that costs \$8.00 and is built around the ESP32-C6-MINI-1 MCU, which itself costs \$4.40, and has a clock speed of 160 MHz. Another option is the ESP32-S3-WROOM-1-N8R8, at \$6.32, which uses the ESP32-S3 MCU with a clock frequency of 240 MHz. [41]

3.6.1.4 Technology Comparison - MCU

The Arduino GIGA R1 will not be chosen. Not only does it include features we do not currently have a use for, it and its MCU are far and away the most expensive options, which would not be friendly to our budget if we order more for redundancy or because of malfunction. The Raspberry Pi Pico 1 and 2 meet our needs quite well, being among the fastest options for chips and development boards, designed for simplicity, and also being extremely affordable. The Pico series retain a high clock frequency and still remain the cheapest options when ordering more individual IC's, as the cost of the Espressif MCU's is significantly higher. However, due to the difficulty of soldering the Raspberry Pi Pico's small QFN package, we have selected the ESP32-S3-WROOM.

TABLE 3.17: Microcontroller Technology Comparison

Name	Max Clock Speed (MHz)	Development Board Cost (USD)	Standalone MCU Cost (USD)	Total Cost (USD)	In Stock (Mouser, DigiKey)
Arduino GIGA R1	480	\$89.69	\$19.56	\$109.25	Yes
Arduino UNO R4	48	\$25.33	\$5.36	\$30.69	Yes
Arduino Nano Every	20	\$16.69	\$1.74	\$18.43	Yes
Raspberry Pi Pico 1	133	\$4.00	\$0.70	\$4.70	No
Raspberry Pi Pico 2	150	\$5.00	\$1.00	\$6.00	Yes
ESP32-C6-MINI-1	160	\$8.00	\$4.40	\$12.40	Yes
ESP32-S3-WROOM-1	240	\$15.00	\$6.32	\$21.32	Yes

3.6.2 Component Selection - MCU

3.6.2.1 ESP32-S3-WROOM-1/ESP32-S3-WROOM-1U

The ESP32-S3-WROOM is available in two main variants, the WROOM-1 and the WROOM-1U. The WROOM-1 has an antenna embedded in the module package, and requires considerations to be made in PCB layouts to avoid interference from signals on traces near the antenna, whereas the WROOM-1U foregoes the antenna and simply has a port to attach an external antenna, requiring an extra purchase if the MCU's Wifi and Bluetooth capabilities are desired.

3.6.2.2 Flash Size/PSRAM

Among both the ESP32-S3-WROOM-1 and WROOM-1U are additionally a variety of chips with different memory sizes, with the ESP32-S3-WROOM-1/1U-N4 having 4MB of flash memory, the WROOM-1/1U-H4 having a higher ambient temperature rating, and chips like the WROOM-1/1U-N8R8 having larger flash memory as well as additional PSRAM. The addition of PSRAM allows for heavier computation at the expense of 4 GPIO pins on the module, as such pins will be used internally for the PSRAM.

3.6.2.3 Component Comparison - MCU

Among all options for the ESP32-S3-WROOM, every chip has a maximum clock frequency of 240 MHz, and so the only differences are whether an antenna is included in the package, and how much extra flash memory and PSRAM would be available. Although Wifi and Bluetooth capabilities are not necessary for the goals of the PTC project, having such capabilities allows room for the software to grow beyond its goals if time allows. Choosing the WROOM-1 package over the WROOM-1U allows Wifi and Bluetooth to be used if desired without having to buy an external antenna and manually attach it, in favor of simply placing the module on the edge of a PCB to avoid interference from surrounding traces. Additionally, having additional flash memory and PSRAM would provide significant overhead for the firmware, avoiding any issues with memory space, at the cost of 4 GPIO pins. The PTC is meant to be operated at room temperature conditions, and so a higher ambient temperature rating is not necessary. Additionally, the H4 was not available on DigiKey or Mouser. With all this in mind, the ESP32-S3-WROOM-1-N8R8 was chosen.

TABLE 3.18: Microcontroller Component Comparison

ESP32-S3	Clock Speed MHz	Module Cost	GPIO Pins	Flash/PSRAM Memory	Embedded Antenna
WROOM-1-N4	240	\$5.21	36	4MB/0MB	Yes
WROOM-1U-N4	240	\$5.21	36	4MB/0MB	No

WROOM-1-H4	240	N/A	36	4MB/0MB	Yes
WROOM-1U-H4	240	N/A	36	4MB/0MB	No
WROOM-1U-N8R8	240	\$6.32	32	8MB/8MB	No
WROOM-1-N8R8	240	\$6.32	32	8MB/8MB	Yes

3.6.2.4 Development Board

Instead of trying to program and constantly debug a chip soldered to a board, it makes sense to also acquire a development board so that software can be developed alongside hardware designs, and both can be tested together.

While there are many of the same options as above in earlier sections for a development board, familiarity and software compatibility are of the utmost importance. And so, the discussion of which development board to choose is a short one. It makes sense to develop functionality with hardware similar to what we will actually be using, so the ESP32-S3-DEVKITC-1-N8R8 will be used, and can be purchased for \$15.

3.7 Computational Technology - Image Processor

3.7.1 Single Board Computers

One objective of the PTC project is to capture multiple images of the projectile in flight and extract spatial information from these images. Due to the complexity of digital image processing, a normal microcontroller does not have sufficient processing power to handle the procedural analysis of photographs, as commonly listed hardware requirements for OpenCV are far beyond that which a microcontroller is capable of citehardware-requirements-for-opencv. To solve this issue yet still comply with project constraints, a more powerful computer will be used to handle image processing. The image processor will only be used for image processing, and all other signals and data must be handled by our microcontroller. Much like our options for the MCU, there are a few small single board computers that will be capable of image processing, such as the Raspberry Pi, Orange Pi, and Odroid.

3.7.1.1 Raspberry Pi

Raspberry Pi is widely known for their Single Board Computers, and their latest products are variants of the Raspberry Pi Model 5, and the Zero 2 W. Raspberry Pi computers often come with their own Operating System called Raspberry Pi OS, and hardware specifications focused on image and video processing; including GPUs that support the

latest hardware graphics API's, high resolution display ports and high speed USB ports, MIPI camera/display ports, as well as Wifi and Bluetooth support [citeraspberry-pi-5-brief](#). Raspberry Pi also provides a step by step manual to install the Raspberry Pi OS and how to use Python to control GPIO pins on the Raspberry Pi device itself, alongside standard documentation and software packages available on their website. All these features allow Raspberry Pi computers to be readily used for image processing and other projects, which will be beneficial to our use case [citeraspberry-pi-documentation](#). Additionally, Raspberry Pi also provides peripheral devices like cameras, including various lens types, which are guaranteed to work with Raspberry Pi products. It is also worth noting that Raspberry Pi is based in the UK, and as such their products may be easier to get a hold of in today's geopolitical climate.

3.7.1.2 Orange Pi

Orange Pi is another manufacturer of single board computers, with a naming scheme reminiscent of Raspberry Pi. Among their top products are the Orange Pi 5 Ultra, Orange Pi 4 Pro, and Orange Pi 6 Plus. Orange Pi computers are advertised with high processing power, hardware optimized for AI computation, and advanced graphics capabilities. Like Raspberry Pi computers, Orange Pi computers tend to come with Wifi and Bluetooth support, high speed USB ports, and powerful GPUs. Unlike Raspberry Pi computers, Orange Pi computers tend to have more HDMI ports and do have less MIPI camera/display ports or none at all. For example, the Orange Pi 6 Plus has no MIPI ports, but the Orange Pi 5 Ultra has one, and the Orange Pi 4 Pro has 2. Orange Pi also provides their own operating system, called Orange Pi OS, with three specializations for certain applications, such as Orange Pi OS (Droid), which is based upon android software and Orange Pi OS (Arch), based upon the popular Linux distribution. Orange Pi does include a documentation page on their website where documentation and software for all available products can be found. Like Raspberry Pi, Orange Pi does offer cameras as well, but they mostly vary in image quality rather than lens type. All these features allow Orange Pi computers to be readily used for computationally and graphics intensive projects, but they do not allow us to easily connect cameras due to the variable amount or lack of MIPI ports, and since this manufacturer is based in China, is likely subject to large tariffs and shipping delays [42].

3.7.1.3 Odroid

Odroid, based in South Korea, advertises single board computers meant for advanced computing for industrial embedded systems. As such, Odroid devices are built with efficiency, affordability, and longevity in mind, as many newer devices list improvements in these areas over their predecessors. Odroid also makes it easy to see their product specifications and compare device benchmarks. Odroid devices are run on Linux based distributions or Android software, and tend to have more focus on processing power, efficiency, and I/O rather than graphics processing, and as such have less ports for carrying video information, often having only one HDMI port and one MIPI port for cameras. Odroid offers a wiki for each available product and an OS installation guide. Odroid does offer a variety pack of lenses of different sizes, but these lenses are without IR filters and Odroid only offers one camera, potentially limiting our options for image quality and

what wavelengths of light to capture. While also likely subject to tariffs and shipping delays, an Odroid device may be a good middle ground option due to its competitive pricing and reliability, but lacks some variety available in other options [43].

3.7.1.4 Technology Comparison - Image Processor

A few criteria important to this selection process are the number of MIPI ports available, the cost of the devices, and of course whether or not they are actually available and will arrive in a timely manner. Orange Pi products Amazon or Aliexpress, and Odroid products are only reliably available through their international website, whereas Raspberry Pi products can be bought either via Amazon or Digikey. Raspberry Pi Single Board Computer products start at \$15, but this is for the Zero 2 W. Orange Pi's comparable Zero 2 W starts at \$56 on Amazon, and Odroid starts at \$55 with the Odroid C5. None of these prices include shipping. Another criteria is ease of use, and this can be classified by how much documentation is readily available for us to find and use. Given that Raspberry Pi offers documentation, software, and user guides, this makes Raspberry Pi the best option in terms of usability. Orange Pi and Odroid do however have a larger list of devices that we could potentially use, but this comes with the added detriment of extra research necessary to figure out which of these products could best suite our needs. With all of these factors considered, it makes sense to choose a Raspberry Pi product for their extensive documentation, ready availability, and competitive pricing [44] [42] [43]

TABLE 3.19: Image Processor Technology Comparison

Name	Raspberry Pi	Orange Pi	Odroid
Max MIPI Ports Available	2	2	1
Starting Price	\$15.00	\$56.00	\$55.00
Range of Products	Minimal	Wide	Medium
Availability	In Stock	Almost Out of Stock	In Stock
Vendor	DigiKey, Amazon	Amazon	Odroid
Documentation and Support	Overwhelming	Extensive	Sufficient

3.7.2 Component Selection - Image Processor

Raspberry Pi has a smaller product line, and as such, this makes it far easier to compare devices and find one most suitable for our project. Since we plan to use cameras, it is imperative that the device in question have MIPI-CSI ports so that the cameras can be connected to the device and communicate image information.

3.7.2.1 Raspberry Pi Model 4

The Raspberry Pi Model 4 ,from \$34, has plenty of high speed ports for USB 3.0, USB 2.0, as well as ethernet, and also has 2 MIPI ports. These two MIPI ports, however, are not of the same type, as one is a MIPI-DSI display port and the other is a MIPI-CSI

display port, meaning that the Raspberry Pi Model 4 can only host one camera module, and we would likely need an adapter to use a different port to handle two at the same time [45].

3.7.2.2 Raspberry Pi Model 5

The Raspberry Pi Model 5 hosts many improvements over the Model 4, namely significantly faster processing speed and better graphics capability. For the PTC project, the most important improvement is that the Model 5 has two MIPI ports that are capable of both MIPI-DSI and MIPI-CSI communication, meaning that the Model 5 can host two cameras at the same time, as is desired for our use case. The standard Model 5 costs \$45 [45].

3.7.2.3 Raspberry Pi Compute Module 5

The Raspberry Pi Compute Module 5 is a variant of the Model 5 that is meant for embedded applications, and is built with personalization and scalability in mind and includes a larger amount of GPIO pins for external control and communications. Naturally, the Compute Module 5 is more expensive, starting at \$67.50, and since we can't use most of its features for this project, overkill [45].

3.7.2.4 Raspberry Pi Zero 2 W

The Raspberry Pi Zero 2 W is the cheapest single board computer available at \$15, and an excellent consideration for saving space, as it fits an entire computer on a 65 mm by 35 mm board. With such a small form factor, extra adapters may be necessary to use it, as the ports in its specifications are all of a mini or micro type, like micro USB and mini HDMI. The Raspberry Pi Zero 2 can support a single camera, but it uses a small MIPI CSI-2 port, which would require an extra cable to convert a camera's larger MIPI CSI output to a CSI-2 input. Space isn't necessarily a concern for the PTC project, so a large board may be more suitable to reduce the need for extra adapters [45].

3.7.2.5 Component Comparison - Image Processor

Of the listed devices, the Raspberry Pi Model 5 and Compute Module 5 are the only devices that would allow us to easily and simultaneously connect two camera modules. While the Zero 2 W has an excellent, small form factor, saving space is not a priority for this project, and we desire two MIPI-CSI ports. As such, our choice for image processor is the Raspberry Pi Model 5.

TABLE 3.20: Image Processor Component Comparison

Name	Zero 2 W	Model 4	Model 5	Compute Module 5
MIPI-CSI Ports Available	1	1	2	2
Starting Price	\$15.00	\$34.00	\$45.00	\$67.50

Size (mm x mm)	65x35	85x56	85x56	55x40
Power Requirements	5V/2.5A DC	5V/3A DC	5V/5A DC	5V/5A DC

3.8 Interfacing Technology - Tactile

3.8.1 Types of Tactile Interfacing Technologies

3.8.1.1 Buttons

Buttons are some of the most commonly seen components of user interfaces. Buttons work by either closing or opening a circuit, and this change in voltage can be detected by the MCU to perform an action. Each button will occupy a single GPIO pin of the MCU, and software will be able to control its function, as well as filter out bouncing, a phenomenon that occurs when the physical contacts of the button bounce on the conductors, sending false signals to the MCU. De-bouncing, as the process is called, can also be achieved with other methods.

3.8.1.2 Switches

Switches are also very commonly seen components of user interfaces, and work similarly to buttons, either closing or opening a circuit, or switching between circuits, but for an indefinite amount of time rather than a short moment like a button press. A switch could occupy one or more GPIO pins of the MCU, and software could be used to detect which state the switch is in. Since a switch remains in its position until an action is performed by the user, the software may be less fluid than if the component was a button.

3.8.1.3 Potentiometers

Potentiometers use a wiper on a resistive pad to create variable resistance, adjustable by the user. This wiper is also available as a third pin on the package, meaning that potentiometers inherently also function as voltage dividers. With this variable resistance and voltage division, variable voltages can be sensed by the MCU on a single GPIO pin, and such values can be processed to finely tune or adjust some setting in software. Potentiometers are, however, limited in the range that they can spin and the voltage range and resolution they can provide, e.g. a knob that can only make one rotation. These factors are all dependent on the type of potentiometer and the voltage source in use. Additionally, since this is a resistive circuit component, power will be consumed and let off as heat.

3.8.1.4 Rotary Encoders

Rotary Encoders are a more complex component of user interfaces, but are commonly seen on devices that require a large range of input values, like volume and frequency controls on a radio. While such uses cases can be serviced with a potentiometer, Rotary Encoders are more conductive than resistive, and do not consume much power like a potentiometer would. Additionally, they do not have a limited range of turns, and can be rotated indefinitely. Consequently, they do need more GPIO pins to use, requiring two for encoders without a built in button, and three for encoders with a built in button. Rotary Encoders function by alternating two voltage signals as they spin, with an inherent phase shift between the two signals. The MCU is then able to determine which signal alternates first, essentially conveying whether the rotary encoder was rotated clockwise or counter-clockwise.

3.8.1.5 Technology Comparison - Tactile Interfacing Technology

In this instance, it would be prudent to select at least two of these technologies. By doing so, the PTC can provide multiple avenues of providing inputs to the machine, which is far more desirable than pushing a single button multiple times to select one option, or some other similarly annoying action. While potentiometers are simple, to use them as an input would require actively supplying them power, and as such they would waste power. Switches are limited in the kind of input they can supply, and so buttons and potentiometers are our choices. Buttons provide a way to quickly provide an input to a system, and rotary encoders, with they're infinite spin, would allow a user to quickly peruse menus. Furthermore, our choice of MCU already requires a few buttons for key features like debugging.

TABLE 3.21: Tactile Interfacing Technology Comparison

Name	Buttons	Potentiometers	Rotary Encoders	Switches
Minimum GPIO Pins Required	1	1	2	1
Variable Input?	No	Yes	Yes	Yes
Range of Variable Input	N/A	Limited by Outside Factors	Unlimited	Limited, Discrete
Resistive?	No	Yes	No	No

3.8.2 Component Selection - Button Technology

3.8.2.1 Grayhill 95C06A4GWRT

The Grayhill 95C06A4GWRT is a standard tactile button like those commonly seen in use for prototype circuits on breadboards. Naturally, they also work in plenty of other use cases, and can handle 50 mA of current at 12V. This particular model is square shaped

and covers an area of 6 mm squared, has a life rating of 500,000 cycles (500,000 button presses), and is normally open; requiring the button to be pressed in order to complete a circuit citegrayhill-tactile-switch-datasheet. It costs \$3.25 for ten of these.

3.8.2.2 E-Switch LC2255EENPTAGBLK

The E-Switch LC2255EENPTAGBLK is a black latching button that can handle up to 30 mA at 30V DC. It has a larger profile, being 29.05 mm long and 7.20 mm wide. Furthermore, it is a latching button, meaning that when pressed, the button will remain in its position instead of returning to its original position. This causes the button to act more like a switch than a button, having two states and requiring user action in order to switch between them citee-switch-pushbutton-datasheet. It would cost \$8.53 for ten of these.

3.8.2.3 C&K D6C60 F1 LFS

The C&K D6C60 F1 LFS is a blue, square shaped key switch button in a circular housing that can handle up to 100 mA at 32V DC. It is larger than the Grayhill option but still smaller than the E-Switch option with a diameter of 11.4 mm. This button is normally open, and also customizable with the option to switch out button caps from the housing citeck-key-switch-datasheet. It would cost \$10.30 for ten of these, but if ordered it may be necessary to also order the button caps, as it is unclear if the vendor sells both together.

3.8.2.4 Component Comparison - Buttons

Between these three options, the Grayhill button, the E-Switch button, and the C&K button, the Grayhill button stands out as more cost effective. Therefore, our choice of button is the Grayhill 95C06A4GWRT.

TABLE 3.22: Tactile Interfacing Component Comparison - Button

Brand	Grayhill	E-Switch	C&K
Size	2.45mm x 2.45mm	29.05mm x 7.20mm	11.4mm diameter
Switching Type	Momentary	Latching	Momentary
Switching State	Normally Open	Normally Open	Normally Open
Cost for 10	\$3.25	\$8.53	\$10.30

3.8.3 Component Selection - Rotary Encoder Technology

3.8.3.1 PEC11R-4220K-N0024

The PEC11R-4220K-N0024 is a rotary encoder with a bushing, a 12.5 mm by 13.4 mm base, and a 20 mm long knurled shaft. It costs \$1.89 per unit, or \$9.15 for 5 units. This rotary encoder does not have a momentary push switch, and so only has three signal pins: Channel A, Channel B, and Common, which are aligned in parallel with the shaft axis [46].

3.8.3.2 PEC12R-2120F-N0012

The PEC12R-2120F-N0012 is a rotary encoder that also has a 12.5 mm by 13.4 mm base, but instead has a metal-flatted shaft that is also 20 mm long. It costs \$1.51 per unit, or \$6.65 for 5 units. It also does not have a momentary push switch, and does not have a bushing. Its three pins are aligned radially [47].

3.8.3.3 PEC11R-4325F-S0012

The PEC11R-4325F-S0012 is another rotary encoder of the same size as the other options, except its shaft is a metal-flatted shaft that is 25 mm long. It does come with a bushing and a momentary push switch, and as such has two extra pins to support its functionality. It costs \$2.23 per unit, or \$18.80, and its pins are aligned in parallel with the shaft axis [46].

3.8.3.4 Component Comparison - Rotary Encoders

While all of these components are very similar, there are clear price differences between them based on whether or not they have a built in button. Thus, it would be more cost effective to simply get dedicated buttons, as rotary encoders with switches seem to be far more expensive. These encoders are also oriented slightly differently. With radial pins, the shaft remains perpendicular to the pins, and with axial pins they remain parallel with the shaft. If we were to place these components on a PCB, it may be harder for users to interact with rotary encoders situated on radial pins (think knobs on the bottom of a box, rather than coming out the front). If the rotary encoders were to be mounted directly on some casing, a bushing would help hold it in place. Thus, the PEC11R-4220K-N0024 offers the most versatility while still being the second cheapest option, and significantly cheaper than the most expensive option.

TABLE 3.23: Tactile Interfacing Component Comparison - Rotary Encoder

Name	PEC11R-4220K-N0024	PEC12R-2120F-N0012	PEC11R-4325F-S0012
Pin Orientation	Axial	Radial	Axial
Bushing	Yes	No	Yes
Momentary Push Switch	No	No	Yes
Cost per Unit	\$1.89	\$1.51	\$2.23

3.9 Interfacing Technology - Visual

3.9.1 Types of Visual Interfacing Technologies

For the PTC project, we intend on having some form of visual output for the end-user to see and interpret, in this case, information about a projectile's measured speed

and trajectory. There are many varieties of visual displays, and all could potentially accomplish the same goal, but each function differently and display visual information using different methods.

3.9.1.1 LCD

LCD stands for Liquid Crystal Display, and LCDs are quite common in small electronics and applications that only require a predetermined set of visual outputs. For example, an LCD may be used in a calculator, where the output is primarily numerical. In this case, the LCD would not be able to show anything other than numbers and some specialized characters, as what areas of the screen the LCD can actually alter or display to is physically built into its construction.

3.9.1.2 ePaper

Electronic paper displays maintain an image without power after it is written, offering excellent readability in bright light and very low power consumption. However, they have slow refresh rates, making them unsuitable for real-time updates during measurement cycles. [48]

3.9.1.3 TFT

Thin-Film Transistor displays are full-color graphical LCDs that provide high resolution, fast refresh rates, and good color reproduction. They are ideal for showing detailed graphs and user-friendly interfaces, but consume more power than basic LCDs. [49]

3.9.1.4 Technology Comparison

LCD technology was selected as the primary visual interfacing method because it offers the best balance of low power consumption, adequate refresh rate for real-time results, and low cost while still meeting the display requirements of the PTC system.

TABLE 3.24: Visual Interfacing Technology Comparison

Characteristic	LCD	ePaper	TFT
Power Consumption	Low	Very Low	Moderate
Refresh Rate	Good	Very Slow	Excellent
Color Capability	Limited	Monochrome	Full Color
Cost	Low	Moderate	Higher
Suitability for Real-time Data	High	Low	High
Readability in Bright Light	Good	Excellent	Good

3.9.2 Component Comparison - Visual Interfacing Technology

3.9.2.1 Waveshare 2.8-inch Capacitive Touch LCD

The Waveshare 2.8-inch Capacitive Touch LCD was selected as the display for the PTC. This module features a 320×240 resolution TFT LCD with a capacitive touch overlay, allowing both information display and simple user input through the screen. It connects directly to the Raspberry Pi via GPIO and is fully supported by existing Python libraries. The display provides clear, readable output for velocity, trajectory graphs, and status messages while keeping the overall system cost and power consumption low. [50]

3.9.2.2 Adafruit TFT Touchscreen

The Adafruit 3.5-inch TFT Touchscreen offers higher resolution and full-color graphics with capacitive touch input. It provides excellent visual quality but requires more GPIO pins, draws significantly more power, and increases overall system cost compared to smaller displays. [49]

3.9.2.3 Generic 16 x 2 Character LCD

The Generic 16 x 2 Character LCD is a low-cost, text-only display commonly used in embedded projects. It can show two rows of 16 characters and requires only a parallel GPIO interface. While inexpensive and easy to implement, it lacks graphical capability and cannot display trajectory plots or modern user interfaces. [51]

3.9.2.4 Component Comparison - Visual Interfacing Technology

The Waveshare 2.8-inch Capacitive Touch LCD was chosen because it provides the best balance of graphical capability, touch interaction, cost, and power consumption for the PTC system. It enables a modern, intuitive user interface while maintaining the overall system simplicity and cost targets.

TABLE 3.25: Visual Interfacing Component Comparison

Characteristic	Waveshare 2.8-inch Capacitive Touch LCD	Generic 16 x 2 Character LCD	Adafruit 3.5-inch TFT Touchscreen
Resolution	320 × 240	16 × 2 characters	480 × 320
Touch Input	Yes (capacitive)	No	Yes (capacitive)
Graphics Capability	Yes	No	Yes
Interface	GPIO (SPI)	GPIO (parallel)	GPIO (SPI)
Cost (single unit)	\$18.50	\$4.50	\$32.00
Power Consumption	Low	Very Low	Moderate
Suitability for PTC	High	Low	Moderate

3.10 Transimpedance Amplification Technology

Since it has been established that the PTC will shoot lasers into photodiodes and wait for the interruption of the beam in order to detect projectiles, a system must be put in place to make the output of the photodiodes legible to the MCU, as photodiodes output a current rather than a voltage. The solution is to use a transimpedance amplifier that will convert the current output of the photodiodes into a stable, almost linear voltage, and then impart massive gain on that voltage to get it high enough to be read by another device.

3.10.0.1 Specialized IC

Transimpedance amplifiers are often used in fiber optic applications and high speed photodiode applications, and so are specialized in operating with bandwidths greater than a megahertz. Since these come as a complete package in integrated circuits, they would require no extra components. Their use case is often specialized, and so they would be more expensive and exceed the PTC's specifications, allowing us to trade increased cost for reliability in signal propagation speed. However, this cost may not be worth it as we only expect the PTC to be able to measure projectiles as fast as 100 m/s, which does not quite exceed a megahertz bandwidth, and these IC's are generally quite expensive when compared to other options.

3.10.0.2 Generic Operational Amplifier

Using general purpose op-amps, a transimpedance amplifier can be designed and assembled that meets our requirements. This will of course require extra external components, as the device in use would not be a complete transimpedance amplifier alone, but an operational amplifier. Such designs will likely be cheaper, but may be more susceptible to excessive noise and may have a lower bandwidth due to the generic nature of the components, limiting response speed. Additionally, an insufficient slew rate could cause additional delays in signal propagation, and all these factors mean that great importance will be placed on our choice of operational amplifier and additional components, such that the amplifier has a large enough bandwidth and high enough slew rate, and the external components do not impart a large amount of noise.

3.10.0.3 Comparator

While the transimpedance amplifiers focus on providing a stable and somewhat linear voltage output to the MCU, another option could be reading the current output of the diode and constantly comparing to previous measurements to determine a drop in current. This could likely be accomplished with parallel outputs fed into a comparator. One parallel output of the photodiode would be fed straight into a resistance to ground and the input of a comparator, and the other would be fed into a capacitor to ground that is also attached to the other input of the comparator. With this, it may be possible to determine a change in the photodiode's output due to the delay caused by the capacitance on one track, allowing the comparator to detect a difference in voltage in outputs and send a signal to the MCU. This approach would likely require more experimentation, and may

be even more susceptible to ambient light than our other options.

3.10.0.4 Technology Comparison

A preliminary search of transimpedance amplifiers shows that specialized op-amps for transimpedance amplification vary wildly in price, from about \$5 for a single chip to more than \$20. General Purpose Op-Amps however, are far more affordable and are capable of serving the same function, though to a lesser degree. The Comparator based circuit may in theory work, but it is likely to require much testing and experimentation, which is undesirable for this project. Therefore, a generic op-amp will be used.

TABLE 3.26: Transimpedance Amplifier Technology Comparison

Name	Generic Op-Amp	Specialized IC	Experimental Comparator Circuit
Extra Components	Required	Not Required	Required
Performance	Variable	High	Unknown
Noise Susceptance	Medium	Minimal	High
Cost	Cheap	Expensive	Cheap

3.10.1 Component Selection - Amplifiers

3.10.1.1 TL084

The TL084 comes from a family of FET-input operational amplifiers, reducing input bias currents and noise imparted by the device to a negligible amount. It can operate with a 30 V difference between its positive and negative power pins, and has a high slew rate of 20 V per microsecond and a gain bandwidth product of 5.25 MHz. This features would allow us to use the TL084 as is without further regulating a high supply voltage to a lower value, and also should provide ample bandwidth and slew rate to detect changes in a photodiode's current output. The TL084 also is a quad package, with 4 op-amps inside, allowing us more amplifiers to use if necessary. At a price of \$0.34 per unit and an extended price of \$2.38 for 10, the TL084 seems like an all around great option [52].

3.10.1.2 MCP6489

The MCP6489 is a quad package operational amplifier that maintains a high slew rate like the TL084, at 20 Volts per microsecond, and supports almost double the gain bandwidth product at 10 MHz, and additionally has protections against electro-magnetic interference. At \$0.40 per unit, it would no doubt be a cost effective choice. However, it can only support a supply voltage of up to 5.5 V, and this would likely require us to insert another voltage regulator into the circuit to deliver power without damaging this device. Contrary to the TL084, the MCP6489 is actually a rail-to-rail op-amp, and so it will be able to make full use of its voltage supply. [53].

3.10.1.3 OPA2727AIDR

The OPA2727 is a dual package amplifier advertized as a high-speed CMOS amplifier, and is the highest performing amplifier among these options, with a gain-bandwidth product of 20 MHz and a slew rate of 30 V per microsecond. It also uses a supply voltage higher than the MCP6487, with a maximum input of 12 V. At \$2.90 per unit, this would be the most expensive, but highest performing option, as this would also likely require its own voltage regulator to prevent damage to the component [54].

3.10.1.4 Component Comparison - Transimpedance Amplifier

The TL084 may be able to handle a wide range of voltage inputs, allowing for significant gain to be applied to the TIA signal, but it does not quite match up to the MCP6489's specifications for its price point. At nearly the same price, the MCP6489 can handle nearly twice the bandwidth with a much lower noise floor, almost matching the noise specification of the OPA2727 for a significantly cheaper price. Although another stage of voltage regulation may be necessary to safely provide power to this chip, this may actually benefit the design as it can be used to filter out any ripple in the chip's supply, encouraging stable sensing of laser occlusion from the photodiode.

TABLE 3.27: Transimpedance Amplifier Component Comparison

Name	TL084HIPWR	MCP6489	OPA2727
Op-Amps in Package	4	4	2
Slew Rate	20 V/us	20 V/us	30 V/us
Gain Bandwidth Product	5.25 MHz	10 MHz	20 MHz
Voltage Noise Density (at 10 kHz)	21 nV/ $\sqrt{Hz}$	10 nV/ $\sqrt{Hz}$	10 nV/ $\sqrt{Hz}$
Rail-to-Rail	No	Yes	No
Cost per Unit	\$0.35	\$0.40	\$3.64

3.11 External Light Sensor Technology

For calibration purposes, it may be useful to have an ambient light sensor housed in the PTC's imaging chamber. With the output of this device, it would be possible to determine how bright the imaging chamber already is before operation, due to outdoor sunlight or other ambient sources, and better adjust shading manually or possibly even adjust how bright the strobe circuits strobe. Below are a few technologies that could accomplish this.

3.11.1 Photosensors

3.11.1.1 Photoresistor

A Photoresistor is a kind of resistor whose resistance changes based on the amount of light incident on itself. Photoresistors start out at high resistances and are reduced to low resistances when in bright environments, allowing a measured output current or voltage to be directly affected by an environment's light levels. This can then be interpreted by an MCU, but would likely require a software formula to quantify brightness in some way.

3.11.1.2 Photodiode

A photodiode produces a current when light reaches it. In this instance, a measured voltage and current could be directly generated by the environment's ambient lighting. This eliminates the need to actively provide a power source whose output is altered by an optoelectronic device, like what would be necessary for components like photoresistors and phototransistors. The photodiode's generated current can then be interpreted by an MCU by using a resistor connected in series with the photodiode to ground. Again, a software formula would likely be necessary to quantify the ambient brightness.

3.11.1.3 Phototransistor

Phototransistors are often specialized BJTs, and a phototransistor, instead of generating a current or changing resistance, changes how much current it will allow through its collector and emitter. Basically, the transistor turns more 'on' with more light, and more 'off' with less light. This, like the photoresistor, would require a power source, and the output could be interpreted by an MCU, which would likely require a software formula to calculate and quantify brightness.

3.11.1.4 Optical Sensor IC

Optical Sensor ICs combine the properties of optoelectronics with digital circuitry and serial communications, taking the sensing of light one step further and actually quantifying it, and sending a message to a controller via I2C. Rather than manually building a formula in software to interpret the output of the other options, these ICs will send binary values that correspond to actual values of Lux, a measure of illuminance.

3.11.1.5 Technology Comparison - Photosensors

Though many of these technologies are not expensive, comparatively, to each other, ICs would be more expensive than the other options. However, they have the advantage of being able to calculate Lux and send a code to their controller, simplifying measurement. Photoresistors and phototransistors would constantly drain current, but photodiodes would be able to constantly generate current. Even so, the ability to quickly calculate and communicate Lux is well worth the cost, and so the PTC will use an optical sensor IC.

TABLE 3.28: External Light Sensor Technology Comparison

Name	Photoresistor	Photodiode	Phototransistor	Optical Sensor IC
Efficiency	Poor	Excellent	Satisfactory	Excellent
Easy to Interpret	No	No	No	Yes
Cost	Less Expensive	Less Expensive	Expensive	More Expensive

3.11.2 Component Selection - External Light Sensor

3.11.2.1 TSL25403

The TSL25403 is a high-sensitivity light-to-digital converter that uses a visible light channel and an infrared light channel together to accurately calculate ambient light. It also includes an interrupt pin that can be used to trigger firmware interrupts in hardware controllers. Additionally, it requires a 1.8 V supply, and costs \$0.97 per unit [55].

3.11.2.2 LTR-303ALS-01

The LTR-303ALS-01 is another light-to-digital converter, covering a range from 0.01 to 64 thousand lux, also utilizing both a visible light channel and an infrared light channel together to produce accurate results. It also has an interrupt pin, and can handle a supply voltage of up to 3.6 V, and costs \$0.70 per unit citeltr-303als-datasheet.

3.11.2.3 LTR-329ALS-01

The LTR-329ALS-01 light-to-digital converter, like the LTR-303ALS-01, also covers a wide range from 0.01 to 64 thousand lux, and can handle a supply voltage up to 3.6 V. Unlike the other version though, the LTR-329ALS-01 does not include an interrupt pin, and so costs \$0.39 per unit citelte-329als-datasheet.

3.11.2.4 Component Comparison - External Light Sensor

All three components in question have excellent resolution, but the interrupt pins would not be necessary for this application, and using a supply voltage of 1.8 V would likely necessitate the use of a voltage regulator. With a maximum 3.6 V supply voltage, the LTR family sensors could be powered directly by the MCU or the voltage regulator powering it. Therefore, the LTR-329-ALS-01 is the optimal choice for its price and higher max input supply voltage.

TABLE 3.29: External Light Sensor Component Comparison

Name	TSL25403	LTR-303ALS-01	LTR-329ALS-01
Interrupt Pin	Yes	Yes	No

Supply Voltage	1.8V	3.6V	3.6V
Cost per Unit	\$0.97	\$0.70	\$0.39

3.12 Power Technology

3.12.1 Power Distribution Requirements

To aptly select power distribution technologies and components, it is necessary to analyze the power requirements of each active component. The components listed below will be the main components actively drawing power from the supply, and vary rather widely in maximum input voltage and the current they may require. The MCU, cameras, and ambient light sensor can all operate on a 3.3 V supply, and could all be powered by a single regulator, one that could provide about at least 1100 mA. The Line laser, display screen, and Raspberry Pi can all be powered by a 5 V source, but such a source would need to supply at least 5185 mA. The op-amp can handle up to a 30 V supply voltage, but does not necessarily require 30 V. The IR LEDs, as part of the strobe circuit, will be powered by a capacitor bank, allowing energy to accumulate and be stored over time so that it can be instantly released as a high current signal that can drive the LEDs. This removes the strain of powering the strobe circuit from the main power supply, and places it on a capacitor bank and switching circuit. In total, the PTC would require at least 6.3 A at 5 V. Furthermore, to drive the IR LEDs at 1 A, each LED would exhibit a voltage drop of about 3.2 V citeAC353A-YRR-1000mA-IR-LED-Datasheet. Of course, if each LED was placed in its own parallel circuit, that would place an extra burden of about 30 A on the PTC, likely on 30 separate capacitor banks. Putting all of the LEDs in series would require a voltage of more than 90 V. But, by placing 5 LEDs in series, in 6 parallel circuits, a common voltage of 24 V can be used to power each parallel strobe circuit, and this would greatly reduce the total amount of current needed during strobing, and would also reduce the number of capacitor banks necessary to supply said current.

TABLE 3.30: Component Power Requirements

Component	Max Supply Voltage	Max Supply Current
Adafruit 1057 Line Laser	5.2V	25 mA
Raspberry Pi Global Shutter Camera	3.3V	Negligible
AC3535A-YRR-1000MA IR LED	N/A	1.5 A
MCU	3.3V	1.0 A
Raspberry Pi Model 5	5.0V	5.0 A
Waveshare 2.8-inch Screen	5.0V	160 mA
TL084 Op-Amp	30V	Negligible

LTR-329ALS-01 Ambient Light Sensor	3.6V	Negligible
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3.12.2 Power Source Technology

3.12.2.1 Battery

Batteries would allow our device to work in any suitable environment without the need for a power receptacle nearby. In order to use a battery, however, we must conform to project requirements, and cannot implement a charging circuit. Batteries can also become unreliable at colder temperatures, or dangerous at higher temperatures, necessitating strict safety standards. However, in ideal circumstances achieving 24 V would be as simple as wiring a few batteries in series, and supplying 6.3 to 6.5 A should be simple, as many batteries are capable of safely discharging large currents.

3.12.2.2 Switched-Mode Power Supply

Switched-mode power supplies, much like switched converters, use a switching action to modulate the input voltage into a square wave. The duty cycle of this square wave is controlled such that the average value is the desired output voltage, and then this signal is filtered to produce a smooth output with minimal power loss, although there will be a slight ripple. Typically, switched power supplies are more efficient when switching a high voltage to a lower voltage. Finding one that could output at least 6.3 A at 24 V would not be hard.

3.12.2.3 Linear Power Supply

A linearly regulated power supply uses a mixture of passive and active components to control the output voltage level, restricting the flow from input to output using a feedback loop. Typically, linear regulators are most efficient when the input voltage is within a small range above the output voltage, and handling greater voltage differences between the two will cause excessive heat dissipation and power loss. Finding one that could supply more than 6.3 A at 24 V may be difficult.

3.12.2.4 Technology Comparison

Although batteries would be very portable and less expensive than some other options, they constrain how long the PTC can operate for, as batteries would need to be recharged. A linear supply, while usually the cheaper option, would be far more expensive here due to the difficulty of safely and efficiently regulating power with linear technology at such high voltage and currents. A switched mode supply is a good option, but may struggle to supply high currents efficiently. Therefore, a transformer would be the best option because it would be able to take wall power and efficiently convert it into a high current supply at 24 V.

TABLE 3.31: Power Source Technology Comparison

Name	Switched-Mode Supply	Battery	Linear Supply
Stability	Reliable	Less Reliable	Reliable
Efficiency	Efficient	Efficient	Least Efficient
Portability	Less Portable	Most Portable	Less Portable
Cost	Least Expensive	Less Expensive	Most Expensive

3.12.3 Component Selection - Power Supply

3.12.3.1 Alitove 192W Transformer

The Alitove 192W transformer is capable of delivering 8 A at 24 V, far exceeding the minimum projected current necessary to run all components of the PTC. The Alitove also has the added benefit of being housed inside a package much like that of a laptop charger, with plugs included, allowing our members to safely use wall power and the transformed output without directly connecting bare wires to screw terminals. It is priced at \$39.99 [56].

3.12.3.2 LRS-150-24

The LRS-150-24 is a 156 watt power supply capable of delivering up to 6.5 A at 24 V. Its honeycomb shell allows ample airflow to keep itself cool, and it has two output channels. While certainly capable of supplying the PTC, its near open-air construction brings some danger into its use, as 120-240V wall power and the 24 V, 6.5 A output must be connected to the LRS-150-24 via screw terminals. Using this power supply would necessitate clear caution to prevent risk of and harm from electrocution. It is priced at \$18.40 per unit [57].

3.12.3.3 Bingotec 150W Transformer

The Bingotec 150W transformer shares similar specifications to the LRS-150-24, with 24 V output up to 6.5 A, and rated for 150 W. At a price of \$18.85, it also delivers a slightly smaller form factor. However, its design is much like that of the LRS-150-24, and uses screw terminals for all connections and a honeycomb casing for airflow, increasing the risk of shock. Using this component would also require clear caution to prevent such circumstances [58].

3.12.3.4 Component Comparison - Power Supply

Due to safety concerns and convenience, there is one clear winner. Both the LRS-150-24 and the Bingotec 150W would require members of this project to handle bare 120VAC wires in order to wire them into the devices' screw terminals, as well as handle 24 V, 6.5 A wires on the output. The Alitove eliminates these concerns as it not only comes in a housing that does not leave inner components exposed, but also comes with plug

terminations so that bare wires do not have to be handled. In this case, the Alitove transformer is worth the cost.

TABLE 3.32: Power Source Component Comparison

Name	Alitove	LRS-150-24	Bingotec
Max Current (A)	8.0	6.5	6.5
Housing	Enclosed	Exposed	Exposed
Terminations	Plugs	Screw Terminals	Screw Terminals
Cost per Unit	\$39.99	\$18.40	\$18.85

3.12.4 Voltage Regulation

To ensure components are powered properly and that their requirements and specifications are met and not exceeded, voltage regulation is necessary. This can be achieved with a small variety of technologies. With the strobe LEDs in mind and the large voltage drop across them necessary in order to power them, it is likely that we will need a power supply that supplies a larger voltage, and as such, we should select our voltage regulation technologies accordingly.

3.12.4.1 Switching Voltage Regulator

Switching voltage regulators employ high frequency switching to interrupt the source voltage and produce an intermittent waveform. This waveform is like a square wave, and its duty cycle determines the voltage of the regulator's output. In order to achieve a stable output, the square wave is filtered into a smooth DC output. Due to the switching action inside, a small ripple will still appear on the output, varying the output voltage by a small amount. Switching regulators often have higher efficiencies because of their switching, and are often suitable for regulating large voltages down to smaller ones without significant power loss and heat dissipation. Switching regulators often require external components to function, as their timing circuits may require a large inductance, and inductors are typically too large to fit into a small integrated circuit.

3.12.4.2 Linear Voltage Regulator

In a linear regulator, the output voltage is controlled linearly by an Op-Amp and transistor switch, constantly adjusting how much current is let through the device based on the voltage across the load. Since linear regulators control the output voltage by controlling how 'on' a transistor is, they are typically less efficient, and dissipate more heat as a result. Linear regulators are typically unsuitable for regulating large voltages down to small ones, as a larger difference directly correlates to lower efficiency. Linear regulators also exhibit dropout behavior, where if the input voltage falls too close to the output voltage, the output voltage can no longer be correctly maintained, and falls as a result.

3.12.4.3 Low Dropout Voltage Regulator

Low dropout regulators are just like standard linear voltage regulators, but with optimized circuitry inside to minimize the effects of dropout behavior, greatly increasing the available margin available between input and output voltage before a decrease on the input causes the regulation of the output to fail. This property allows LDOs to be used in circuits where the input voltage has to be close to the regulated output voltage.

3.12.4.4 Zener Diode

A Zener diode is a type of diode that has a controlled avalanche breakdown, and is meant to operate in such a state. The breakdown voltage can be manufactured, and this allows us to create a rudimentary voltage regulation system by placing a Zener diode in reverse bias from the power rail to ground. Voltages above the Zener voltage will cause the diode to start conducting, causing the voltage of the power rail to stay under a certain limit. This accounts for over-voltage conditions by essentially causing a short, which may not be ideal if such a condition persists. In order to maintain a voltage above a certain level, another diode would need to be used.

3.12.4.5 Technology Comparison - Voltage Regulator

There are many components that will be used to make the PTC function, and as such it would be prudent to select more than one of these technologies. Switching regulators are generally more expensive than linear regulators, but usually are very efficient because of their switching action. Low-dropout regulators are less efficient, but simpler to implement. This makes switching regulators an ideal choice for any instances where we would need to convert a higher voltage, and LDOs an ideal choice for conversions where the voltage difference between input and output is not so large. Regular linear regulators simply don't have the extra advantage of a low-dropout design, and Zener diodes cannot sufficiently maintain a stable voltage, only clamp it. So, the PTC will use a combination of switching regulators and LDOs.

TABLE 3.33: Voltage Regulator Technology Comparison

Name	Switching Regulator	Linear Regulator	Low-Dropout Regulator	Zener Diode
Efficiency	High	Medium	Medium	Low
Adjustable	Yes	Optional	Optional	No
Output Ripple	Yes	No	No	No
Adaptable to changes in Input	Yes	Yes	Yes	Somewhat
Cost	More Expensive	Cheap	Less Expensive	Cheap

3.12.5 Component Selection - Voltage Regulators - 3.3V

3.12.5.1 AP5100

The AP5100 is suitable for our needs, being able to handle a rated input voltage anywhere from 4.75 V to 24 V, while supplying 1.2 A. The Raspberry Pi RP2350 Hardware Design guide suggests a 1 A supply current to be suitable for computationally intensive projects, so the AP5100's current capabilities are suitable for both the MCU we will be using as well as other components that will not draw much current. The AP5100 is adjustable, and its datasheet also supplies an example application circuit that perfectly suits our needs, a 3.3 V regulator. The AP5100 costs \$0.60 per unit, and comes with built-in protections for the regulator [59].

3.12.5.2 LM2575-3.3WT

The LM2575-3.3WT is a fixed output switched buck regulator, capable of taking in inputs varied from 4 to 40 V, well exceeding our 24 V supply. It has an enable pin to be turned on or off, and, additionally, it can supply up to 1 A of current to its load. The example circuits in the datasheet show applications with an adjustable version, or the 5 V fixed output version. While sufficient, this regulator may not be able to handle both the MCU and other 3.3 V components at the same time during worse-case peak-current consumption. It costs \$1.72 per unit, but comes in a larger and easier to handle package **LM2575 datasheet**.

3.12.5.3 LM2594M-3.3-EV

The LM2594M-3.3-EV is also capable of managing inputs from 4 V to 40 V, and can supply up to 1.5 A of constant current. It also has an enable pin to turn it on or off with a signal. It comes with built-in protections, and costs \$1.27 per unit. With 1.5 A of supply current capability, this component should have no issues powering the MCU as well as other 3.3 V components **LM2594 datasheet**.

3.12.5.4 LM2576S

The LM2576S is another buck regulator, capable of handling input voltages of up to 37 V, and can handle outputting up to 3 A of current. It comes in a large and easy-to-handle package, and is available for a variety of voltage levels, including 3.3V and an adjustable version. At \$1.31 per unit, it competes with the LM2575 and LM2594 with higher current throughput.

3.12.5.5 Component Comparison - 3.3V Regulators

The LM2575-3.3WT does not seem to come with internal protections, and is also the most expensive of the options. Not having internal protections could leave the PTC's components open to danger. While the LM2594M-3.3-EV has the highest input voltage tolerance, it also has the lowest efficiency, wasting power and generating excess heat during operation. Meanwhile, the AP5100 will be able to support our MCU and other devices with 1.2 A, a good middle ground between the other two options, has internal

protections, and is the most cost-effective option. But, it operates at a high switching frequency of 1.4 MHz, which necessitates certain considerations in the PCB layout that may not be possible to achieve with hand-placed and soldered components, leading us to choose the LM2576S adjustable version for its ease-of-use.

TABLE 3.34: 3.3V Regulator Component Comparison

Name	LM2576S	AP5100	LM2575-3.3WT	LM2594M-3.3-EV
Max Load Current	3A	1.2A	1.0A	1.5A
Max Input Voltage	37V	24V	40V	45V
Built-In Protections	Yes	Yes	No	Yes
Adjustable	Yes	Yes	No	No
Typical Efficiency	80%	87%	80%	75%
Switching Frequency	52 kHz	1.4 MHz	52 kHz	150 kHz
Cost per Unit	\$1.31	\$0.60	\$1.72	\$1.31

3.12.6 Component Selection - Voltage Regulators - 5.0V

3.12.6.1 R78K5.0-0.5

Like other switching regulators, the R78K5.0-0.5 can efficiently regulate voltages, and this one would also be able to handle a 24 V source and supply 500 mA of current. The R78K5.0-05 will regulate to a 5.0 V output, suitable for our line laser and display screen. The added advantage of this regulator is that it is completely housed within a single package, requiring no external components. As is, this regulator can be directly connected to a circuit. It costs \$2.79 per unit [60].

3.12.6.2 MPQ4341GLE-5-AEC1-Z

The MPQ4341GLE-5-AEC1-Z is capable of taking an input voltage ranging from 3.3 V to 36 V, and regulating to 5 V while supplying 5 A of continuous current. This is sufficient to power our Raspberry Pi Model 5 while also powering other devices like our display screen. Its switching frequency is also configurable from 350 kHz to 2.5 MHz, allowing us to choose a higher frequency to minimize ripple, and this chip can be synchronized with other regulators of the same type across different phases. It costs \$5.77 per unit **MPQ4341GLE**.

3.12.6.3 TPS54531DDAR

The TPS54531DDAR is capable of handling up to a 28V input, and has an adjustable output that can continuously supply 5 amps of current. Like the MPQ4341GLE, this would be able to supply power to the Raspberry Pi 5, and contrary to the MPQ4341GLE, the TPS54531DDAR does not include excessive features that we will likely not make use of, and costs \$2.10 per unit [TPS5431DDAR].

3.12.6.4 AP1501A-50K5G-13

The AP1501A-50KG-13 is a buck DC/DC converter capable of handling inputs ranging up to 40V, and is able to supply 5A of load current. It also has internal protection circuitry to limit thermal runaway and excessive currents. While seemingly perfectly suitable to power our Image Processor, the datasheet for this device is watermarked with a warning that it is not suitable for new designs. It costs \$3.85 per unit **AP1501AA**.

3.12.6.5 Component Comparison - 5.0V Regulators

The Raspberry Pi 5 will consume 5 A, and so, even though it would be possible to incorporate our own power regulation for it, doing so would necessitate a heat sink and other considerations for heat dissipation on our PCB layout, and may further complicate the arrangement of subsystems if the Raspberry Pi 5 is directly linked to our boards. For these reasons, we will elect to use the accompanying power supply provided with the Raspberry Pi 5 when purchased. For our 5V logic chips, an easy to use regulator is suitable as these components will not require as much current. It is also well worth heeding the manufacturer's warning for the AP1501A, so we have chosen the R78K5.0-0.5 for its affordability and ease of use.

TABLE 3.35: 5.0V Regulator Component Comparison

Name	R78K5.0-0.5	MPQ4341GLE	AP1501	TPS54531DDAR
Max Load Current (A)	0.5	5.0	5.0	5.0
Max Input Voltage (V)	36	36	40	28
Typical Efficiency (%)	90	90	80	87
Built-In Protections	Yes	No	Yes	Yes
Adjustable	No	No	No	Yes
Cost per Unit	\$2.79	\$5.77	\$3.85	&2.10
Hand Solderable footprint?	Yes	No	Yes	Yes

3.12.7 Component Selection - Voltage Regulators - Strobe

For the strobe circuit, since it will be powered by a local capacitor bank instead of our main supply, it is necessary to maintain a stable voltage so that all LEDs in series have a similar brightness. As the LEDs draw about an amp, a Low-Dropout regulator can pull current from a local capacitor bank to supply the LEDs while maintaining a constant output voltage. Low-Dropout regulators are especially advantageous here because, as the capacitor bank decreases in voltage while discharging, LDOs will be able to maintain their output longer than standard linear regulators.

3.12.7.1 Alternative Current Regulation Strategy

After designing the strobe circuitry to use a voltage regulator combined with a small resistor to maintain constant current, we came up with a much more elegant solution for current limiting. Instead of dissipating power across a linear voltage regulator, which tend to get expensive above about 1 or 2 amps, a voltage to current converter could have been used that would have dissipated the power across a MOSFET. By using an op-amp to adjust the gate voltage of a MOSFET based on the voltage across a resistor in series with the LEDs, the LEDs could have been turned on and off and had current regulation just by adjusting the voltage on the other input to the op-amp. Since we had already designed and simulated our circuitry and were just about to send off the PCBs for manufacturing, we decided not to switch the current regulation strategy.

3.12.7.2 LD1086DTTRY

The LD1086DTTRY is an automotive grade low-dropout regulator that is a reasonably priced option at \$1.76 per unit. It can handle inputs up to 36V and will allow us to deliver large currents of up to 1.5 A and a dropout voltage of 1.2V at maximum output current. Additionally, the output is adjustable with a simple formula that can be calculated by hand, allowing us to change how many LEDs we power in a strobe circuit if necessary [61].

3.12.7.3 LT1086

The LT1086 is a more expensive option, at \$6.42 per unit, but it can handle inputs up to 36V and will also allow us to deliver 1.5A of current with a 1V dropout. It is also adjustable, although the formula to do so is slightly more complex than the simple formulas provided for the LD1086 and the LT3080. The LT1086 has the added benefit of having a spice model in LTspice to simulate with citeLT1086.

3.12.7.4 LT3080

The LT3080 is another option that has the added advantage of having a spice model in LTspice, and priced at \$6.05 per unit, it can handle inputs up to 36V and is capable of outputting 1.1A. It is also adjustable with a simple formula like that of the LD1086DTTRY it also has a very low dropout voltage of 350mV citeLT3080.

3.12.7.5 Component Comparison - Strobe Voltage Regulators

Both the LT1086 and LT3080, being products from Analog Devices, have ready-made spice models that will be useful in circuit simulations. Additionally, the LT3080 has the lowest Dropout Voltage. While it is helpful that the LT1086 and the LT3080 have spice models in LTspice, the LD1086DTTRY is an LDO with similar performance ratings, with a dropout voltage less than that of the LT1086, and remains far cheaper than the other options. This is of great importance here specifically because of how many the PTC will require, with an estimated 10 strobe modules each requiring one regulator. The LD1086 is also adjustable with the same simple formula as the LD3080, but with more current delivery capability. Due to the short transient nature of our strobe circuits, thermal

performance was not a key metric being compared for these voltage regulators.

TABLE 3.36: 5.0V Regulator Component Comparison

Name	LD1086DTTRY	LT3080	LT1086
Max Load Current (A)	1.5	1.1	1.5
Max Input Voltage (V)	30	36	30
Dropout Voltage (V)	1.3	0.5	1.5
Spice Model Available	No	Yes	Yes
Adjustable	No	No	No
Cost per Unit	\$1.76	\$6.05	\$6.42

3.12.8 Inrush Current Regulation

The PTC may employ a custom strobe circuit in order to capture images of projectiles moving through the system, and as such may require methods of current regulation to protect the system and its components from overheating or straining the power supply. In this, there is one main area of concern: the capacitor banks that will supply each strobe circuit. Due to their potentially large capacitance, the capacitor banks will act as short circuits until they charge up, potentially causing surges of several amps worth of electricity, and no doubt damaging several components along the way. Below are a few technologies that could manage inrush current.

3.12.8.1 Soft Start Circuit

Using a MOSFET, it is possible to implement a soft start circuit that, upon startup, will limit current, and slowly reduce resistance as the gate of the MOSFET charges and it turns 'on'. The inrush current will then have settled, effectively protecting components from massive current surges due to capacitors acting like short circuits when empty. This circuit also has the added benefit of not causing much of a voltage drop, allowing its output to remain at voltage close to that of its input. This approach requires more components than a simple resistive element, but would reduce power loss and heat dissipation.

3.12.8.2 NTC Thermistor

A thermistor changes resistance based on its temperature. With a Negative Thermal Coefficient thermistor, it would be possible to limit inrush current in a simple manner: the thermistor would exhibit high resistance at first, but then slowly become less resistive as it warmed up, preventing massive surge currents. However, because this component is still resistive, it would have a voltage drop across itself, reducing the available voltage at its output compared to the input. Thermistors also often have long 'reset' times, on the order of several seconds to tens of seconds, and will take a while to return to their base state and resistance. This means that inrush currents may not be effectively dealt with

if the system is shut off, the capacitors are drained, and then the system is immediately turned on again, as the thermistor may still be at a temperature that correlates with low resistance, potentially leading to component damage.

3.12.8.3 Typical Resistor

While simple, a typical resistor must be able to handle the power it absorbs, and this could mean that this resistor ends up being larger than others in the circuit, and depending on how much power is expended, could necessitate a heat sink or other method of dispersing heat due to lost power. If used in a section of power delivery, the output voltage could be greatly decreased based on the resistance value of the resistor, reducing efficiency and generating heat.

3.12.8.4 Constant Current Limiter

A constant current limiter would limit inrush current, but will also prevent large amounts of current from entering the strobe circuit at all times, instead of just at startup. While this may seem like it limits the strobe circuitry, it actually encourages the current draw to come from the local capacitor banks on the board instead of the system's main power supply, and does not suffer from 'reset' times, allowing the PTC to be switched on and off repeatedly without risk of damaging components.

3.12.8.5 Technology Comparison - Inrush Current Regulation

Since we rely on a large capacitor bank to locally provide current to the strobe circuit, which houses sensitive LEDs, managing inrush current in a timely manner and without exposing the circuitry to unnecessary danger is important. Because of this, it makes sense to use a constant-current limiting circuit. This will prevent damage to the PTC if it is turned off and on again, whereas an NTC thermistor may not be able to protect the circuitry in such circumstances, and a soft-start circuit will potentially allow current to be drawn from the main power supply instead of the capacitor bank. Additionally, a constant-current limiting circuit allows the capacitor banks to be charged to max voltage, avoiding a significant voltage drop between the supply and the capacitor bank due to a resistive element.

TABLE 3.37: Current Regulation Technology Comparison

Name	CC-Limiter	Soft-Start Circuit	NTC Thermistor	Resistor
Efficiency	High	High	Medium	Low
Complexity	Low	Medium	Low	Low
Safety	Safe	Safe	Less Safe	Safe
Cost	Cheap	More Expensive	Less Expensive	Cheap

3.12.9 Component Selection - Inrush Current Regulators

Constant-current limiting circuits are quite common, and their construction is rather simple. As such, it has been difficult to find a single component that could accomplish

this task in an IC, and so, because the design is simple, we have elected to build such a circuit ourselves. By relying on the threshold voltages of Bipolar Junction Transistors, an NPN transistor and a PNP transistor can be placed in a configuration such that the current through the circuit causes the pair to self-regulate to a particular current output. Additionally, this can be implemented with nearly any pair of BJTs.

3.12.10 Transistor Switches

The PTC must be capable of capturing projectiles at different points in its journey through the PTC in order to calculate trajectory information. For this, it is imperative that the strobe circuits in use can be switched on and off in a timely manner.

3.12.10.1 BJT

Bipolar Junction Transistors (BJTs) are current controlled semiconductor devices known for their fast switching and simplicity. The downside is that they are current controlled, and currents from the source and load can flow into and out of the base, leading to current draw on the MCU, or potentially backflow, if voltages or currents exceed the transistor's specifications. BJTs are often limited in the amperage they can switch, and are therefore not used often for high-power switching tasks.

3.12.10.2 JFET

Junction Field Effect Transistors (JFETs) share an insulated Gate with other transistor technologies, and have the added advantage of being able to be used with AC signals without extra considerations due to the absence of a 'body diode'. This means that the drain and source pins are considered interchangeable, and the orientation of a JFET does not matter. But, JFETs are relatively uncommon and expensive. Furthermore, the operation of their gate works differently than other transistors, as for a P-Channel JFET, a positive voltage on the gate will turn it 'off', a voltage of 0 V will turn it completely 'on', and a negative voltage will likely cause damage to the device, and within specifications, this happens regardless of the voltages on the drain and gate. This is different from something like a PNP BJT, where the emitter must be at a higher voltage than the base in order for the BJT to conduct, and won't do so otherwise.

3.12.10.3 MOSFET

Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs) don't often use a metal oxide anymore, but the name stuck around. These transistors have an insulated gate, preventing any current draw from or backflow into the MCU. MOSFETs often require driver circuits to ensure they are properly powered and switch fast enough for their applications due to gate capacitance, but these capacitances also allow them to be used in soft-start circuits. The orientation of a MOSFET must be taken into consideration, as the wrong orientation can cause forward-biasing of an internal 'body-diode' and cause unwanted conducting, invalidating the purpose of the switch. MOSFETs can have very low drain source on resistance, allowing for high current and high power applications. One weakness of MOSFETs is the susceptibility to static shocks or transient voltage

spikes, which can burn through the insulating oxide layer of the gate. We will use a MOSFET for switching the current to the strobe lights.

3.12.10.4 Enhancement Mode / Depletion Mode

Field Effect Transistors come in either Enhancement Mode or Depletion Mode. Depletion mode transistors are far less common than enhancement mode transistors, and therefore more expensive. This project does not require the unique properties of a depletion mode transistor, so we will be using enhancement mode transistors.

3.12.10.5 NPN/PNP/N-Channel/P-Channel

BJTs come in either NPN or PNP variants, and FETs come in either N-channel or P-channel variants as well. NPN and N-channel transistors turn 'on' with a positive voltage applied to their base or gate relative to the emitter or source pins, and PNP and P-channel transistors turn 'on' with a negative voltage applied to their base or gate relative to the emitter or source pins.

3.12.10.6 Technology Comparison - Transistor Switches

MOSFETs were selected for the PTC project due to their efficient, high-current switching capabilities while maintaining safe and reliable interfacing with the microcontroller.

TABLE 3.38: Transistor Comparison

Feature	MOSFET	BJT	JFET
Power Capability	High	Low	High
Ubiquity	High	High	Low
Control Method	Voltage	Current	Voltage
Ease of use	Moderate	Easy	Moderate
Cost	Low	Low	High

3.12.11 Component Selection - MOSFETs

3.12.11.1 Component Comparison - MOSFETs

There are many different MOSFETs, each for a different purpose. For switching the strobe LEDs, we will need a low $R_{DS(on)}$ or the resistance between drain and source while it is on. Our strobe circuit will have 1 or 2 ohms of resistance, and drive around 1 amp of current. Therefore we want $R_{DS(on)}$ to be less than 100 milliohms to avoid changing the series resistance of the strobe circuit by more than 10%. The strobe circuit needs to turn on for 100 μs , so the turn-on time needs to be less than 10 μs . We will be switching a voltage of up to 24 V, so the MOSFET needs to have a breakdown voltage of higher than 24 V. Since we plan to use a MOSFET driver, we don't need to have the gate work at logic level voltages like 3.3 V, instead we can drive it with 12 V - 24 V, which expands the selection of components considerably. One common "jellybean" MOSFET is the 2N7000, however the $R_{DS(on)} = 5 \Omega$, which is much worse than what

we need. The PJA3406_R1 MOSFET by Panjit is a good fit, with a voltage, rise time, and other specifications that meet our needs. The PJA3404A_R1 MOSFET is slightly better due to the lower $R_{DS(on)}$, so that is what we chose. The MMFTN3402 by Diotec Semiconductor would switch faster, but has a higher $R_{DS(on)}$, and since we only need under 1 to 10 microseconds of rise time, the faster switching speed of nanoseconds is unimportant.

TABLE 3.39: MOSFET Comparison

Feature	2N7000	PJA3404A	PJA3406	MMFTN3402
Manufacturer	Microchip	Panjit	Panjit	Diotec Semiconductor
$R_{DS(on)}$	5 Ω	23 m Ω	35 m Ω	55 m Ω
Gate Charge Q_g	200 pC	12.8 nC	5.8 nC	5.9 nC
Rise Time	10 ns	34 ns	39 ns	3.3 ns
Drain Current	0.2 A	5.6 A	4.4 A	1.9 A
Drain-Source Voltage	60 V	30 V	30 V	30 V
Gate Threshold Voltage	3 V	2.1 V	2.1 V	1.4 V

3.12.12 MOSFET Driver

MOSFETs work by charging or discharging the gate capacitor to turn the transistor on or off. The capacitance of the gate means that the transistor takes time to turn on or off, limited by the current into or out of the gate. While the simplest way to control a MOSFET is to use a pull-up or pull-down resistor combined with a resistor on a GPIO pin of the microcontroller, this leads to slow switching times, and is limited by the microcontroller voltage in how high the gate voltage can be driven. A MOSFET driver is a microchip that can quickly source and sink large amounts of current in order to charge and discharge the gate of a MOSFET, turning the MOSFET on or off rapidly. Often using BJTs to amplify both the voltage of the microcontroller and the current, these can take the low voltage low current GPIO of the microcontroller and provide a high current and higher voltage signal to the MOSFET gate.

3.12.13 Component Selection - MOSFET Driver

3.12.13.1 Component Comparison - MOSFET Driver

A 4.5 amp high-speed power MOSFET driver, the MCP1403/4/5 is a solid general purpose MOSFET driver. The MCP1406/07 is a higher current version, capable of 6 amps instead of just 4.5 amps. The IXDN602 has specifications similar enough for our purposes, but only 2 amps of current. The ZXGD3009DY was a far less expensive option, yet it still meets the specifications that we required.

TABLE 3.40: MOSFET Comparison

Feature	ZXGD3009DY	MCP1404	MCP1407	IXDN602
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Manufacturer	Diodes	Microchip	Microchip	IXYS
Peak Source/Sink Current [A]	2	4.5	6	2
Delay [ns]	40	40	40	38
Max Supply Voltage [V]	40	20	20	40
Cost	\$0.19	\$2.62	\$1.17	\$1.39

3.13 Communication Technologies

Dedicated sensors and external ICs can accomplish various tasks, and perhaps to a greater degree of effectiveness than the MCU, without using up much of the MCU's processing power. Although, in order to use these external sensors and IC's, they must be able to communicate with the MCU and trade information. This process can be facilitated through a variety of communication protocols that are common in industry. Additionally, our MCU and Image Processor must be able to communicate with each other, and this may necessitate using another protocol.

3.13.1 Communication Protocols

3.13.1.1 I2C

I2C, which stands for Inter-Integrated Circuit, is a synchronous communication protocol that utilizes two wires from the MCU as a bus to send and receive information from multiple devices. I2C is able to facilitate communication between many devices with a total of 2 wires: a clock wire driven by the master chip, and a data wire that is used intermittently based on which device the master chip wishes to receive information from. This allows us to control when information is queried from sensors, partially allows us to control how fast this process happens, and saves space on our board and conserves our GPIO pins by limiting the amount of wires in use.

3.13.1.2 SPI

SPI stands for Serial Peripheral Interface, and is another communication protocol that is commonly used, especially for small displays. Unlike I2C however, it is not thoroughly standardized, and there can be small differences in how different pins used for SPI may be named. SPI is also a synchronous protocol, but in order to use multiple devices with the SPI protocol, they must be daisy-chained. In a daisy-chain, data that sent to a device further down the chain must first pass through all previous devices, which can complicate software and slow down the transfer of information. SPI also typically involves 4 data pins, more than I2C or UART.

3.13.1.3 MIPI CSI-2

MIPI CSI-2, which stands for Mobile Industry Processor Interface Camera Serial Interface 2, is a high-speed serial communication interface designed specifically for transferring image data between camera modules and image processors. Unlike more general-purpose protocols such as I2C, SPI, and UART, CSI-2 is optimized for camera applications and supports high-bandwidth image transfer. In the PTC system, this protocol is relevant because the Raspberry Pi 5 camera modules are expected to communicate with the Raspberry Pi through the CSI interface, making it essential for rapid image acquisition in the projectile tracking subsystem.

3.13.1.4 UART

UART is an often used asynchronous protocol, and stands for Universal Asynchronous Receiver-Transmitter. UART is simple and especially useful for communications between devices that operate at different clock speeds, and can be configured as such. UART typically requires two data lines and a ground connection. The PTC may require a simple serial connection between the MCU and the Image Processor, and UART is a practical option because it is easy to implement and does not require a shared clock line between devices. This communication is facilitated by using an agreed upon baud rate, or rate of transmission. By doing so, both devices can exchange data reliably without needing a separate clock signal as part of the interface.

3.13.1.5 Technology Comparison

The PTC project requires a user-interface and communication between two computational devices. The user-interface will incorporate a screen display, and this will likely be driven by the SPI protocol. As for communication between the MCU and Image Processor, it makes sense to use UART, since speed of computation and data transmission is of less importance after the superimposed images of the projectile have been taken and processed. If extra sensors are added to improve calculations and extrapolation of results, these will likely use I2C. For the camera subsystem, MIPI CSI-2 is the most appropriate protocol due to its ability to support rapid image transfer between the camera modules and the Raspberry Pi 5. Therefore, all of these technologies are extremely useful and will be beneficial to the implementation of the PTC.

TABLE 3.41: Comparison of Communication Protocols

Protocol	Type / Key Feature	Notes / Advantages
I2C	Synchronous, 2-wire bus	Facilitates communication with multiple devices using a clock and data line; conserves GPIO pins; allows controlled querying speed
SPI	Synchronous, daisy-chain	Commonly used for displays; may require 4 pins; devices must be daisy-chained, which can complicate software and slow transfer

MIPI CSI-2	High-speed serial camera interface	Designed for camera-to-processor communication; supports high-bandwidth image transfer for rapid image acquisition
UART	Asynchronous	Useful for devices with different clock speeds; uses 2 data lines + ground; baud rate ensures synchronized transmission

3.14 Software Technologies

The software component of the Projectile Tracking Chronograph (PTC) is responsible for real-time hardware control, high-speed image acquisition and processing, trajectory computation, and user interface rendering on the Raspberry Pi 5. Selection of appropriate development tools, programming languages, and libraries was critical to achieve reliable real-time performance within the constraints of an embedded platform.

Since the system must react quickly to projectile detection events, the software must be efficient, modular, and capable of handling multiple tasks such as sensor monitoring, image processing, and data visualization simultaneously. This requires careful consideration of both performance and maintainability during development.

In addition, version control is essential for tracking changes, enabling collaboration, and maintaining code integrity in a multi-module project. Git was easily selected as the version control system due to its widespread adoption, excellent branching capabilities, and seamless integration with Visual Studio Code and GitHub. It allows the team to work concurrently on different subsystems while maintaining a stable main branch. [62]

3.14.1 Integrated Development Environments

Several Integrated Development Environments (IDEs) were evaluated for Python-based development and debugging on the Raspberry Pi 5. The primary options considered were Thonny, PyCharm Community Edition, and Visual Studio Code.

3.14.1.1 Thonny

Thonny is a lightweight IDE that comes pre-installed on Raspberry Pi OS and is designed primarily for beginner-level Python development. It provides a simple and intuitive interface along with built-in debugging tools that allow users to step through code and inspect variables in real time. This makes it useful for quick testing, prototyping, and verifying small portions of the PTC software, such as sensor input or basic image capture routines. However, Thonny lacks advanced features such as strong Git integration, project-level organization, and support for large multi-file systems. Since the PTC software consists of multiple interacting modules, including image processing, hardware control,

and user interface components, these limitations reduce its effectiveness for full system development. [63]

3.14.1.2 PyCharm

PyCharm Community Edition is a professional-grade IDE that offers advanced code analysis, intelligent autocompletion, and powerful debugging tools. It is well-suited for large-scale software projects where maintainability and code structure are important. In the context of the PTC system, PyCharm provides strong support for managing complex logic such as trajectory computation and multi-module integration. However, one major drawback is its high resource usage. When running on the Raspberry Pi 5, PyCharm can consume significant system memory and processing power, which may interfere with real-time tasks such as image acquisition and processing. This makes it less ideal for development directly on the embedded platform. [64]

3.14.1.3 VS Code

Visual Studio Code is a lightweight and highly extensible code editor that provides a strong balance between performance and functionality. It supports Python development through extensions that enable debugging, linting, and intelligent code completion. Additionally, it includes built-in Git integration, allowing seamless version control and collaboration within the development team. For the PTC system, VS Code is particularly advantageous because it runs efficiently on the Raspberry Pi 5 while still supporting a modular project structure. Its ability to handle multiple files, integrate extensions, and maintain responsiveness during development makes it well-suited for managing the combined hardware and software complexity of the system. [65]

3.14.1.4 Technology Comparison - IDEs

Visual Studio Code was selected as the primary IDE for the PTC project. While Thonny offers simplicity and PyCharm provides advanced features, VS Code achieves the best balance between performance, flexibility, and usability on the Raspberry Pi 5. Its efficient resource usage ensures that development can occur alongside real-time system testing, while its extensibility supports the complex, multi-module nature of the PTC software.

TABLE 3.42: Integrated Development Environment Comparison

Characteristic	Visual Studio Code	Thonny	PyCharm
Resource Usage on RPi 5	Low	Very Low	High
Python Support	Excellent	Good	Excellent
Debugging Capabilities	Excellent	Excellent	Excellent
Git Integration	Excellent	Basic	Good
Extension Ecosystem	Extensive	Limited	Moderate
Ease of Use on Embedded Hardware	High	Very High	Moderate

Suitability for PTC Project	High	Moderate	Low
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3.14.1.5 Technology Comparison - IDEs (updated)

Although Visual Studio Code was originally selected during the design phase, the final implementation of the Projectile Tracking Chronograph was developed primarily using Thonny on the Raspberry Pi 5. During system integration, Thonny proved to be more practical because it is pre-installed on Raspberry Pi OS, starts quickly, and allows rapid testing and debugging directly on the target hardware. Since the software frequently required testing with cameras, GPIO, UART communication, and external trigger synchronization, the lightweight nature of Thonny made development more efficient than Visual Studio Code while still providing all of the functionality required for the completed system.

3.14.2 Available Languages

The choice of programming language directly affects development speed, execution performance, and maintainability on the Raspberry Pi 5. The two main candidates evaluated were Python and C++.

3.14.2.1 Python

Python is a high-level, interpreted programming language known for its simplicity and rapid development capabilities. It is widely used in embedded Linux environments such as the Raspberry Pi and provides extensive support for scientific computing and computer vision through libraries such as OpenCV and NumPy. For the PTC system, Python enables quick implementation of image processing algorithms, trajectory calculations, and hardware interfacing. Its readability also improves maintainability, which is important for a multi-developer project. Although Python is slower than compiled languages, its performance is sufficient for the PTC system when combined with optimized libraries and efficient coding practices. [66]

3.14.2.2 C++

C++ is a compiled programming language that offers high execution speed and precise control over system resources. It is commonly used in performance-critical applications and embedded systems requiring low-level hardware interaction. In the PTC system, C++ could provide faster execution for image processing and timing-sensitive operations. However, it introduces increased development complexity, longer implementation time, and more difficult debugging. Given the project timeline and the availability of optimized Python libraries, the performance benefits of C++ do not outweigh the added complexity for this application. [67]

3.14.2.3 MicroPython

MicroPython is a lightweight implementation of Python designed for microcontrollers and resource-constrained embedded systems. It provides a simplified version of Python that can run on devices with limited memory and processing power. In the context of the PTC system, MicroPython is not suitable for the Raspberry Pi's image processing tasks due to its limited library support and lack of compatibility with OpenCV. However, it is well-suited for use on microcontroller-based subsystems, where it can be used to handle simpler tasks such as sensor interfacing or signal triggering. This allows for consistency in programming style across different parts of the system. [68]

3.14.2.4 Technology Comparison - Available Languages

Python was selected as the primary programming language for the PTC system. While C++ offers higher performance, Python provides significantly faster development, better library support, and easier integration with the Raspberry Pi hardware. These advantages are critical for implementing real-time image processing and system control within the project timeline. MicroPython may still be used in supporting subsystems, but Python remains the most suitable choice for the main processing unit.

TABLE 3.43: Programming Language Comparison

Characteristic	Python	C++	MicroPython
Development Speed	High	Low	High
Execution Speed	Moderate (adequate with optimization)	High	Moderate
Library Support (Computer Vision)	Excellent (OpenCV, NumPy)	Good	Limited
Learning Curve	Low	High	Low
Real-time Suitability on RPi 5	High (with optimization)	Excellent	Moderate
Suitability for PTC Project	High	Moderate	Moderate

3.14.3 Image Processing Software

To determine the most effective software technology for projectile detection and trajectory estimation, several image processing libraries were evaluated for use within the PTC system. In addition to selecting an image processing library, the overall software organization of the image processing subsystem must also be considered to ensure that image acquisition, preprocessing, feature extraction, trajectory computation, and user interface updates can be performed in a structured and maintainable manner.

3.14.4 Platform

At the platform level, the PTC image processing subsystem is intended to operate on the Raspberry Pi 5 using a Linux-based operating system and a Python development environment. This platform supports direct integration with the camera subsystem, execution of image processing libraries, and interfacing with the remainder of the embedded software stack. Compared to a desktop-only workflow, this approach is more suitable for final deployment in an embedded system. Compared to using only a microcontroller, it provides substantially greater computational capability and software support for image-based analysis.

3.14.4.1 Technology Comparison - Software Execution Platform

A Raspberry Pi 5 running a Linux-based software environment was selected as the software platform for the PTC system. This choice provides the best balance between computational performance, embedded deployability, and software compatibility. It allows the image processing subsystem to operate directly on the final device while supporting the software libraries and development tools required for projectile detection and trajectory estimation.

TABLE 3.44: Software Execution Platform Comparison

Characteristic	Raspberry Pi 5 + Linux	Desktop Laptop	Microcontroller
Embedded Deployability	Excellent	Poor	Excellent
Real-time Image Processing Capability	High	Excellent	Poor
Camera Interface Support	Excellent	Good	Limited
Portability	High	Low	High
Software Ecosystem Support	Excellent	Excellent	Limited
Suitability for PTC	High	Moderate	Low

3.14.5 Libraries

At the library level, the primary image processing candidates considered for the PTC system were OpenCV, MATLAB Image Processing Toolbox, and Scikit-image.

3.14.5.1 OpenCV

OpenCV is an open-source computer vision library specifically designed for real-time image processing applications. It provides highly optimized implementations of algorithms such as frame differencing, edge detection, contour extraction, and centroid calculation. These features are essential for detecting and tracking high-speed projectiles within sequential image frames. OpenCV also includes tools for camera calibration and coordinate transformation, which are necessary for converting pixel data into real-world measurements in the PTC system. Additionally, it integrates seamlessly with Python and

can efficiently utilize the processing capabilities of the Raspberry Pi 5, making it ideal for embedded real-time applications. [69]

3.14.5.2 MATLAB

MATLAB Image Processing Toolbox provides a structured and mathematically rigorous environment for developing and analyzing image processing algorithms. It offers strong visualization tools, making it useful for understanding system behavior and validating algorithm performance during early development stages. However, MATLAB requires paid licensing and is not optimized for deployment on embedded platforms such as the Raspberry Pi 5. Its higher resource requirements and limited hardware integration capabilities make it unsuitable for real-time execution in the final PTC system. [70]

3.14.5.3 Scikit-image

Scikit-image is a Python-based image processing library built on top of NumPy and SciPy. It provides a wide range of image analysis functions and is easy to use for algorithm development and testing. However, Scikit-image is not optimized for real-time performance and lacks direct support for high-speed video processing and hardware-level camera interfacing. This limits its effectiveness in applications like the PTC system, where rapid frame processing and accurate timing are critical. [71]

3.14.5.4 Technology Comparison - Image Processing Library

OpenCV was selected as the primary image processing library. Its strong compatibility with embedded systems, excellent real-time performance, zero licensing cost, and seamless integration with Python make it the optimal choice for the PTC project. MATLAB was used only for early conceptual validation, while Scikit-image served as a secondary reference during algorithm development.

TABLE 3.45: Image Processing Library Comparison

Characteristic	OpenCV	MATLAB Toolbox	Scikit-image
Real-time Performance	Excellent	Moderate	Moderate
Embedded (RPi 5) Compatibility	Excellent	Poor	Good
Cost	Free	High (license required)	Free
Integration with Python	Seamless	Limited	Excellent
Speed	High	Moderate	Moderate
Suitability for PTC	High	Low	Moderate

3.14.6 Framework

At the framework level, the organization of the PTC image processing subsystem must also be defined. Several software architecture frameworks were considered, including

layered architecture, event-driven architecture, and Model-View-Controller.

Layered architecture separates the software into functional levels such as hardware interfacing, image acquisition, image preprocessing, projectile extraction, ballistic computation, and user interface output. This improves modularity and makes the system easier to test and maintain. Event-driven architecture organizes software behavior around events such as projectile detection, strobe triggering, image capture completion, and user input. This is especially useful in systems that must respond to asynchronous hardware events in real time. Model-View-Controller separates software into data handling, user interface display, and control logic. While this approach is useful for user interface organization, it is less appropriate as the primary framework for the full PTC system because the project also requires tight coordination between hardware events and processing stages.

3.14.6.1 Technology Comparison - Framework

A layered software architecture with event-driven execution was selected as the primary framework for the PTC system. The layered structure provides a clear separation between the major functional portions of the software, while the event-driven behavior allows the system to respond efficiently to projectile detection, image acquisition, and result presentation events. MVC principles may still be applied within the user interface portion of the design, but they are not used as the primary framework for the complete system.

3.14.6.2 Technology Comparison - Framework (updated)

During the implementation phase, the software architecture evolved from an event-driven approach into a polling loop architecture. While event-driven software can provide excellent responsiveness, the completed system needed to continuously monitor multiple subsystems, including UART communication with the ESP32, camera capture status, image processing, and the graphical user interface. A polling loop provided a simpler and more predictable execution flow while maintaining the real-time performance required by the system. This architecture also simplified debugging and subsystem integration throughout development.

TABLE 3.46: Software Architecture Framework Comparison

Characteristic	Layered + Event-Driven	MVC	Pure Event-Driven
Modularity	Excellent	High	Moderate
Support for Hardware-Triggered Operation	Excellent	Moderate	Excellent
Ease of Integration with UI	High	Excellent	Moderate
Maintainability	High	High	Moderate
Suitability for Embedded Real-Time Processing	High	Moderate	High
Suitability for PTC	High	Moderate	Moderate

3.14.7 Model

At the model level, the selected framework must be applied in a specific way to organize how data flows through the image processing subsystem. For the PTC system, the preferred model is a staged processing model in which image acquisition, preprocessing, projectile extraction, trajectory computation, and user interface updates occur in a defined sequence. This model is especially appropriate for a system in which each captured image must pass through multiple processing stages before the final ballistic outputs can be displayed.

Alternative software organization models were considered, such as a more monolithic single-script implementation or a loosely coupled event-only structure. A monolithic implementation may be simpler, but becomes difficult to maintain, debug, and scale as the system grows. A purely event-driven model can be effective for trigger handling, but by itself it does not clearly represent the sequential transformations applied to captured image data. The staged processing model preserves the advantages of layered software organization while more clearly defining how image data progresses through the subsystem.

3.14.7.1 Technology Comparison - Model

A staged processing model was selected for the PTC image processing subsystem. This model provides a clear and maintainable representation of how captured images are transformed into projectile position, trajectory, and user-facing results. It also fits naturally within the selected layered, event-driven framework by allowing each software layer to perform a specific step in the image processing pipeline.

TABLE 3.47: Software Organization Model Comparison

Characteristic	Staged Processing Model	Monolithic Implementation	Pure Event-Only Model
Clarity of Data Flow	Excellent	Low	Moderate
Maintainability	High	Low	Moderate
Scalability	High	Low	Moderate
Support for Sequential Image Operations	Excellent	Moderate	Low
Suitability for PTC	High	Low	Moderate

3.14.8 Selected Software Approach

The selected image processing software approach for the PTC system consists of a Raspberry Pi 5 running a Linux-based software environment as the platform, OpenCV as the primary image processing library, a layered architecture with event-driven execution as the software framework, and a staged processing model for organizing the flow of image data through the subsystem. This combination provides strong real-time image processing

capability while maintaining a clear and maintainable software structure appropriate for embedded projectile detection and trajectory estimation.

4 Standards and Design Constraints

The PTC system was designed according to established engineering standards to ensure safe operation, reliable measurements, and maintainable system development. Since the project integrates lasers, optical components, embedded electronics, and real-time software processing, multiple categories of standards were considered during both the design and implementation phases. [72]

4.1 Engineering Standards

While a variety of standards are in use, there are a few in particular that we absolutely must understand and adhere to in order to successfully implement our design.

4.1.1 Communication Standards

In order to program certain devices, and for the end user to receive trajectory information from the PTC, certain devices must be able to communicate with each other and transfer data. To power the entire project, our MCU and Image Processor must first be programmed with one communication standard. These two devices must also communicate with each other during operation with another, and, additionally, the display screen must be driven with yet another standard.

4.1.1.1 USB

The USB, or Universal Serial Bus, is an industry standard maintained by the USB-IF (USB - Implementers Forum), a non-profit corporation founded by the companies that originally worked together to create the USB protocol, companies such as Apple, Microsoft, and Texas Instruments. The USB-IF is thus solely capable of defining what criteria a device must meet in order to be considered a proper USB device. The USB 2.0 Specification, originally released on April 27, 2000, serves as the governing document for USB 2.0 compliance. [73]

According to the USB 2.0 standard, in section 4.1, a USB system is made up of 3 categories: the USB interconnect, the USB devices, and the USB host. Every USB system only has one host in a tiered system, and, according to the USB 2.0 standard, the host can only maintain a connection with a maximum of six lower tiers, with a hub at the center of all tiers except the last one. This means that should the PTC project require it, we could build a USB connection several tiers deep (From host to hub, hub to hub, etc.) without violating the standard, ensuring proper functionality. However, our use case is limited to just programming our devices. [73]

The USB 2.0 Specification requires that all high-speed capable devices support specified test modes for their ports, ensuring that there is interoperability across various implementations [74]. This specification defines three signaling rates to accommodate different device requirements. For our application, the low-speed data rate configuration exceeds our requirements for programming and system configuration:

- **High-speed:** Defined at 480 Mb/s $\pm$ 0.05% in section 7.1.11 of the specification.
- **Full-speed:** 12 Mb/s
- **Low-speed:** 1.5 Mb/s

The USB 2.0 Electrical Compliance Test Specification Version 1.07 defines a set of electrical test criteria for USB 2.0 products. For example, for upstream facing ports, the specification requires testing for low-speed and full-speed signal quality, as well as inrush current and back voltage. Additionally, low-speed and full-speed signal quality testing as well as drop/droop characteristics must be categorized for downstream facing ports [74]. Section 7.1.2.2 of the base specification defines template waveform requirements measured at specific test points. A USB 2.0 downstream facing port must meet the Template 1 transform wave requirements measured at TP2 (each hub downstream port) and a USB 2.0 upstream facing port (without a captive cable) must meet the Template 2 transform wave requirements measured at TP3. [75]

It is our responsibility as engineers to ensure the products we use conform to the USB-IF's specifications like the USB 2.0 Specification, released in the year 2000 and continually updated to optimize performance across a variety of technologies. Other specifications exist for newer USB versions. In order to do this, we can simply check that the manufacturer of a so-called USB device is in fact recognized by the USB-IF as a Standard Adopter, meaning that the manufacturer has proven that their devices meet the USB-IF's specifications. The USB 2.0 specification itself and the list of standard adopters can both be found on the USB-IF's website, USB.org. [73]

4.1.1.2 UART

The Universal Asynchronous Receiver-Transmitter (UART) protocol is a hardware communication protocol that used asynchronous serial communication with a configurable speed. UART communication only need two wires to connect devices, a TX (transmit wire) and RX (receiver wire). UART does not require a clock signal to work, instead relying on both devices being configured to have the same baud rate. A common baud rate for this protocol is 9600 bits per second, with higher rates supporting faster data transfer for time-sensitive applications. For the PTC system, UART can facilitate communication between the microcontroller and other peripherals where simple serial communication is sufficient. [76]

4.1.1.3 SPI

The Serial Peripheral Interface (SPI) protocol is a synchronous serial communication protocol that enables high-speed, full-duplex data exchange between a master device and one (or more) slave device(s) [77]. SPI operates using a four-wire interface:

- **Slave Select (SS):** Here, each device contains a dedicated SS pin if it is a slave device. Multiple slave devices can be shared with the same MOSI, MISO, and SCK lines but must have separated SS lines. [77]
- **Master Out Slave In (MOSI):** In this protocol, data is shared from the master device to other slave devices.[77]
- **Master In Slave Out (MISO):** In this protocol, data is shared from the slave device with the master device. [77]
- **Serial Clock (SCK):** This is the clock signal used by the master and slave devices for coordinating the timings for data transfer. [77]

In the PTC system, SPI can be used for communication with the more high-speed peripherals where timing predictability is crucial for system success.

4.1.1.4 MIPI CSI-2

The camera modules used in the PTC system communicate with the Raspberry Pi 5 through the Camera Serial Interface standard, specifically MIPI CSI-2. On the Raspberry Pi 5, the camera is connected through one of the two CAM/DISP connectors which use the 22-pin mini camera connector form factor. The CSI connection uses high-speed differential signaling over the MIPI D-PHY physical layer, allowing image data from the camera sensor to be transferred efficiently to the Raspberry Pi image processor. In addition to the differential data and clock lanes, the connector also includes auxiliary lines such as I²C for camera control and configuration. Since the PTC system depends on reliable and high-speed transfer of image frames from the camera modules to the Raspberry Pi 5 for the trajectory estimation, adherence to the CSI-2 and associated physical interface requirements is essential for correct operation. [78]

4.1.1.5 CAN

Controller Area Network (CAN) is a serial communication protocol originally developed for industrial and automotive applications. This is a CSMA/CD protocol, which means that each node on the bus can detect collisions and stop trying to transmit the data for a certain amount of time before trying to then retransmit. CAN makes use of differential signaling on a two-wire bus (CAN_H and CAN_L), where the differential voltage corresponds to the dominant and recessive states of the CAN signals. While this protocol is very reliable for applications requiring high safety regulations, the current plan for the PTC does not include the usage of CAN. [79]

4.1.2 Laser Safety Standards

Laser safety is the discipline of identifying, evaluating, and controlling the hazards associated with the usage of lasers. The primary concern with these devices is the tightly concentrated beam of optical power that the laser produces. A 1 mW laser operating the visible spectrum produces an irradiance at the retina approximately 100,000 times greater than looking directly at the sun. This is because the laser is a coherent source with a low-divergence, which can cause great damage to the eye of a person. Higher-power lasers that are used in fields such as medicine, research, and manufacturing cause injuries that are often permanent and severe. [80]

Laser hazards are often categorized into two broad categories: beam hazards and non-beam hazards. Beam hazards are associated with the emitted radiation from the laser itself either through direct, reflected, or scattered contact with the eye or skin. Non-beam hazards come from interactions that are typically caused by laser usage, such as electrical shock from power supplies, fire ignition by high-powered lasers, or toxic fumes generated by certain laser-material interactions. [80]

4.1.2.1 Regulatory Framework

There are three principle documents for laser safety that govern the manufacturing, sale, and workplace use of lasers:

- **FDA/CDRH Regulations (21 CFR 1040):** The FDA's Center for Devices and Radiological Health (CDRH) regulates the manufacturing and sale of laser products under the Federal Laser Product Performance Standard (FLPPS) in the United States. This standard establishes requirements for laser product classification, labeling, and other safety features.
- **ANSI Z136.1:** The American National Standards Institute (ANSI) publishes the ANSI Z136.1, which is documentation on how lasers should be used in the workplace. This standard provides many details on training requirements, control measures, program administration, and other workplace-related protocols.
- **IEC 60825-1:** The International Electrotechnical Commission (IEC) publishes the IEC 60825-1 document, which defines safety requirements and hazard classifications internationally. This standard shares many similarities with the U.S. standards, but there are differences in labeling requirements and certain numerical limits.

Commercial lasers that are purchased with a hazard classification provided by the manufacturer must conform to the classification requirements set by the FLPPS. These standards all share a common technical foundation, but differ in qualities such as administrative detail and certain requirements/limits. [81]

4.1.2.2 Laser Hazard Classification System

The laser hazard classification is a system that ranks every type of laser product based on its potential to cause biological harm. The classification is determined by comparing the laser's accessible emission to the Accessible Emission Limit (AEL) for each class, with characteristics such as maximum power output, wavelength being determining factors for this classification. The different classes of lasers are as follows:

- **Class 1 Lasers:** These lasers emit radiation that may be visible or invisible, but are incapable of producing radiation levels that would be damaging under normal operating conditions. These lasers may have an accessible beam with very low intensities or even potentially fully enclosed. Class 1 laser are not required to follow personal protective equipment (PPE) or control measure requirements due to their low-level of potential harm. [81]
- **Class 1M Lasers:** These types of lasers are safe for viewing to the naked eye, but could potentially cause harm if viewed through optical instruments such as magnifying lenses. These lasers are still low-power, but could cause harm, so they should have special consideration when optical components are present in the same environment. [81]
- **Class 2 Lasers:** Class 2 lasers are categorized by their emission in the visible spectrum (400-700 nm) and their higher intensity beams. These lasers trigger the eye's natural aversion response, but are generally safe under normal circumstances. [81]
- **Class 3R Lasers:** These lasers are still considered "low-risk" for causing injury to the eye, but exceed the limits of Class 2 lasers. Direct beam viewing could be dangerous, especially for prolonged exposure, so these lasers require basic administrative controls. [81]
- **Class 3B Lasers:** Class 3B lasers are more hazardous to the eye from direct beam viewing as well as reflections. These lasers can also present a minor hazard to biological tissue under prolonged exposure conditions. These lasers require administrative and engineer controls, and necessitate protective eyewear to be worn from exposed individuals. [81]
- **Class 4 Lasers:** These are the lasers that present the highest hazard classification. They are capable of causing significant eye injury from direct, reflected, or scattered radiation. They also present burning hazards to skin or fire hazards to combustible materials. These laser require the most strict administrative controls and procedures as well as mandatory PPE for personnel. [81]

4.1.3 Electrical and Hardware Safety Standards

Electrical safety standards guided the hardware architecture to prevent shock hazards, unsafe operating conditions, and damage to components. The system design aligns with principles described in IEC 61010, which governs safety requirements for laboratory equipment and measurements. Since the Projectile Tracking Chronograph (PTC) operates as a precision measurement device involving optical sensors, high-intensity strobe lighting, and external power sources, these guidelines directly influence decisions related to grounding, insulation, and safe power distribution. Proper grounding techniques are used to prevent unintended current paths and ensure stable operation during high-speed measurements. [82]

In addition to grounding and power distribution, protection against transient voltage spikes and improper GPIO usage was carefully considered. The Raspberry Pi 5 interfaces with photodiodes, laser modules, and triggering circuitry, making it vulnerable to overvoltage conditions. To address this, voltage regulation and level shifting techniques are incorporated to maintain safe operating levels between components. Current-limiting resistors and protective elements such as diodes are also included to reduce the risk of short circuits, component damage, or failure during repeated testing cycles. These protections are especially important due to the rapid switching behavior of the detection system. [83]

Another important consideration was electromagnetic interference due to the presence of high-speed switching elements such as strobe lighting and digital communication signals. These elements can introduce noise that affects sensor readings and image capture accuracy. To mitigate this, careful PCB layout practices, proper wire routing, and common grounding references are used to reduce interference. Shielding and separation of analog and digital signals are also considered where necessary. These design practices ensure reliable signal integrity and improve the consistency of projectile detection and trajectory calculations under real operating conditions. [72].

Finally, system-level safety was considered in relation to the energy stored within the strobe system. Since the strobe requires rapid discharge of energy from capacitors to produce high-intensity light, proper component ratings and discharge paths are necessary to prevent overheating or component stress. Safety margins were applied to voltage and current ratings, and controlled discharge mechanisms were considered to ensure safe and repeatable operation. These considerations are critical for maintaining both user safety and long-term system reliability in the PTC design.

4.1.4 Data and User Interface Standards

User interaction design for the PTC system follows established human-computer interaction and usability engineering standards to ensure clarity, consistency, and reduction of operational errors. In particular, the interface design is aligned with ISO 9241, which defines ergonomic requirements for human-system interaction, and ISO/IEC 25010, which outlines software quality models including usability and user satisfaction.

Measurement results are displayed using standardized formatting so users can easily

interpret velocity outputs and trajectory information. The interface provides consistent feedback during operation, including system readiness, detection events, and processing status. These design decisions follow ISO 9241 guidelines, which emphasize clarity of information presentation and user control during interactive processes. In addition to clarity and consistency, the interface design incorporates principles of visual hierarchy and minimal cognitive load as described in usability heuristics such as Nielsen's usability principles. Important system states such as "charging," "idle," and "detection complete" are visually distinct to prevent user confusion during operation and to support rapid decision-making in time-sensitive scenarios.

Color coding and text indicators are used together to ensure accessibility and reduce ambiguity in interpretation. This approach aligns with ISO 9241 recommendations for multimodal feedback, ensuring that users can interpret system status reliably even under varying environmental or viewing conditions. For example, warning or non-ready states are visually differentiated from operational states to clearly communicate system readiness and prevent incorrect usage. Furthermore, response latency in the user interface is minimized to ensure that feedback appears effectively instantaneous to the user. According to human factors guidelines, system response times below perceptual thresholds are critical for maintaining user engagement and trust in real-time systems. This is particularly important in measurement applications where delays could negatively impact usability and perceived system reliability.

4.1.5 Software and Coding Standards

Software development for the PTC system follows structured and modular programming practices to ensure maintainability, scalability, and reliability. The system is implemented in Python due to its flexibility, readability, and strong support for image processing libraries such as OpenCV. Code organization is divided into functional modules, including image acquisition, projectile detection, trajectory computation, and user interface control. This modular design allows individual components to be development, tested, and debugged independently. To maintain consistency across the development team, coding practices follow general guidelines inspired by the Python PEP8 standard. These include consistent naming convention, indentation rules, and code formatting to improve readability and collaboration. [84]

Additionally, inline comments and documentation are used to explain complex logic, particularly in image processing routines and mathematical computations. Error handling is also a critical component of the software design. The system must handle potential failures such as camera disconnection, improper image capture, or unexpected input values. Instead of allowing the system to crash, an exception handling mechanism will be implemented to ensure recovery and continued operations. These software standards contribute to a stable and maintainable codebase that supports real-time projectile tracking and future system improvements. [85]

4.2 Design Constraints

Engineering constraints significantly influenced the PTC system architecture by limiting available design choices and forcing tradeoff decisions among safety, performance, cost, and usability considerations.

4.2.1 Safety Constraints

Safety constraints are the most influential factors in system development. Laser exposure risk requires strict beam control and enclosure design to maintain eye-safe operation. Since the projectiles we will measure travel at a higher velocity, projectile containment and controlled firing direction are necessary to prevent unintended impacts. Indoor operation requirements further restricts the power levels for lasers and demands careful management of reflections. Electrical isolation between subsystems will be required to prevent shock hazards as well as protecting sensitive electronics.

4.2.1.1 Laser Exposure Risk

Laser exposure risk requires strict beam control and enclosure design in order to maintain operation safe to the human eye. The laser used for the light gate must be positioned in such a way that the beam path does not intersect with any areas where users may be present. The housing of the PTC system will incorporate beam stops and other additional light collecting methods to capture or block and stray reflections that could potentially redirect laser light toward users. The choice of laser directly impacts safety requirements, and by selecting a Class 1 laser, we minimize the required safety infrastructure while still achieving adequate detection sensitivity. If we were to use a higher-class laser, additional safety procedures would have to be implemented such as PPE and engineering controls for the user. For this project, the PTC will be demonstrated in an indoor environment, which can introduce more reflective surfaces around the system. This further drives the need for additional beam blocking controls in order to minimize the risk of uncontrolled beam paths hitting a user or bystander.

4.2.1.2 Projectile Containment and Electrical Isolation

Since the projectiles measured by the PTC travel at high velocities, projectile containment and controlled firing direction are necessary constraints to consider in order to prevent unintended impacts. The PTC must be positioned within a controlled range environment where projectiles can be captured by appropriate backstops, as opposed to capturing the projectile within the device itself. This system was designed with the intention to be operated in environments like shooting ranges (for higher velocity projectiles) as well as indoors (for lower velocity projectiles).

Electrical isolation between subsystems is required to prevent shock hazards and protective sensitive electronics within the device. Adding safety features such as level shifters or other isolating circuits can prevent ground loops and protect against transient events that could damage components or pose safety risks. Power supply designs are also important, as appropriate fusing and overcurrent protection can prevent hazards like electrical fires.

4.2.1.3 Fail-Safe System Behavior

Another key consideration is fail-safe system behavior. In the event of power loss, sensor failure, or unexpected software errors, the system must default to a safe state. This includes disabling laser outputs and preventing further triggering until the issue is resolved. These safety measures reduce the likelihood of accidental exposure or incorrect system operation. User training and clear operational procedures are also considered part of the safety constraints. Even with engineered protections, improper use can still introduce risk. Therefore, the system design emphasizes intuitive operation and clear instructions to minimize user error. [82]

4.2.2 Performance Constraints

Performance limitations were defined by measurable system requirements such as camera frame rate and processing latency. Accurate velocity measurement requires precise synchronization between projectile detection, strobe activation, image capture, and computational analysis.

4.2.2.1 Timing Requirements

The system must detect a projectile, trigger a strobe event, capture sequential images, and compute velocity within strict timing constraints. Camera hardware limits the frame acquisition speed while the software processing time introduces latency that must remain low enough to maintain measurement accuracy. For a projectile traveling at 300 m/s through a 30 cm measurement area, the transit time is about 1 millisecond. Within this window, the system must capture at least two distinct images to find the positional and other ballistic data of the projectile.

Camera hardware limits the frame acquisition speed greatly. The Raspberry Pi camera module is able to support various frame rates depending on the resolution, with their being a significant tradeoff between image resolution and frame rate. This tradeoff directly impacts the measurements of the strobe imaging subsystem, where higher resolution provides more precise positional determination, but lower frame rates may miss the faster moving projectiles entirely. [69]

4.2.2.2 Synchronization Accuracy

One critical performance consideration is system synchronization accuracy. The alignment between the laser detection subsystem, strobe illumination, and camera capture must occur within extremely small time windows to ensure valid measurements. Even minor timing mismatches can introduce significant errors in trajectory estimation. The Raspberry Pi's operating system introduces non-deterministic scheduling, meaning that precise timing control can be difficult. This limitation requires the software design to implement strategies to minimize timing variability, such as using hardware-triggered capture modes like the light gate subsystem. [86]

4.2.2.3 Computational Performance

Computational performance must be balanced with energy consumption and thermal limitations of the Raspberry Pi 5. Prolonged high CPU usage can lead to thermal throttling, reducing processing speed and affecting real-time performance. As a result, efficient algorithms and optimized processing pipelines are necessary to maintain consistent system operation. Open CV operations must be optimized in order to reduce processing time and minimize unnecessary computations that will affect performance. The tradeoff between computation complexity and real-time responsiveness directly influences the measurement rates of the PTC system.

4.2.3 Economic Constraints

Economic limitations strongly influenced the component selection. This project was not sponsored, therefore all the funding came from the team itself. After researching the current technologies and what is commercially available, a budget of five-hundred was set. Optical sensing was chosen over radar-based measurement due to lower cost and easier integration. A Raspberry Pi platform was selected instead of an FPGA to reduce development complexity and expense while still meeting the processing requirements. These decisions illustrate the engineering tradeoffs between performance, complexity, and affordability. [72].

4.2.4 Environmental Constraints

Environmental conditions such as indoor lighting variation, temperature changes or vibrations can affect the optical sensing accuracy. The system must maintain reliable operation despite the fluctuations in light and other mechanical disturbances, requiring further controlled lighting and a stable housing structure.

Lighting variability is one of the most significant environmental challenges affecting system performance. Changes in ambient lighting conditions can impact the effectiveness of image differencing and contour detection algorithms. To mitigate this, the system relies on controlled strobe illumination to provide consistent lighting during image capture.

Vibrations and mechanical disturbances can also introduce alignment errors in both the optical and camera systems. Even small deviations in alignment can affect trajectory accuracy. Therefore, rigid mounting structures and vibration-resistant designs are necessary to maintain system stability.

Temperature variations may also impact electronic components and sensor performance. Prolonged operation in elevated temperatures can affect processing efficiency and potentially reduce the lifespan of components. These environmental constraints necessitate careful system design to ensure reliable operation under varying conditions. [72].

4.2.5 Manufacturing Constraints

Manufacturing considerations include the limitations of available fabrication methods, particularly with respect to 3D printing and mechanical assembly. Components must be designed with tolerances that can be reliably achieved using accessible manufacturing techniques. Misalignment in optical components, such as lasers and mirrors, can significantly impact system accuracy, making precision in mounting structures a critical requirement.

Additionally, the availability of standard hardware components influenced the design process. The system was designed to utilize parts 'off the shelf' whenever possible to reduce cost and simplify assembly. This includes standard mounts and enclosure components. These constraints required careful consideration of part compatibility and assembly procedures to ensure that the final system could be constructed reliably without specialized manufacturing equipment.

4.2.6 Maintainability Constraints

The system is to be designed with modular subsystems to allow easy replacement of sensors and simplified troubleshooting. The use of the Raspberry Pi 5 will allow software updates without hardware modification, granting long-term usability.

To further enhance maintainability, the system incorporates clear separation between hardware and software components. This allows updates or replacements to occur without requiring full system redesign. For example, camera modules or sensors can be upgraded independently of the core processing software.

Documentation is also an important aspect of maintainability. Clear code documentation, wiring diagrams, and system architecture descriptions ensure that future developers or users can understand and modify the system effectively. Without proper documentation, even a well-designed system can become difficult to maintain over time.

In addition, modular software design allows for easier troubleshooting by isolating faults within specific subsystems. This reduces debugging time and improves overall system reliability during long-term use. [85]

4.2.7 Usability Constraints

Usability constraints are important in the design of the PTC system because the device must be easy to operate while still producing accurate measurements. The system is intended for users with different levels of technical experience, so setup and operation must be as simple as possible. To address this, the design minimizes manual calibration by using fixed hardware alignment and predefined system parameters. This reduces user error and ensures more consistent results across different uses.

The user interface is designed following principles from ISO 9241, which focuses on effective human-system interaction. A touchscreen interface is used to simplify user input

and eliminate the need for complex controls. The system follows an automated workflow, where after initialization it enters an “idle” state and automatically detects, captures, and processes projectile data. This reduces the number of steps required by the user and improves overall system usability.

Clear feedback is also a key usability constraint. The interface provides visual indicators for system states such as charging, ready, and detection complete, ensuring that users always understand what the system is doing. This aligns with usability principles that emphasize visibility of system status and immediate feedback. However, simplifying the interface introduces a tradeoff by reducing advanced user control. Despite this, the design prioritizes ease of use and reliability to ensure safe and effective operation.

4.2.8 Programming Constraints

Programming constraints are largely influenced by the limitations of the Raspberry Pi platform and the use of Python as the primary development language. While Python provides ease of development and strong library support, it is not optimized for high speed processing compared to lower-level languages such as C or C++. This introduces challenges when processing high-resolution images or performing computations within strict timing constraints.

Additionally, the Linux-based operating system used by the Raspberry Pi introduces non-deterministic scheduling, meaning the precise timing control is more difficult to guarantee. This is particularly important when synchronizing camera capture with strobe lighting and projectile detection events. To mitigate these limitations, efficient coding practices and lightweight processing techniques are used wherever possible.

OpenCV operations must also be carefully optimized to reduce processing overhead. Techniques such as reducing image resolution, limiting region-of-interest processing, and minimizing unnecessary computations are used to maintain acceptable performance. These programming constraints directly influence system design decisions and require tradeoffs between computation complexity and real-time responsiveness.

4.2.9 Time Constraints

Project scheduling constraints between Senior Design 1 and 2 required a prototype first development strategy. Early functional demonstrations are prioritized over optimization to help ensure completion deadlines are met.

Time constraints also influenced the prioritization of system features. Core functionality, such as projectile detection and velocity measurement, was prioritized over advanced features like enhanced visualization or extended analytics. This ensured that a working prototype could be completed within the academic timeline.

Iterative development was adopted as a strategy to manage time effectively. Instead of attempting to implement a fully optimized system from the beginning, the team focused on incremental improvements, validating functionality at each stage before progressing

further. This approach reduces risk and ensures steady progress toward project completion.

Testing and validation time was also limited, requiring efficient debugging and verification methods. As a result, simulation and controlled testing environments were used to accelerate development while still ensuring system accuracy and reliability. [87]

5 Application of ChatGPT and Other Similar Platforms

5.1 Case Study 1 - Image Processing Design Using Large Language Models

Please refer to Appendix C, [1a],[1b],[1c],[1d] for the Case Study 1 prompt and outcomes generated by ChatGPT, Google AI, and DeepSeek respectively.

This case study was conducted to evaluate how effectively large language models (LLMs) assist in the design of a real-time image processing pipeline for the PTC projectile tracking chronograph. Unlike previous prompts focused on hardware comparisons, this study emphasized an engineering problem directly related to the project implementation. The prompt requested a complete workflow capable of detecting a high-speed projectile using synchronized camera images captured through a strobe illumination system, followed by velocity and trajectory computation using OpenCV.

The objective of this comparison was not to determine which model produced the most information, but rather to evaluate the practicality and engineering usefulness of each response when applied to an embedded vision system operating under real hardware constraints.

ChatGPT [1b] provided the most structured response in terms of overall system architecture. The model organized the solution into clear processing stages including image acquisition, motion detection, and trajectory calculation. The suggested techniques such as frame differencing and centroid tracking aligned well with standard OpenCV workflows and were directly applicable to the PTC design. One notable strength was the explanation of why each processing step was necessary, allowing the response to function as both documentation guidance and conceptual design support. However, the response assumes ideal imaging conditions and did not account for limitations such as Raspberry Pi processing latency or lighting variability. Though the architecture was useful, engineering judgment is still required to adapt the recommendations.

Google AI [1c] approached the same prompt differently by emphasizing algorithm descriptions and referencing commonly used computer vision methods with stronger ties to external documentation. The information was technically accurate and often included broader comparisons between detection techniques. The response did not clearly describe how individual stages connected within a real-time embedded system. While useful

for research validation and terminology clarification, an engineering interpretation was necessary to translate this information into an executable workflow.

DeepSeek [1d] demonstrated strengths in proposing solutions for implementation suggesting pseudo code structures and optimization considerations. The model discussed alternative tracking strategies and offered suggestions for improving robustness under noisy image conditions. In several cases, DeepSeek proposed computationally intensive solutions that may be better suited for desktop GPUs rather than embedded processors. This highlighted a recurring limitation observed across models: a lack of awareness of hardware constraints unless explicitly specified within the prompt.

Across all responses, a consistent observation emerged that large language models are highly effective during early designs but require careful validation. ChatGPT proved most beneficial for establishing system architecture and documentation structure, Google AI supported verification through a broader context, and DeepSeek contributed implementation focused ideas that expanded possible choices. None of the models independently produced a fully deployable solution, but proved to benefit in accelerating different stages of the engineering design process.

From an engineering perspective, this case study demonstrates that large language models function best as a collaborative effort rather than a single technical source. The results indicate that AI-assisted development can significantly reduce initial research time while still requiring traditional engineering analysis to ensure accuracy, feasibility, and system reliability.

5.2 Case Study 2 - Document Formatting and Table Generation Efficiency

Please refer to Appendix C, [2a.1],[2b],[2c], for the Case Study 2 prompt and outcomes generated by ChatGPT and Copilot respectively. An additional prompt, [2a.2], was used for the case study.

In this case study, the effectiveness of using an LLM to help create a standardized table format was tested. Specifically, two LLMs were leveraged to organize and refine the tables generated by the different authors of this report into one unified structure. The investigation focused on assessing the model's ability to reduce manual formatting effort and improve uniformity. Additionally, the limitations of this approach were studied, including the need for human oversight to verify the accuracy of the translated tables and to ensure compatibility with the pre-established formatting structure of the document. Through the evaluation of this study, insight was gained into the benefits and trade-offs of using LLMs for documentation editing purposes.

ChatGPT [2b] was structurally consistent with its response when converting tables to the defined "Standard Table Format" (STF). The model maintained the row separation, caption placement, and usage of the longtable command. In particular, this model strictly

maintained the column widths. In the original query, the reference table used had only four columns, with the follow-up query containing a table with 5 columns to be converted to the STF. In ChatGPT's response, it prioritized the table structure provided by the reference table over original distinctions made in the follow-up table. This caused the LLM to merge two columns together to align the column widths set by the STF. The LLM finished its query by noting the changes it made to the columns, and also provided an option for the original table's columns remain intact and dynamically update the size of the columns instead of merging them. Upon further prompting, the LLM was able to produce a table that maintained all of the original information, albeit the column sizes were not sized correctly for the document, leading to manual correction. Even though this LLM maintained most of the original information from the follow-up table, this change in table structure necessitated the need for additional human oversight to confirm if these changes were acceptable.

Copilot [2c] was asked the exact same prompt as ChatGPT and was more to the source table than ChatGPT. This response maintained all of the original columns, maintaining full data fidelity. The only correction to be made was manually adjusting column widths, as they no longer adhered to the standard size of the table set by the STF. Copilot finished its response by asking the user if to use different column widths or standardize captions/labels. This response was much closer to the desired outcome of the query, as the data fidelity is more important than strict structural compliance.

Overall, ChatGPT emphasized structural adherence to the source material over data fidelity, leading to more time spent querying to get a more suitable response, whereas Copilot was more faithful to the data in the tables in generating its response. This shows the nuance in how these two models approach a problem when it is up to them to make a decision. In ChatGPT's case, it chose alter the follow-up tables physical dimensions (rows/columns) to better replicate the exact structure of the STF, while Copilot chose to maintain the physical dimensions of the follow-up table and adapt the structure set by the STF to that table. While both LLMs were able to produce workable tables, this study showed the limitations of the transformative nature of certain AI models for tasks such as standardized table generation.

5.3 Case Study 3 - Metaprompt to use AI for ideas on how to use AI in the project

In this case study, LLMs were evaluated on the capability of determining potential applications of AI for the senior design project. Please refer to [appendix] for the prompt and responses.

Gemini clearly thought the prompt was referring to using AI within the operational phase of the project itself, not in the design or research phase as was desired. Gemini mentioned a number of potentially useful advanced uses of AI, including object detection, replacing the kinematic equations with an AI model. One of the limitations is that deep neural networks would require large amounts of training data, which would be impossible to

get without either simulation or automation, either of which would be a large expenditure of effort.

Gemini mentioned using AI for sensor fusion, in which it could be useful for filtering out noise. One suggestion was to compare a Kalman filter to a Gated Recurrent Unit. Signal denoising was also mentioned for allowing lower-cost hardware and compensating for the higher noise with better filtering with AI. Unfortunately, the economics of this don't work out, since the vast majority of the cost is in development time, and BOM costs are nearly negligible. Since there is only a couple prototypes that will be made, reducing development cost and time at the expense of even \$10 in parts is valuable, so spending significant time on developing a use for AI to allow a lower cost part is not beneficial.

Grok interpreted the prompt in a similar way to Gemini. It recommended a number of ways AI can be used in the operational phase of the project. First, Grok recommended using AI for object detection or localizing. Models like YOLO give a bounding box on the objects that are detected within the image.

One previous project involved using YOLO on a security camera video stream. One part of the project involved using the detection of cars to alert the user when there was a car in the driveway, indicating there was a visitor. That way when visitors inevitably knocked as if there was a baby sleeping, such that the user was unable to hear the knock on the door, the alert from the security camera was able to let the user know to go open the door. The bounding box of the detected car was useful, since the camera was pointed at the road in front of the house, so the bounding box of the car detection was used to filter out cars that were simply passing by, or parked in the neighbor's driveway. Another part of this previous project using YOLO was to use the security camera to detect where people were in the yard, and control the outdoor lights to light up only the area of the yard where the user was. This was accomplished using addressable LED strips for the outdoor lighting, so that the location used with the bounding box of the detection was used to select which LEDs lit up. Unfortunately, the positional accuracy of the bounding boxes of models like YOLO leave a lot to be desired. It is a coarse position, and is often not centered on the object. Instead, the bounding boxes of YOLO are useful for things such as determining if a car is within a driveway, like in the aforementioned project, or to get an idea if a person is on the left side, right side, or center of an area. YOLO does not have a bounding box resolution near the resolution of the image, instead it is more coarse. [Cite Ramos and Sappa 2025 YOLO] Since we will be able to take calibration pictures without the projectile, it will be significantly easier to use simple math to determine the location of the projectile rather than using AI for object detection and bounding boxes.

Grok also recommended trajectory prediction, drawing on examples such as using neural networks for trajectory estimation for mortar trajectory estimation in GPS/GNSS denied areas. It also recommended Physics Informed Neural Networks (PINNs) for 3d trajectory estimation from 2d video. It linked to a patent on estimating 3d trajectory using 2d camera images [cite Thornbrue, Cherveney, and Haas patent].

One aspect of the image enhancement and denoising recommendation from Grok that was novel was the recommendation to compare autoencoders or diffusion models versus

classical filters such as Gaussian for improving tracking accuracy. This could be useful for narrowing down the centroid of the projectile in the images for better accuracy of positioning the projectile.

5.4 Case Study 4 - AI Tools in Search Engines

It is apparent that AI has become increasingly powerful and useful, especially in the accumulation of data and recognition of patterns. As such, it has become prevalent in search engines as an automatically implemented tool to try and make research faster and deliver answers quicker. In this case study, the effectiveness of these searching tools were benchmarked with search queries of more obscure topics, engineering standards and protocols in this case.

In my research of the USB standard and protocol, I occasionally struggled to find documents in the USB-IF's archive, and this was sometimes because of a particular document's unique naming scheme, or because the document had been removed due to obsolescence of an old standard. For reference, I was trying to find the USB-IF's standard on USB micro connectors, which debuted in the early 2000's. It was unclear to me whether such connectors conformed to the USB-IF's standards, and if they did, which USB standard they conformed to. The search engine's (DuckDuckGo's) AI search tool was able to help me find the document outlining the USB 1.0 standard by providing me a link to the Wayback machine, an internet archive that preserves such documents, and a link to a Wikipedia article with suitable references. This was the inspiration for this case study, detailed below.

For this case study, the prompt and responses can be viewed in Appendix []. The search results were relevant, and led me to a blog post on the Analog devices website on how to use UART, and a Wikipedia entry. With another search, the AI tool was able to clarify that UART is not a standard like USB, but a communication protocol.

This leads me to believe this tool is useful in matters of research, but may lead me down certain avenues without clarifying my misconceptions. Thus, it is important to always ask multiple questions, and thoroughly read the sources it points me to, so that potential misconceptions don't interfere with our implementation of the PTC.

6 Hardware Design

6.1 Schematic Diagrams

Below are a series of schematics representing every subsystem of the PTC, as well as explanations of their design and features. The PTC's hardware has been designed such that major subsystems are detachable and can easily be replaced, allowing for quick

disassembly or reassembly of the PTC, as well as quick debugging and diagnosing, by allowing each individual subsystem to be operated on independently.

6.1.1 Motherboard

The schematic for the motherboard of the PTC project is shown below, with slots incorporated for connecting other subsystems via either header pins or RJ45 ports. The header pins will be used to seat the MCU module and the 3.3V Regulator module, and the RJ45 ports will be used to connect individual strobe modules, the TIA module, and the camera trigger. Screw terminals will be used for the line laser and the Motherboard's UART connection to the Raspberry Pi 5.

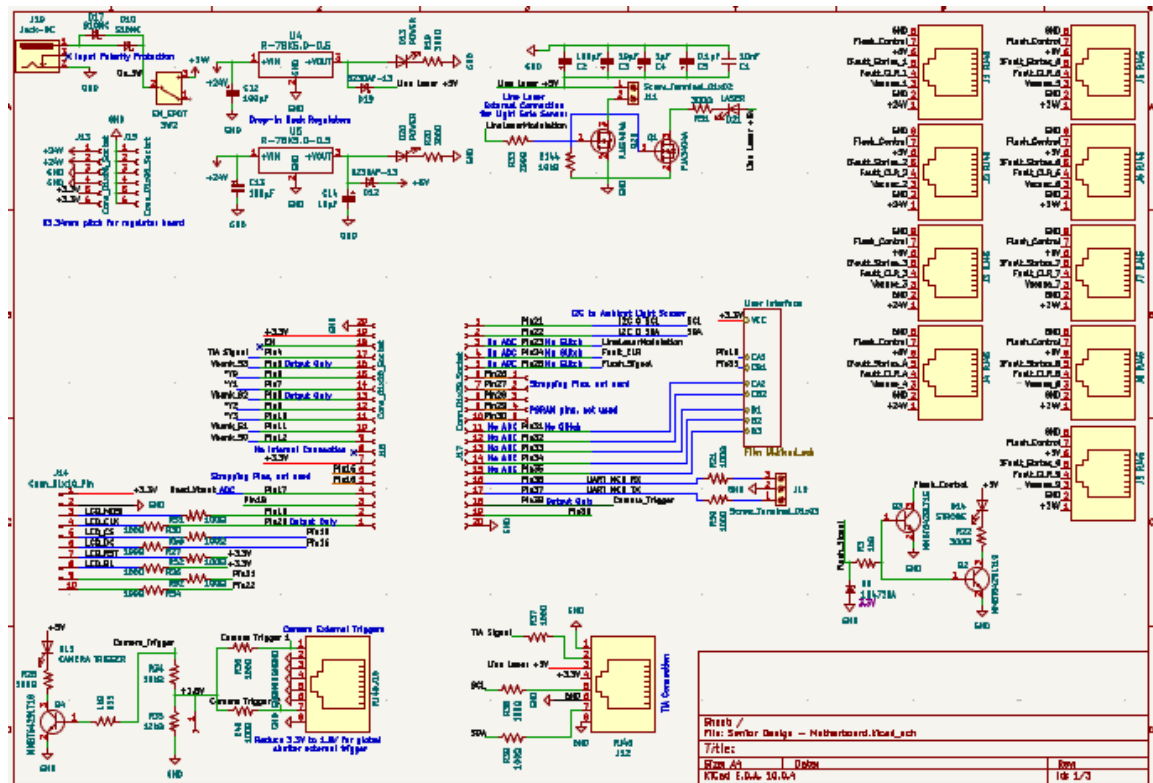


Fig. 6.1: Motherboard Schematic 1

Also included on the motherboard are the PTC's main power delivery systems, LED indicators, and ICs responsible for peripheral functions. The PTC receives power via a barrel jack connector, to interface with common DC power adapters like the one selected for this device, and routes it through the drop-in 5V regulators as well as the 3.3V Regulator module. The 5V regulators create two separate 5V channels, one for logic ICs and the TIA amplifier, and another for the line laser. The line laser channel has more decoupling capacitors than usual to ensure stable operation of the laser and reduce the chance of any noise being transmitted from the laser's power supply to the photodiode in the TIA module. The 3.3V Regulator module will output directly to the MCU module, as well as user-interface components like buttons and the LCD screen.

LED indicators on the motherboard indicate when certain events are occurring in the firmware, namely, the strobes firing, the cameras triggering, whether or not the laser is on, or whether or not the 24V supply is being regulated down to 5V. Other indicator LEDs are present, but are incorporated on separate subsystems.

The aforementioned logic ICs are responsible for several of the PTC's peripheral functions, allowing the MCU to address a particular strobe module and receive information about that particular strobe module's capacitor bank voltage, or send a signal to clear a fault status on a particular strobe module. This is achieved with analog multiplexers, potential dividers, and level shifters. Additionally, a priority encoder allows the MCU to interpret signals from the strobe modules, alerting it to a fault status in a particular strobe module.

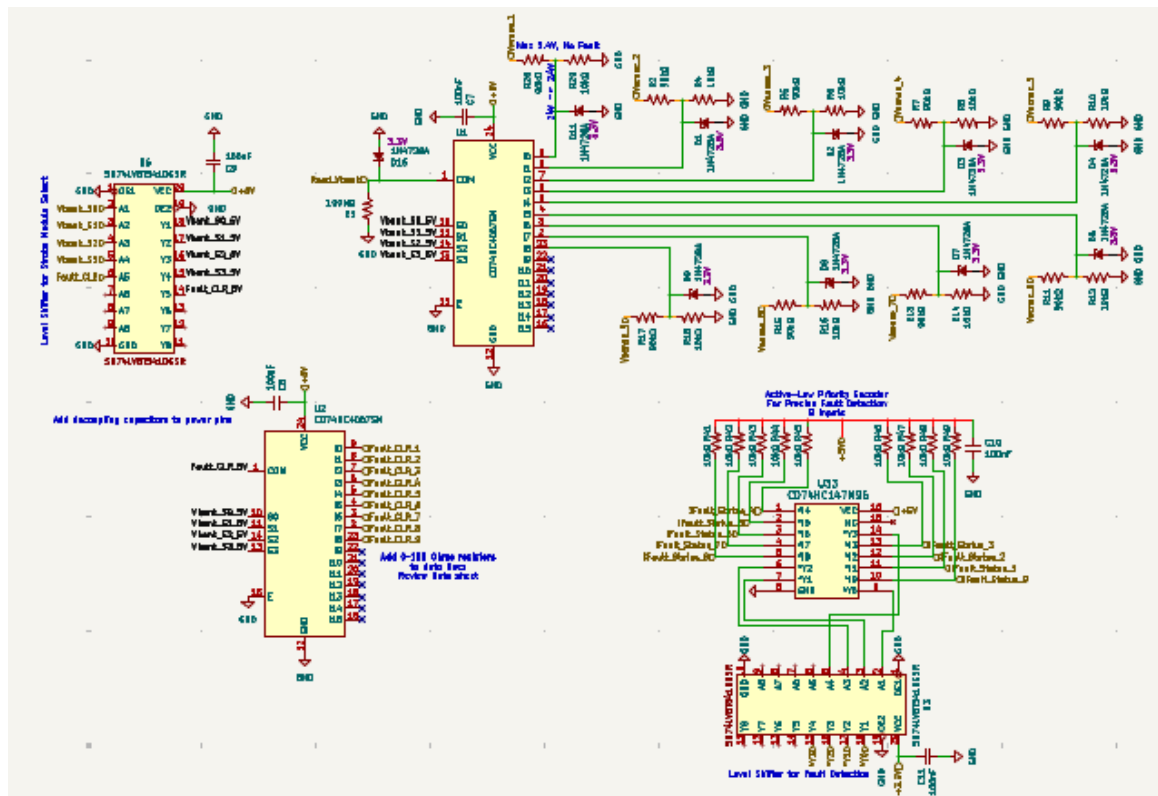


Fig. 6.2: Motherboard Schematic 2

6.1.2 Strobe Module

The PTC's strobe modules are a key subsystem essential to the imaging of a projectile in motion, and as such, a significant amount of time was spent designing and revising them so that no catastrophic issues would arise. Each individual strobe module must momentarily supply an amp of current through 5 infrared LEDs within a span of a few hundred microseconds, and be able to do so precisely and with consistency. Shown below is the full schematic.

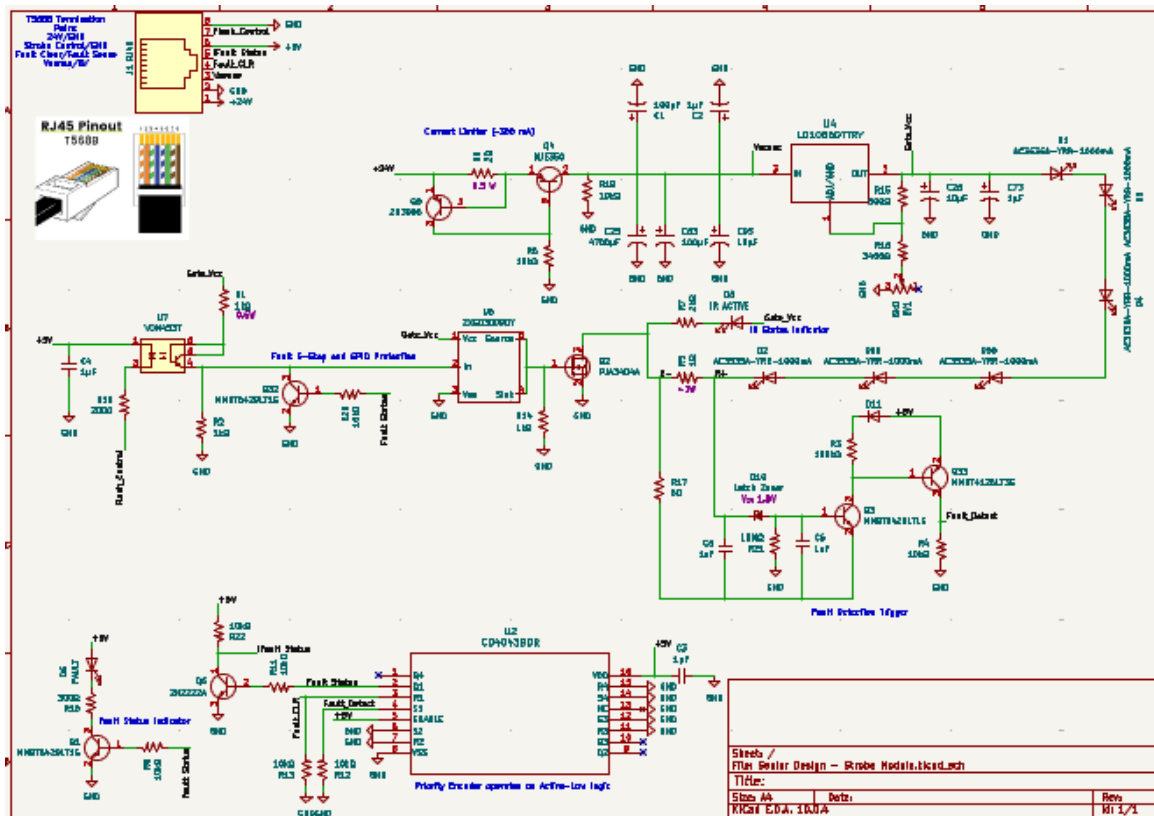


Fig. 6.3: Strobe Module Schematic

The strobe module begins with an RJ45 port, receiving 24V and 5V power from the motherboard, and using several wires for the purpose of sending status related signals. The 24V line goes into a constant-current limiting circuit composed of a resistor and two bipolar junction transistors. This circuit limits the input current to about 300mA, allowing the capacitor bank next to it to charge at a fast and near linear rate, and preventing inrush current whilst also preventing the strobe module from sourcing all of its current from the motherboard when activated. Next, a low-dropout adjustable linear regulator is used to step down the voltage to a suitable level for the IR LEDs, and a trim potentiometer is used for adjustment to allow for fine tuning to ensure that one amp of current is output upon activation. A single resistor is placed after the IR LEDs to ensure the output current remains stable, and an N-channel MOSFET is used to switch the LEDs on and off. The MOSFET is driven by a gate-driver, which in turn is activated from an opto-isolator that receives its turn-on signal from the MCU and motherboard. In parallel with the IR LEDs is an indicator LED to let users know when the infrared is active, warning them not to look at the strobes. In parallel with the resistor at the end of the IR LED chain is a circuit that detects when the voltage across the resistor exceeds a certain threshold (indicating an over-current fault event) and causes an SR latch IC to toggle states and activate the strobe module's fault protection circuitry. This circuitry shorts out the MOSFET gate-driver's signal pin, shutting off and preventing the strobe module from activating again, and also turns on another indicator LED to notify the user of a fault condition.

6.1.3 3.3V Regulator Module

As previously mentioned, the LM2576S-ADJ is a switching step-down converter, and can handle input voltages up to 37V and currents up to 3A. This converter has an adjustable output voltage, and this schematic was assembled with reference to the datasheet's suggested application circuitry. Additionally, this module includes an Under-Voltage Lock-Out circuit made of some resistors, a Zener diode, and a BJT at its input to prevent it from trying to regulate an output when the input voltage is below 3.6V, allowing the regulator to cleanly turn on and power the MCU and UI components. Additionally, a Schottkey diode is placed on the output to prevent backflow into the regulator, and an indicator LED is placed to notify users of operation. Since this module has an adjustable output, a trim potentiometer is used for adjustment.

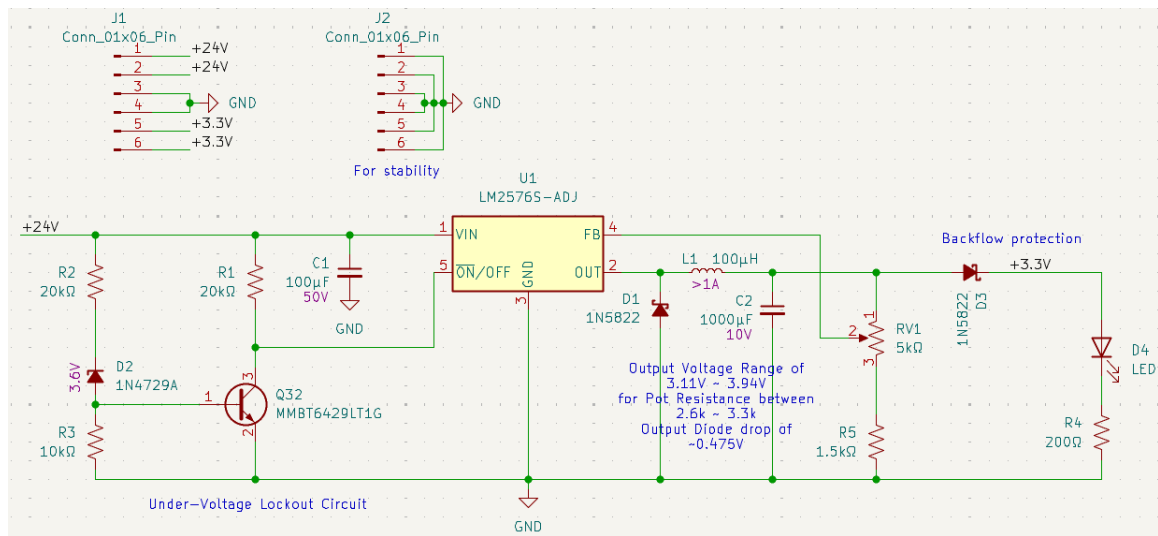
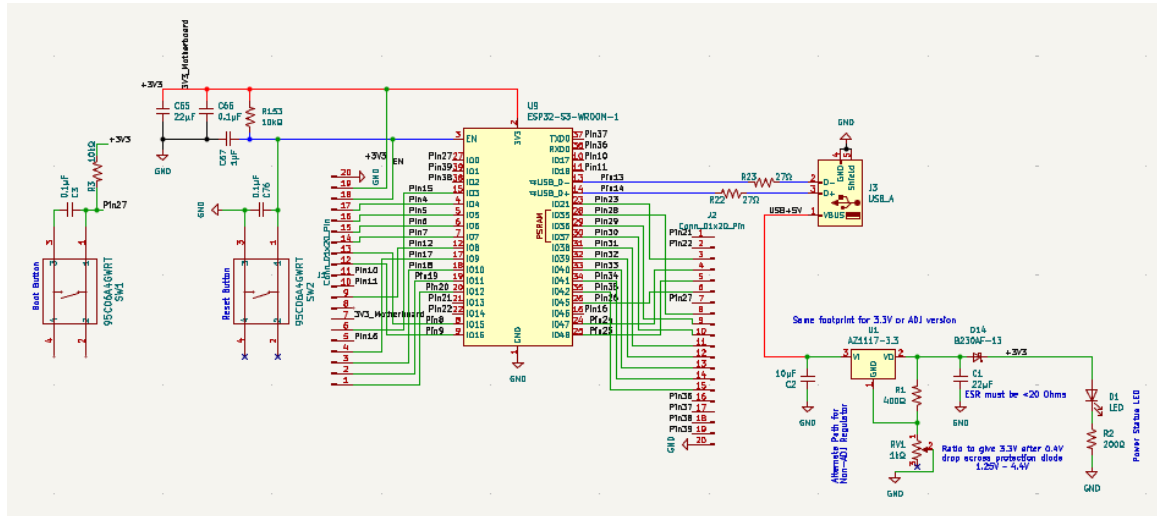


Fig. 6.4: 3.3V Regulator Module Schematic

Additionally, since this regulator operates at a relatively low frequency of 52 kHz, component layout and placement will not have drastic consequences on the efficiency and functionality of the module, which may have caused issues if a regulator that operates at a higher frequency was used without proper considerations.

6.1.4 MCU Module

The PTC's MCU will sit on its own module, allowing for easy replacement and debugging while attached or disconnected from the rest of the system. As such, it includes its own voltage regulator to convert 5V power from a USB-A port down to 3.3V, and this regulator circuit is outfitted with a Schottkey diode on its output to prevent backflow, allowing the MCU to be powered either by the system's 3.3V Regulator module, or the USB port, without conflict. Additionally, each usable pin on the MCU is routed to a corresponding pin on two pin headers so that the module may be placed onto the motherboard. The module includes both a BOOT and RESET button to allow the MCU to be programmed and reset.



6.1.5 TIA Module

The TIA module is another critical subsystem for the PTC, as it is responsible for sensing occlusions of the line laser when a projectile passes through the PTC, and making such a signal detectable to the MCU. Included on the TIA Module is an Ambient Light Sensor, wired to the motherboard and MCU via the RJ45 port, alongside the actual TIA, and communicable via I2C. This sensor runs off of the 3.3V supplied by the 3.3V Module. The operational amplifier that composes the actual TIA and its supporting circuitry are powered by a 3.3V regulator that is supplied 5V from the drop-in regulators on the motherboard. This process of regulating the voltage again, with a linear, low-dropout regulator, reduces noise on the power rail, alongside the efforts of several decoupling capacitors. A voltage divider and a trim potentiometer are also used here to provide bias voltages.

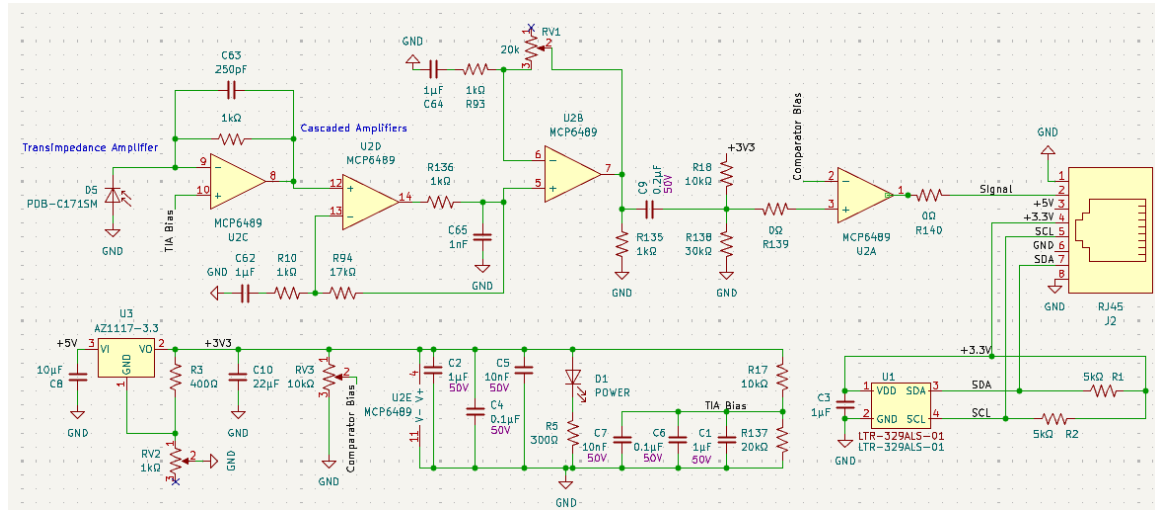


Fig. 6.6: TIA Module Schematic

Starting with the left-most op-amp is the actual Trans-Impedance Amplifier, taking a current from the photodiode and a bias voltage to output a readable voltage. This output is then amplified in two gain stages with a low-pass filter in between and a high-pass filter at the end. The signal then has a bias re-introduced, and it is then fed into the final op-amp stage which is being used as a comparator. This comparator will turn the TIA output signal into a binary value that can be immediately interpreted by the MCU without relying on the slower on-board ADC, and its threshold value is set by the trim pot on the TIA's power rail. The binary output then travels back to the motherboard and MCU via the RJ45 port.

6.1.6 External Components

6.1.6.1 2.8" TFT Display

To facilitate intuitive interactions between the end user and the PTC and display information in an easily presentable manner, a TFT display will be used. This TFT display can be programmed to display various graphical images and menus, and this can be done via a few connections to the MCU using the SPI communication protocol. A pin header is present on the motherboard to allow an easy point of attachment for the data and power connections.

6.1.6.2 Image Processor

A Raspberry Pi 5 will be used in order to actually process the images taken by the PTC's cameras, which will be attached directly to the SBC. In order to communicate with the Raspberry Pi 5, connection points have been added to facilitate UART communication between the MCU and the Image Processor, as this protocol is easy to facilitate, and can share a large variety of data that can be easily interpreted by both devices using ASCII characters.

6.1.6.3 Ambient Light Sensor

The LTR-329-ALS-01 will be able to measure ambient light and ascribe a binary code to that measurement. With an I2C connection, the MCU will then be able to take this measurement and determine if the output from our photodiode and transimpedance amplifier can be trusted, or if extra effort needs to be taken to ensure a darker environment. The communication via the I2C protocol can be facilitated through a 2-wire connection, and an appropriate socket has been placed.

6.1.6.4 Line Laser

The line laser is necessary for the light gate sensor at the beginning of the PTC. It is partly responsible for the generating of signals that the MCU will use to initially calculate the speed of a projectile, as its beam will be interrupted twice when a projectile moves through the PTC, allowing a photodiode's output to fluctuate in correspondence. Below is a zoomed in capture of the circuit that powers the line laser.

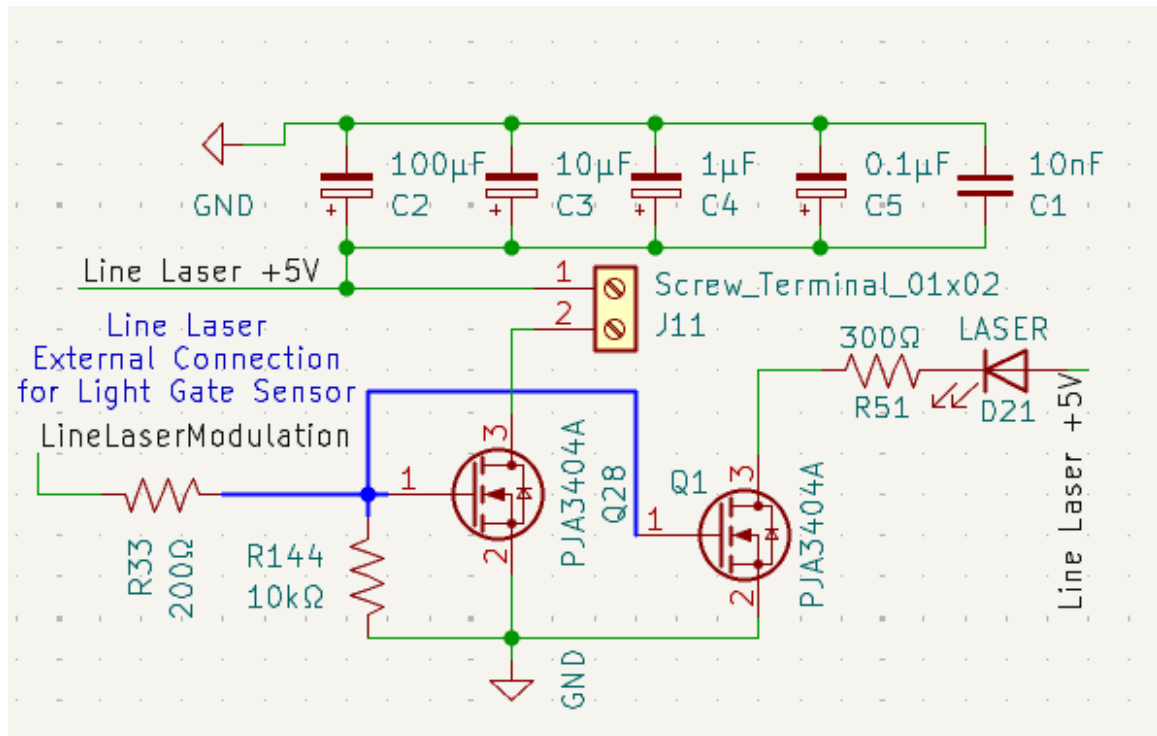


Fig. 6.7: Modulating MOSFET and Terminal Connection for Line Laser

The line laser is an external component, and will not be soldered to the final PCB, so a screw terminal connection is used to incorporate it. From the line laser's datasheet, it requires an input voltage within a range of 2.8 V to 5.2 V and has an internal driver and only requires an input voltage. So, this laser will be powered by the aforementioned R78K5.0-0.5 regulator, and additionally, can be modulated using a transistor on its power input. This modulation can help make any interruption of the beam more noticeable to the photodiode and transimpedance amplifier, and thus, the MCU. Alternatively, no-

modulation has to be applied, and the laser can simply be switched on and off to prevent the user from looking into it when the PTC isn't actively measuring a projectile. An indicator LED is included to notify when the laser is active. [12], [60]

6.1.7 Peripherals

6.1.7.1 Trans-Impedance Amplifier

In order to capture precise images of a projectile as it travels through the PTC, it is necessary to know the speed at which it is traveling before the images are taken. With the laser gate system, this will be possible, but the TIA Module is essential for actually receiving signals and calculating speed. Since the laser gate system will work by using lasers to beam light into a photodiode, a transimpedance amplifier can be used to turn the current produced by the photodiode into a readable voltage output that can be interpreted by the MCU. Here again is the schematic for the TIA Module.

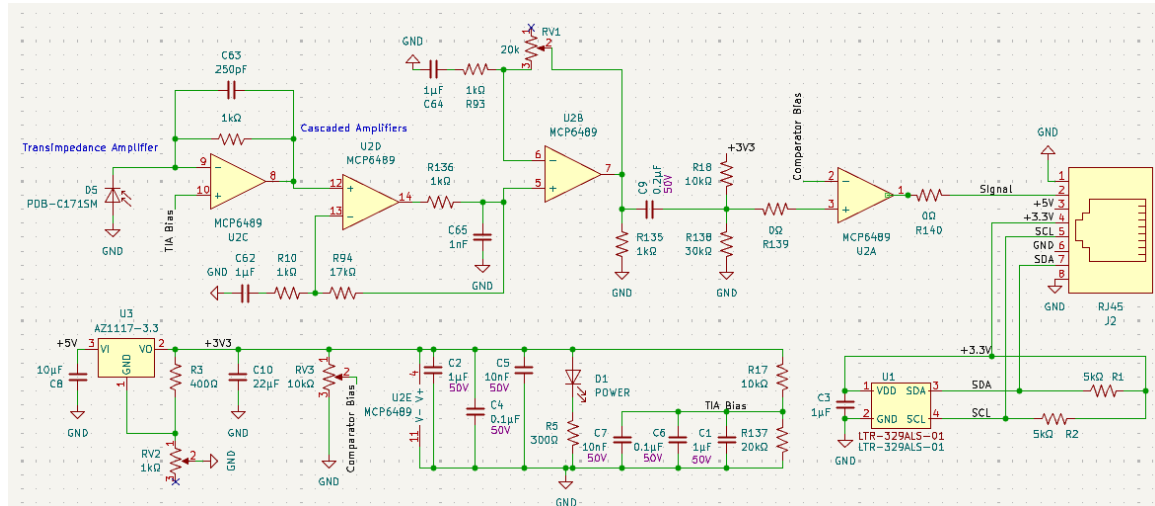


Fig. 6.8: Laser Gate TIA

Using a combination of a TIA and a cascaded 2-amplifier network and output comparator, the small signal from the photodiode can be transformed into a large signal that can be interpreted by the MCU, and the op-amps will sacrifice minimal bandwidth in doing so.

Just before a projectile is shot through the chronograph, the MCU can run a calibration to determine that the TIA Module is outputting correctly: a logic high for no interruption, and a logic low for an interruption. This can be done simply by switching the laser on and off and reading the TIA's output. When a projectile is shot through, the incident light on the photodiode will be interrupted, causing the TIA module to briefly output a logic low, twice in quick succession, allowing the MCU to capture two distinct signals and measure the time between them to calculate the projectile's speed.

carries another peripheral component, the Fault Sensing and Latching circuit.

With the strobe circuit modules drawing a significant amount of current and energy on activation, it is necessary to install circuitry that can protect, first and foremost, the MCU from any potentially dangerous conditions, as well as prevent strobe IR LEDs from burning out. As mentioned before, an optoisolator protects the MCU, and a latching circuit protects the strobe when an over-current condition is detected. This latching mechanism also sends a signal to the motherboard, which is then interpreted by the motherboard's priority encoder and level-shifted to be sent to the MCU. This qualifies the fault-detection circuitry as a peripheral, as using these signals, the MCU can notify the user of a fault in a particular strobe module.

6.1.7.3 Fault Clearing

In order to streamline troubleshooting and diagnosing if and when issues arise for the end-user, a fault clearing system is necessary. The fault clearing circuit will ensure that only specific modules are cleared of faults, instead of clearing the entire system of faults all at once, potentially leaving faults unnoticed since the priority encoder can only alert to one fault at a time. Using an analog multiplexer, the MCU will be able to select exactly which strobe module to clear a fault for and, using a level shifter, can simply activate a single GPIO pin to clear a fault.

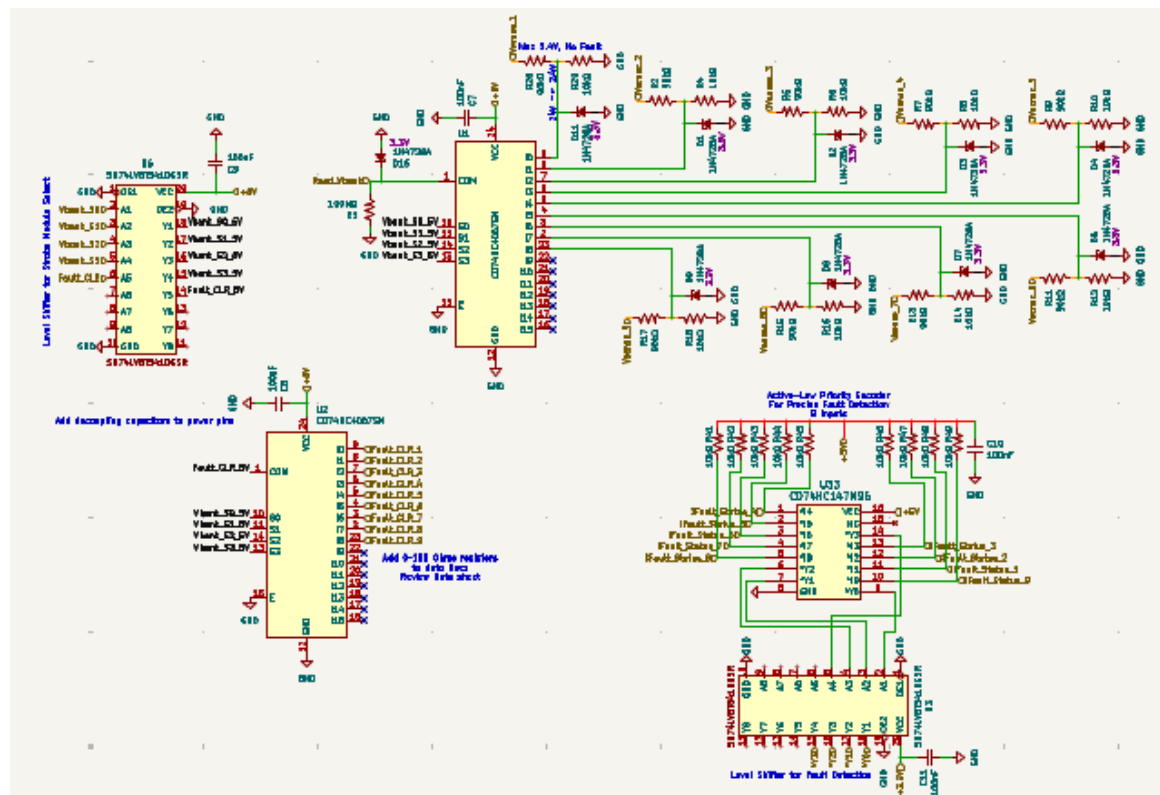


Fig. 6.10: Motherboard: Strobe Selection and Fault Clearing

6.1.7.4 Voltage Monitor

Due to the presence of capacitor banks that charge over time and the PTC's reliance on them, it is beneficial to incorporate a system that is capable of monitoring the voltage of every strobe module's capacitor bank to determine readiness of the PTC.

Using the same strobe selection circuitry as the fault clearing peripheral, a secondary analog multiplexer can be used to transfer a strobe module's capacitor bank voltage to the motherboard to be stepped down and read by the MCU, allowing the user to monitor the voltage of each capacitor bank of every strobe module attached to the MCU.

A fuel gauge IC was considered for this circuit, but fuel gauge ICs are typically configured to specific battery chemistries. Additionally, fuel gauge ICs also typically have specific technologies to monitor battery health and remaining life, such as Coulomb counters, which are unnecessary for this purpose.

6.1.7.5 User-Interface

To facilitate the functions of the PTC project and intuitive interactions with the end-user, a few essential hardware components and circuits are absolutely necessary. Of the user-interface components, we have a couple rotary encoders and a few buttons.

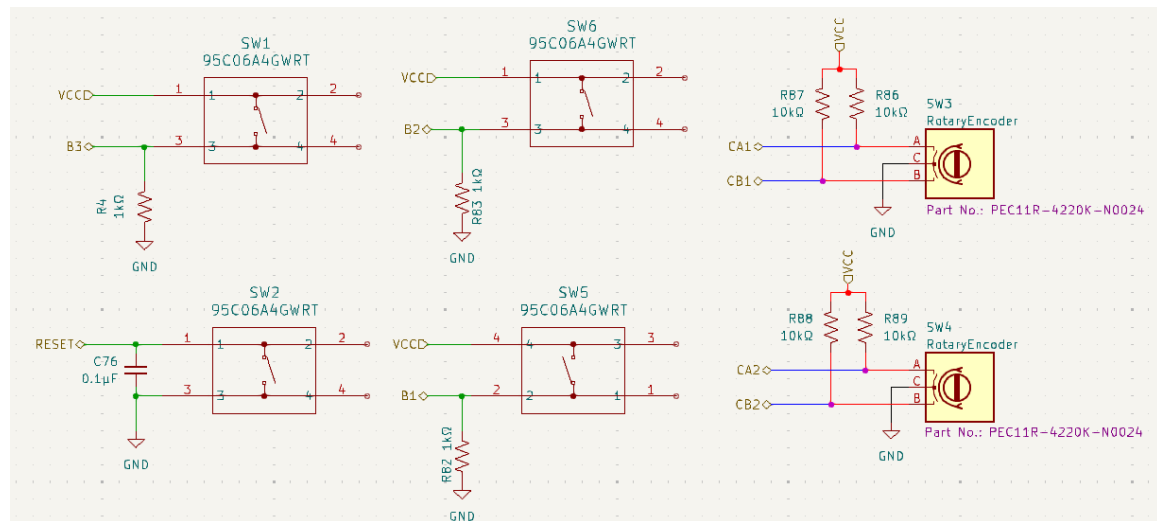


Fig. 6.11: User-Interface Components

The buttons and rotary encoders can be programmed to perform any number of actions that may be required by the user to interact with the PTC, and are not hard-wired to any specific purpose, allowing the firmware to use them as needed.

7 Software Design

7.1 Software Design Overview

The software system for the Projectile Tracking Chronograph (PTC) is responsible for integrating sensor inputs, image processing, and user interaction in a unified real-time measurement platform. The system combines data from the laser-based velocity subsystem with camera-based image processing to generate a complete representation of projectile motion. The software is divided between the MCU and the Raspberry Pi 5. The MCU serves as the central orchestrator for time-sensitive system operation, including sensor monitoring, trigger handling, and synchronization of the light gate and strobe events. The Raspberry Pi 5 is primarily responsible for higher-level computational tasks such as image processing, trajectory visualization, and user interface output. This division of responsibility allows the system to preserve precise timing control while still supporting the heavier processing required for camera-based analysis. [44]

The architecture follows a modular design approach, allowing independent development of key subsystems including image acquisition, projectile detection, trajectory estimation and user interface rendering. This structure improves system maintainability and enables future optimization without requiring an entire redesign. [85]

The high-level functional requirements of the system are illustrated in the use case diagram below.

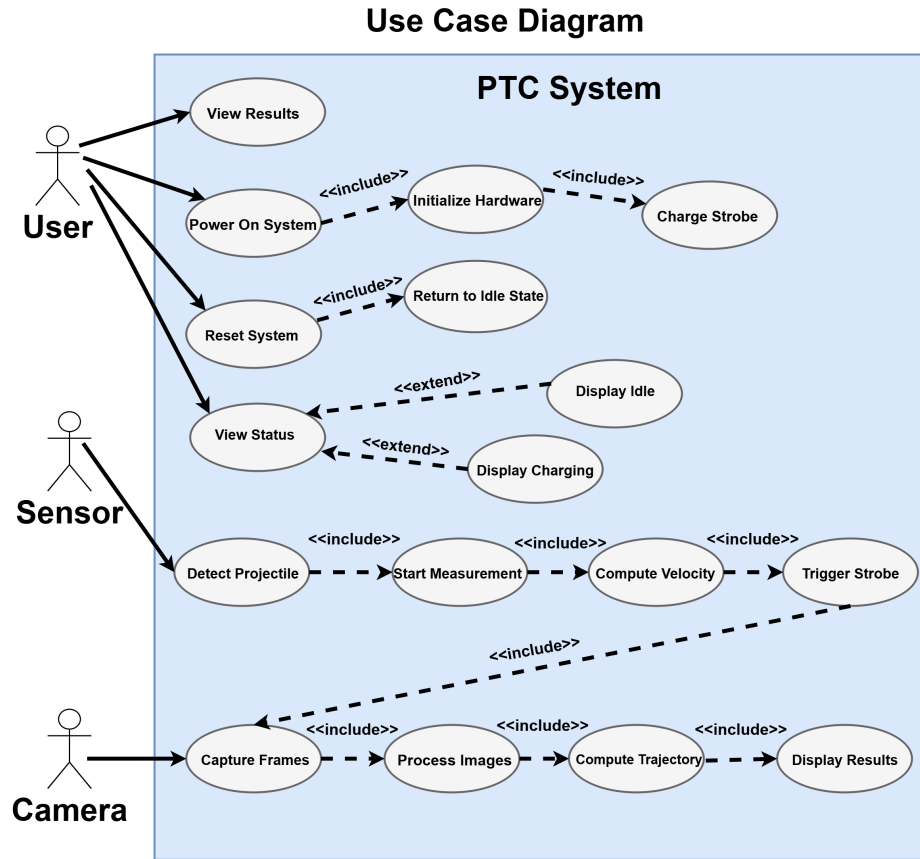


Fig. 7.1: Use Case Diagram of the PTC

7.2 System Integration of Subsystems

A critical aspect of the PTC system is the integration between the laser-based velocity measurement subsystem and the camera vision system. These two subsystems operate using different sensing principles but must function cohesively to produce accurate results. [72]

The laser subsystem provides a precise velocity measurement by detecting the time interval as the projectile passes through a defined optical gate. This measurement serves as a reliable baseline for the system, as it is less affected by image processing noise or environment lighting conditions.

The vision subsystem complements this measurement by providing spatial information about the projectile's position across multiple frames. By combining these two data sources, the system achieves a more comprehensive understanding of the projectile motion than either subsystem could provide independently.

Synchronization between the subsystems is essential for accurate operation. The detection of a projectile by the laser system triggers the strobe lighting and camera capture

sequence, ensuring that images are taken at the correct moment. Any delay or mismatch in timing could lead to incorrect trajectory estimation, highlighting the importance of precise system coordination. This integrated approach demonstrates a key engineering principle of leveraging multiple sensing methods to improve overall system performance and reliability.

7.3 System Execution Flow

The overall execution flow of the PTC software system follows a sequential and modular pipeline that ensures real-time performance and accurate data processing. The system begins in an initialization state, where all hardware components including the camera, laser subsystem, and strobe lighting are configured and verified for proper operation.

Once initialization is complete, the system transitions into a standby or “Idle” state. In this mode, the software continuously monitors for trigger conditions indicating that a projectile has entered the detection region. This event-driven design ensures efficient use of computational resources by avoiding unnecessary processing when no activity is present.

When the projectile passes through the laser-based detection subsystem, the MCU first determines the projectile velocity from the known gate spacing and measured interruption timing. This velocity measurement is then used to calculate the proper time offsets for the strobe events and corresponding image captures. After these delays are determined, the system triggers the strobe lighting and camera acquisition sequence at the appropriate times. The resulting projectile images are then passed into the image processing pipeline, where contour extraction and centroid localization are performed to obtain spatial position information. These image-derived positions are combined with the independently measured velocity from the laser subsystem to estimate the projectile trajectory. Finally, the computed results are transmitted to the user interface, and the system returns to the Idle state.

The detailed step-by-step workflow of a complete measurement cycle is illustrated in the activity diagram below:

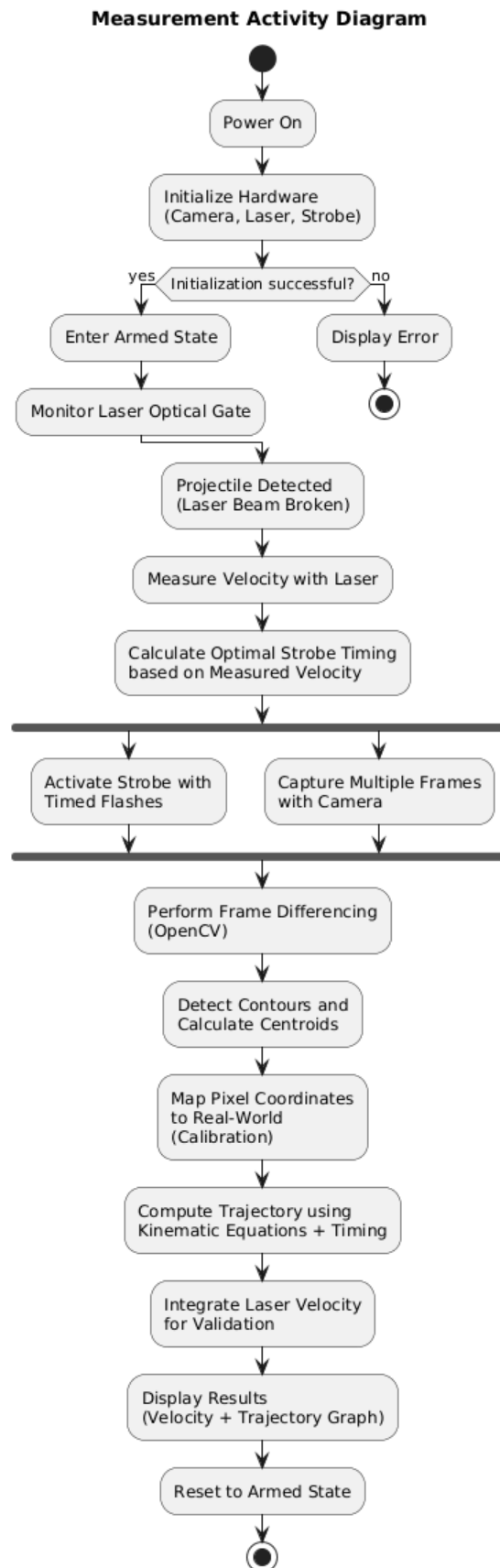


Fig. 7.2: Activity Diagram of the PTC

The various operational states and transitions of the system are further presented in the state machine diagram shown in Figure below.

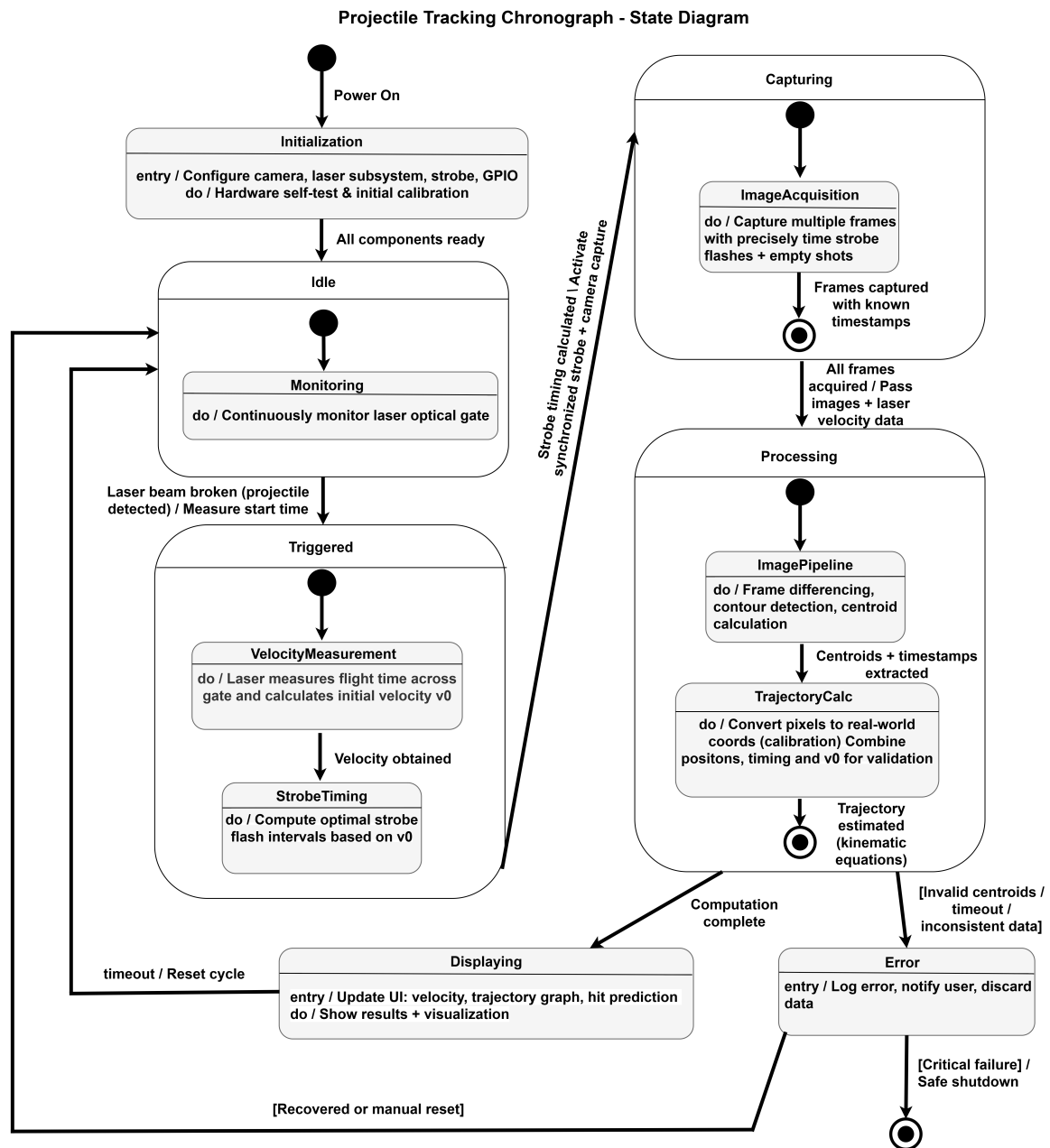


Fig. 7.3: State Diagram of the PTC

This structured execution flow ensures deterministic behavior and efficient coordination between hardware and software components.

7.4 Software Architecture

The software will be implemented in Python due to its ease of development and strong support for frequent prototyping. The system is structured into modular components that handle specific tasks, such as sensor input and handling, image acquisition and processing, data computation and analysis, and user interface control.

This modular approach allows for parallel development, easier debugging, and better maintainability. The static structure of the software, showing the main classes and their relationships, is presented in the class diagram below.

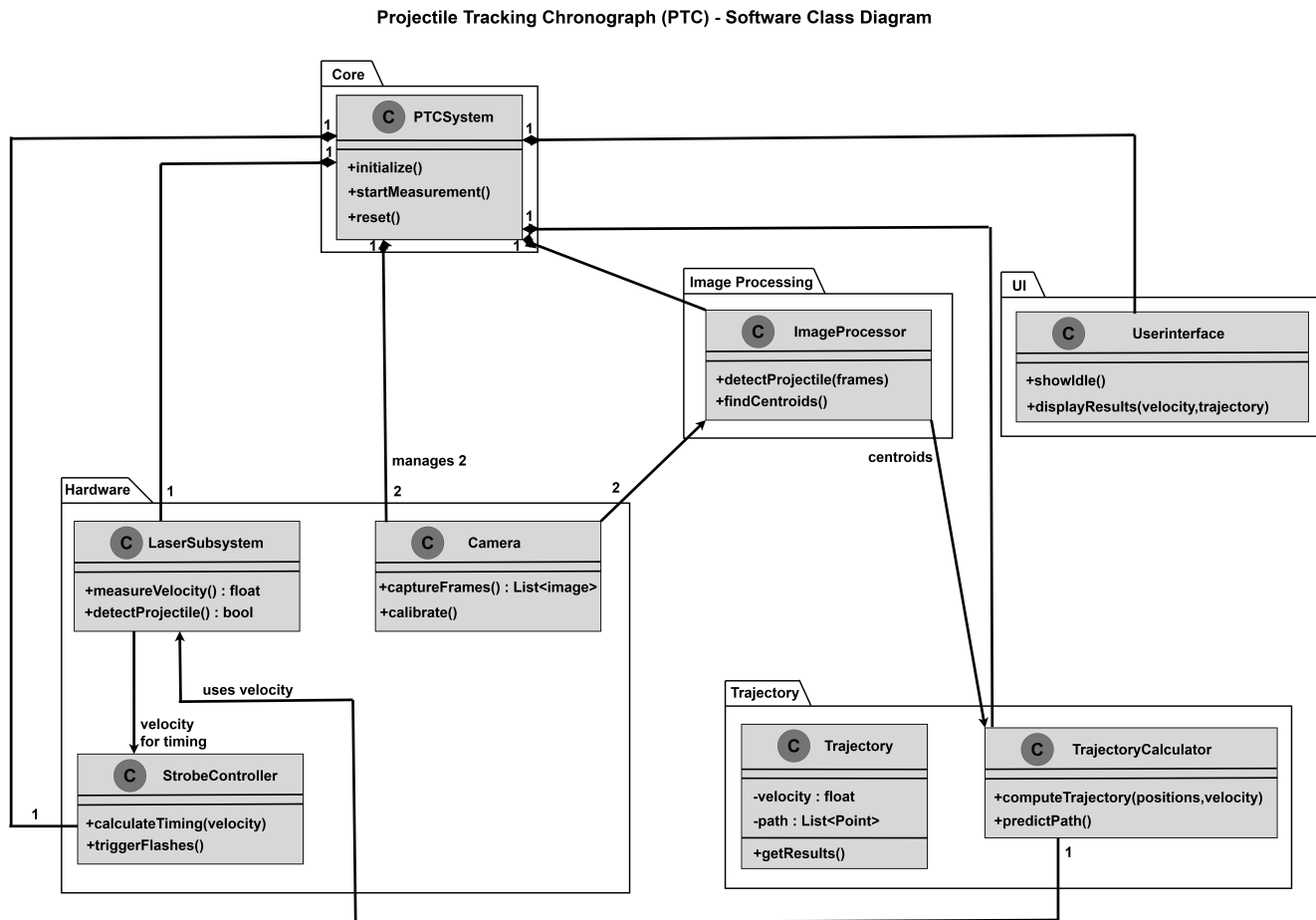


Fig. 7.4: Class Diagram of the PTC

The modular architecture also supports concurrent execution of tasks, which is particularly important for maintaining real-time performance. For example, while one module handles the image acquisition, another may process previously captured frames, and a separate module may update the user interface. This level of concurrency can be achieved through multi-threading or asynchronous programming techniques with Python.

Inter-module communication is handled through well-defined data structures and inter-

faces, ensuring that information flows efficiently between different parts of the system. For instance, the images processing module outputs positional data that is directly consumed by the trajectory computation module. This separation of concerns reduces code complexity and improve system reliability.

Version control practices are also integrated into the development process to track changes and maintain code integrity. By using version control systems, the development team can manage updates, revert changes if necessary, and collaborate effectively. This is especially important in projects where multiple members are modifying the code.

7.5 Image Processing Pipeline

The image processing pipeline is responsible for detecting the projectile within captured frames and extracting positional data required for trajectory estimation. The system will use OpenCV as the primary computer vision library due to its extensive functionality and compatibility with Python. [69]

Image acquisition is performed using a calibrated camera system synchronized with a strobe lighting subsystem. This allows for a clear capture of high speed projectiles to effectively identify the motion within individual frames. Once images the are captured, frame differencing techniques are applied to identify changes between consecutive frames, isolating the moving projectile from the static background.

Following motion detection, contour tracking algorithms are used to identify the shape and location of the projectile within the frame. The centroid of the detected contour is then calculated to represent the projectile's position in pixel coordinates. This process is repeated across multiple frames to track motion over time.

7.6 Data Flow Between Subsystems

The PTC system depends on smooth and timely data exchange between its different parts. While each subsystem has its own job, they must work together quickly and efficiently during a measurement. The sequence diagram below shows exactly how data moves through the system during a typical measurement cycle. It illustrates the step-by-step interaction between the main software, laser subsystem, cameras, image processing module, trajectory computation, and user interface.

As shown in the diagram, the process begins when the laser detects a projectile and sends the velocity data to the main controller. The main software then coordinates the cameras to capture both projectile frames and post-shot empty frames. These images are passed to the image processing module, which returns cleaned positional data (centroids). This data, along with the laser velocity, is sent to the trajectory computation module, which calculates the final results. Finally, all key information is forwarded to the user interface

for display. This clear data flow helps the system operate in real-time with minimal delays and ensures that each component receives the right information at the right time.

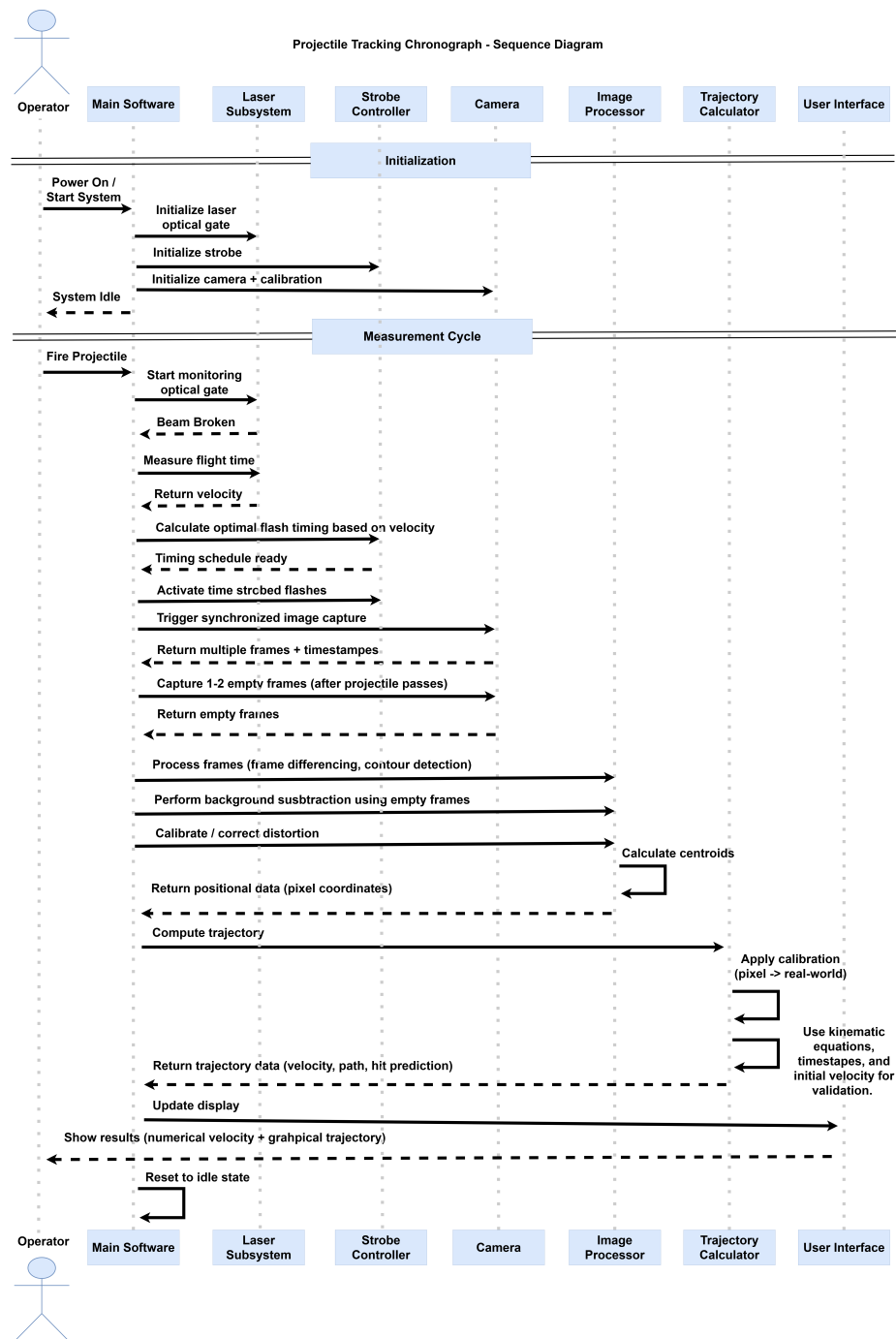


Fig. 7.5: Sequence Diagram of the PTC

7.7 Camera Calibration and Coordinate Mapping

Accurate trajectory estimation requires conversion of image coordinates into real-world spatial measurements. This can be achieved through camera calibration and coordinate mapping techniques. Camera calibration determines intrinsic parameters such as focal length, optical center and lens distortion coefficients. These parameters are used to correct image distortion and ensure accurate positional measurements. Extrinsic calibration defines the spatial relationship between the camera and the real-world coordinate system. This allows pixel coordinates to be mapped into physical distances using transformation matrices.

By combining intrinsic and extrinsic calibration data, the system converts centroid positions from pixel space into real-world coordinates. This transformation is essential for accurate trajectory estimation and ensures that computed results correspond to physical measurements. Calibration is performed prior to system operation and may be repeated if hardware alignment changes. These processes significantly improve the accuracy and reliability of the trajectory computation system. [69]

7.8 Trajectory Computation

Trajectory computation combines data from both the laser subsystem and image processing pipeline. The laser subsystem provides an accurate measurement of projectile velocity, while the image processing system provides spatial position data.

Displacement is calculated by comparing centroid positions extracted from successive projectile images. Using known timing intervals derived from the strobe system, the motion of the projectile can be analyzed spatially across the captured image set. However, the PTC does not rely solely on frame-based velocity estimation. Instead, the laser-based velocity subsystem provides the primary velocity measurement, and the image-derived positional data is combined with physics-based projectile motion relationships to estimate the projectile trajectory. [88]

By combining the measured velocity with its positional slope and effects of gravity, the system will predict the projectile trajectory. This approach improves accuracy and reduces dependence on high frame rate imaging alone.

In addition to basic displacement calculations, the trajectory estimation incorporates fundamental principles of projectile motion, including gravitational acceleration and initial launch conditions. By assuming a constant acceleration due to gravity, the system can model the projectile path using standard kinematic equations. This allows for prediction of the projectile's future position beyond the capture frames, enabling a full trajectory visualization rather than a simple point to point measurement.

To further enhance accuracy, calibration procedures may be applied to convert the pixel coordinates into real spatial measurements. This involves determining a scaling factor

based on known distances within the camera's field of view. Without proper calibration, the system would only provide relative motion rather than actual measurements.

Error sources such as camera misalignment, timing inaccuracies, and image noise are also considered in the trajectory computation process. These factors can introduce deviations in the calculated path, so filtering techniques or averaging methods may be applied to reduce their impact. By addressing these potential errors, the system improves the reliability and consistency of its trajectory predictions.

7.9 Trajectory Modeling and Math

The estimation of the projectile trajectory in space is a critical component of the PTC system. While the laser subsystem provides an accurate measurement of initial velocity, the image processing pipeline provides spatial information required to reconstruct the projectile's path.

The system models projectile motion using kinematic equations under the assumption of constant gravitational acceleration and negligible air resistance for short-ranged measurements. The position of the projectile in space can be described as:

$$x(t) = v_0 \cos(\theta) \cdot t \quad (1)$$

$$y(t) = v_0 \sin(\theta) \cdot t - \frac{1}{2}gt^2 \quad (2)$$

$$z(t) = \text{depth component derived from multi-camera perspective} \quad (3)$$

Where:

- v_0 is the initial velocity measured by the laser subsystem
- θ is the launch angle estimated from image data
- g is the gravitational acceleration (9.91 m/s^2)
- t is the time derived from the strobe synchronization

The depth component (z) is estimated using multi-camera geometry or perspective transformation techniques. By analyzing the displacement of the projectile across multiple camera views, the system approximates its position in space.

To improve accuracy, the system applies coordinate transformation techniques to convert pixel positions to real-world units. This requires camera calibration, including intrinsic and extrinsic parameters, to map image coordinates to spatial coordinates.

Noise and measurement errors are to be mitigated through filtering techniques such as moving averages or Kalman filtering. These methods help smooth trajectory estimates and improve stability in the presence of detection noise.

7.10 Trajectory Modeling and Math (Updated)

During implementation, the trajectory calculations were expanded from two-dimensional angle estimation to full three-dimensional position reconstruction using stereo vision. After the projectile centroid is detected in each camera image, the pixel coordinates are converted into horizontal and vertical viewing angles using the calibrated camera focal lengths. The viewing rays from the two cameras are then intersected through triangulation to determine the projectile's three-dimensional position within the measurement volume.

The reconstruction process produces Cartesian coordinates (x , y , z) for each captured projectile position. Two consecutive synchronized strobe exposures generate two independent 3D positions. The displacement between these two positions is then used to calculate the projectile's horizontal angle, vertical launch angle, and overall direction of travel. This approach allows the system to estimate projectile trajectory using only two synchronized cameras without requiring any moving components or additional range sensors.

7.11 User Interface Design

The user interface is designed to provide clear and immediate feedback on system status and measurement results. The interface operates in multiple states, reflecting the current condition of the system. During system startup and capacitor charging for the strobe subsystem, the interface displays a charging or initialization screen to inform the user of system readiness. Once the system is fully operational, it enters an "idle" state, clearly indicating that it is ready to detect a projectile. Upon detection, the interface transitions to a results display, showing the measured velocity obtained from the laser subsystem along with a visual representation of the estimated trajectory. The visual design and layout of the user interface is illustrated below.

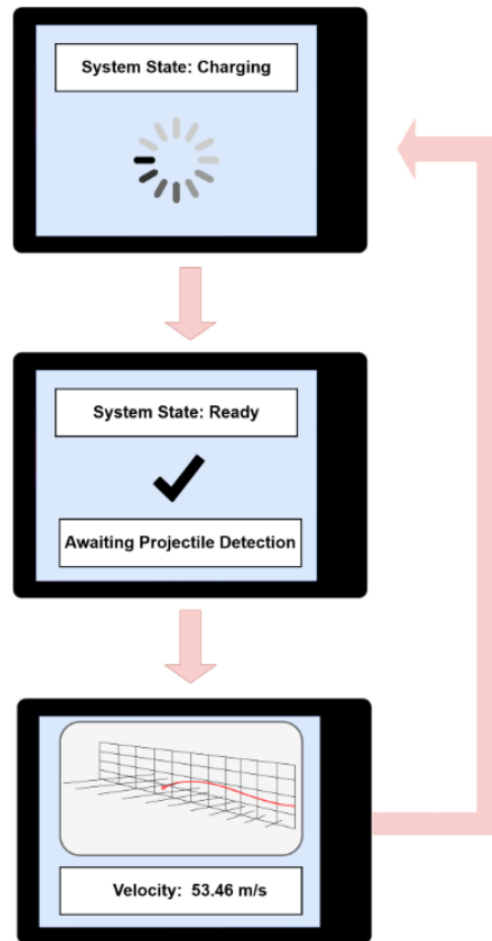


Fig. 7.6: User Interface Design of the PTC

The interface is designed to be simple and intuitive, allowing users with minimal technical experience to operate the system effectively.

In addition to displaying system states, the user interface is designed to enhance usability through clear visual hierarchy and minimal cognitive load. Important information such as velocity measurements and trajectory visualization is prominently displayed, while secondary information is presented in a less intrusive manner. This ensures that users can quickly interpret results without confusion.

The trajectory visualization component provides a graphical representation of the projectile path, which will be displayed to show if or where the projectile hits a target. This visualization helps users better understand the motion characteristics of the projectile beyond numerical values alone. For example, a curved trajectory can visually indicate the effects of gravity, while deviations in the path may suggest inconsistencies in launch conditions.

User feedback mechanisms are also incorporated to improve interaction with the system.

Visual indicators such as color changes, status messages, or simple animations will be used to confirm successful detection events or alert the user to potential issues. These features improve system usability and reduce the likelihood of user error during operation.

Finally, the interface is designed with future expansion in mind. Additional features such as data logging, performance statistics, or adjustable system parameters could be integrated without significantly altering the existing interface structure. This forward-thinking approach ensures that the PTC system remains adaptable to future project requirements.

7.12 Software Optimization Techniques

Due to the computational limitations of embedded systems, optimization techniques are critical for maintaining real-time performance. While the Raspberry Pi 5 is powerful, it still requires efficient use of resources when performing image processing tasks.

One important optimization strategy is limiting computation to the information that is actually needed for trajectory estimation. Rather than applying unnecessarily complex image-processing methods, the software focuses on efficient contour extraction, centroid localization, and image comparison steps that are appropriate for the controlled imaging environment of the PTC system. Another useful technique is restricting processing to a region of interest, so that only the portion of the image where the projectile is expected to appear must be analyzed. Because the PTC system does not require instant sub-millisecond image-processing output, the software can tolerate a modest processing delay while still meeting overall system response requirements. The primary goal is therefore not extreme real-time optimization, but rather achieving reliable processing within an acceptable response window.

Additionally, frame differencing is used instead of more computationally expensive methods such as optical flow. This provides a balance between accuracy and speed, which makes it suitable for real-time applications. Memory management and efficient data structures are also considered to minimize latency. By optimizing these aspects, the system achieves reliable real-time performance within the constraints of the embedded platform. [69]

7.13 Error Handling and System Reliability

Robust error handling is essential to ensure reliable operation of the PTC system under real-world conditions. The software is designed to detect and respond to potential failures without causing system crashes or incorrect measurements.

Common error conditions include camera initialization failure, dropped frames, improper synchronization between the strobe and camera, and invalid sensor readings. To address these issues, the system implements exception handling mechanisms that allow it to

recover gracefully or notify the user when intervention is required. For example, if the camera fails to capture an image, the system will discard the current measurement cycle and return to the armed state. Similarly, if inconsistent positional data is detected, the system avoids computing trajectory results to prevent misleading outputs.

Watchdog timers and system health checks may also be incorporated to monitor continuous operation. These mechanisms ensure that the system remains responsive and can recover from transient faults. By prioritizing reliability and fault tolerance, the software design minimizes the risk of incorrect measurements and enhances overall system robustness. [72]

8 System Fabrication

8.1 PCB Layout

8.1.1 Overview

Below are the full CAD Diagrams of the PTC's circuitry, designed for 2-layer printed circuit boards. These designs were drafted using KiCAD 9.0/10.0, and the overall layouts are shown in independent instances, without their ground plane infills, for ease of viewing component connections and placements. Our emphasis on detachability and easy replace-ability resulted in the separation of our most critical subsystems into their own PCBs, resulting in five total PCB designs: The Motherboard, 3.3V Regulator Module, MCU Module, Strobe Module, and TIA Module; each supporting critical subsystems and peripherals for the PTC, but compartmentalized so that any catastrophic error on one board will not compromise the entire system.

8.1.1.1 Motherboard

The motherboard is responsible for providing power distribution, routing signals, and supporting user-interface components and a few peripheral systems. Large traces were used for main power rails, extra decoupling capacitors were placed near ICs and regulators, the MCU board's seat was placed and oriented so that the MCU's antenna would be situated away from any signal traces, and the 3.3V regulator's seat was placed so that it didn't interfere with placement of the MCU board or the LCD screen's driving pins. Nine total RJ45 ports are present for attaching strobe modules, and an additional two ports are included for the TIA module and the Camera Trigger signals, for a total of 11 RJ45 ports on the motherboard alone. With Cat6 wiring, signal integrity can be maintained across distances if the PCBs must be placed farther away from each other. Extra connection points are available for any pins not actively used by the MCU, in consideration of extraneous circumstances, and screw terminal ports are available for the line laser and the UART connection to the Raspberry Pi 5. Additionally, four mounting holes have been added into the corners of the PCB to allow for easy mounting of the PCB to a surface, if necessary. Below is the full diagram.

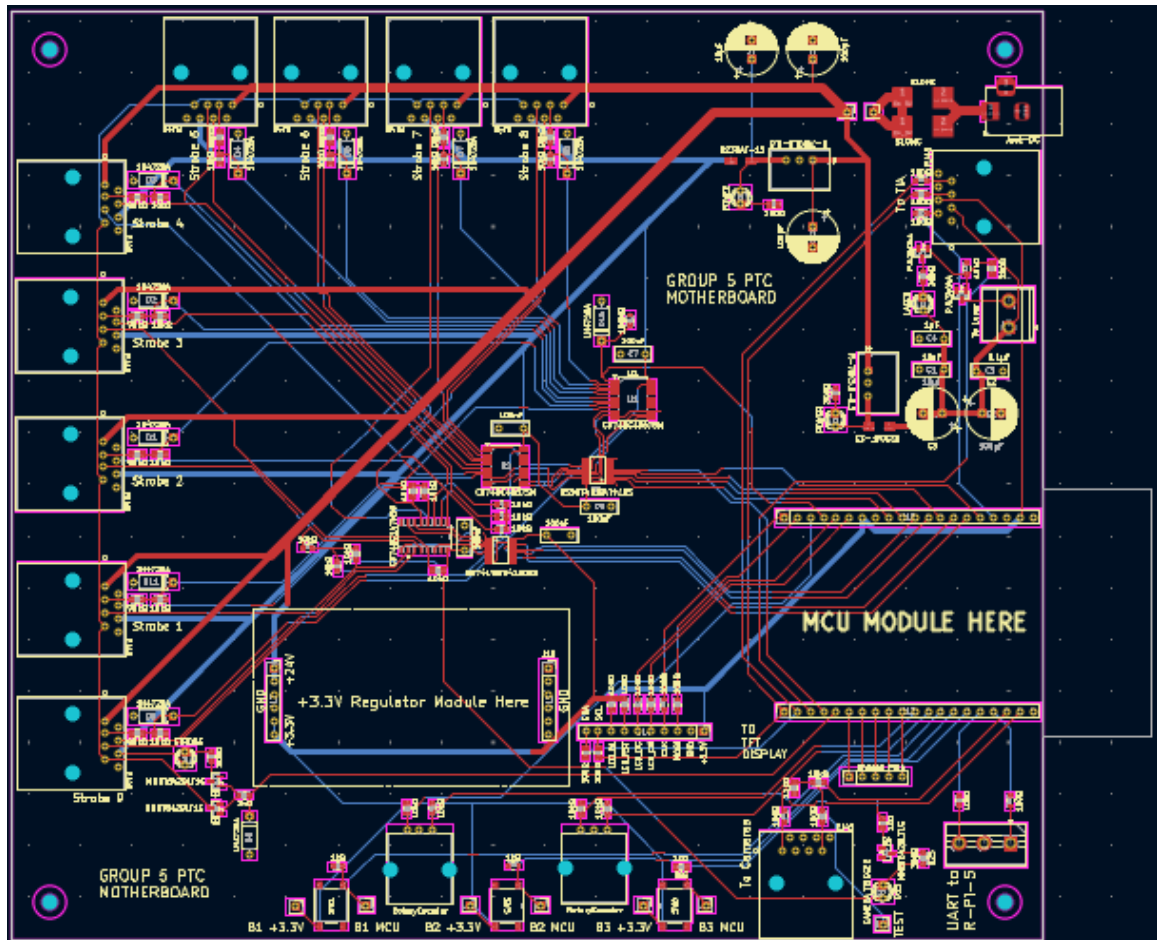


Fig. 8.1: Motherboard PCB Diagram without Ground Plane

8.1.2 MCU Board

The MCU Board allows the ESP32-S3-WROOM-1-N8R8 to be easily detachable from the PTC without having to physically separate it from the circuit board, allowing the end-user to simply replace it with a secondary module if necessary. The components on the board include the MCU itself, placed on the edge to prevent any traces from interfering with its antenna, its reset and boot buttons, and the USB-A port, as well as pin headers to slot into the main board. Additionally, an on-board LDO is used to independently power the ESP32 via USB, allowing the module to be used whether or not it is attached to the rest of the PTC. Again, four mounting holes have been added to this PCB, but they are not necessary or as potentially important as the mounting holes on other PCBs, since the module will be directly seated into the motherboard with its header pin connections. Below is the full diagram.

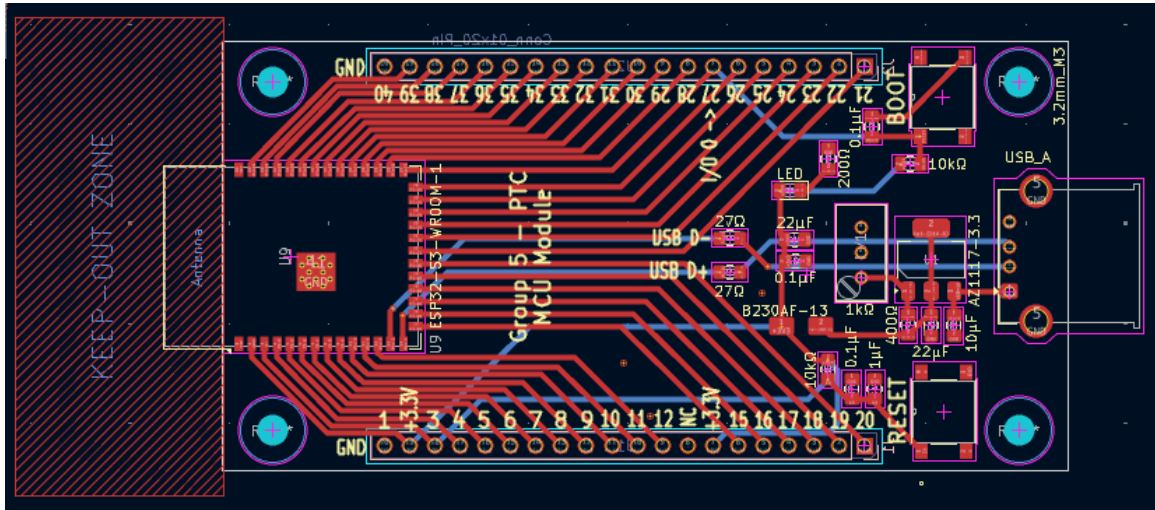


Fig. 8.2: MCU Board with ESP32 and Antenna Keep-Out Zone

8.1.3 TIA Board

The TIA Board being a separate board, in addition to redundancy, allows the photodiode and TIA to be positioned away from the main board to be aligned with the line laser work with the laser gate. On it are the photodiode itself and the TIA and cascaded amplifier network, as well as the ambient light sensor, LDO and decoupling capacitors, and four mounting holes.

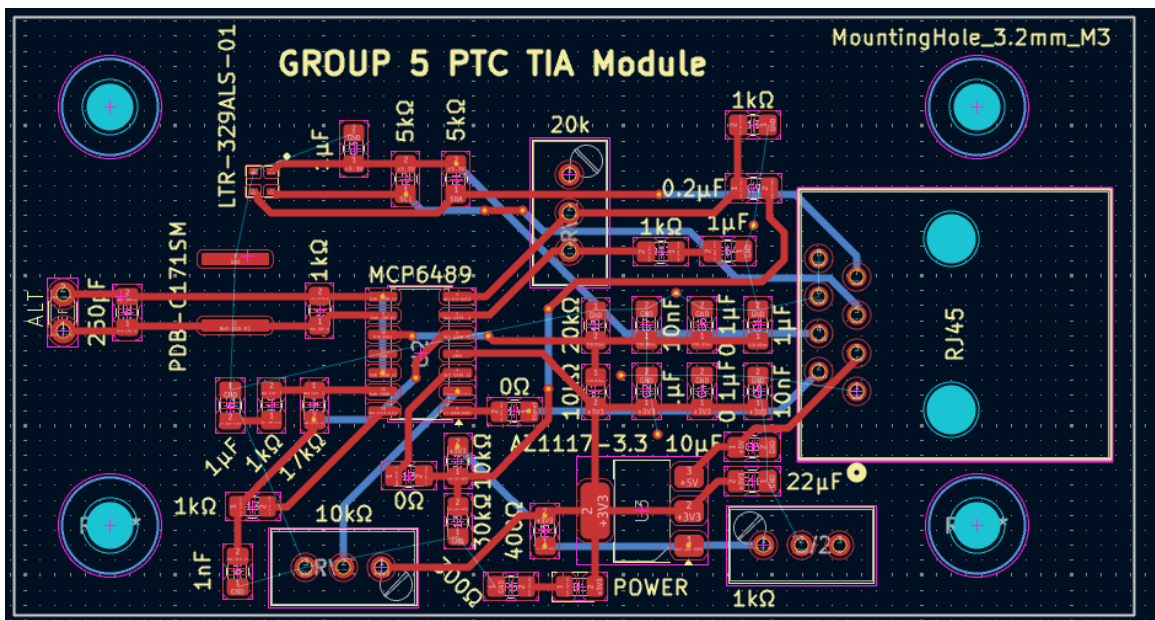


Fig. 8.3: TIA Board with Photodiode and Amplifier Network

With its small form figure, the TIA board will be able to fit in an appropriate location

alongside the laser gate of the PTC, and the photodiode, with its position situated away from the strobe modules, can remain exposed to the line laser without interference from other subsystems.

8.1.4 Strobe Board

The Strobe Board represents a model design that can be used to acquire multiple PCBs. The PTC will require a number of strobe modules, and thus nine slots are available.

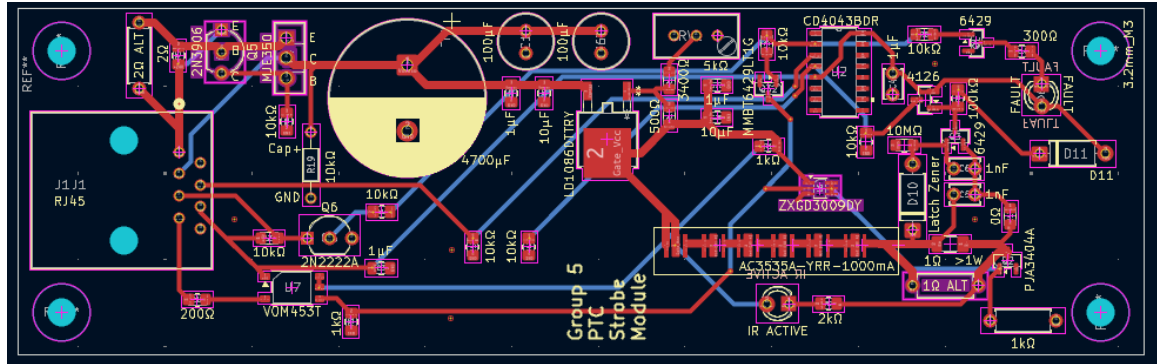


Fig. 8.4: Strobe Board

Incorporated into the strobe board are the constant-current limiter, capacitor bank, IR LED driver, fault detection circuit, and fault latching circuit, as well as an opto-isolator to protect the motherboard and MCU, and four mounting holes to allow for upside down placement on a surface for projectile imaging.

8.2 CAD Diagrams - Senior Design 1

Primarily, the majority of the PTC's optical subsystems will be mounted using 3D printed parts. This includes but is not limited to the mounts for the parabolic mirrors, the mounts for the laser diode and photodiode, and the rigging for the strobe LED discharge circuit and cameras. Many of these diagrams will need to be resized and/or adjusted for further prototyping, as many of these designs are early diagrams for demo/testing purposes. The modeling software of choice for the PTC is an online 3D modeling software called OnShape.

8.2.1 Parabolic Mirrors

The parabolic mirrors are a key 3D printed component of the PTC, so the majority of these mirrors need to be modeled using CAD software. To model the shape of these mirrors, we will be using the equation for a parabola:

$$y = \frac{x^2}{4f} \quad (4)$$

where f is the focal distance of the laser diode. For a collimating mirror, this means that the deepest part of the parabola will be an f distance away (in mm) from the origin of the laser beam. To produce a focusing mirror, a distance of $2f$ from the photodetector will be used to focus the beam down to a single spot. Below, a standalone piece that could be moved around in free-space during testing was produced.

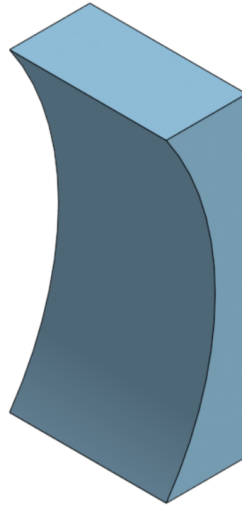


Fig. 8.5: Standalone Parabolic Mirror Design

Expanding upon this design, we produced a parabolic mirror setup (using the same focal distance) that is able to hold our laser diode in place. Additionally, this slot is angled, meaning that we were able to bounce the collimated beam directly off of a flat facet of the model, as seen in the figure here:

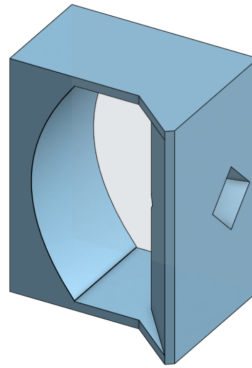


Fig. 8.6: Improved Parabolic Mirror Design

8.3 CAD Diagrams and Physical Models - Senior Design 2

This section presents the diagrams for the various 3D-printed components used in the final version of the PTC, as well as their physical counterparts. This includes all previously

specified components, such as the laser diode mount, along with new additions like the motherboard and TIA board housings. The same modeling software used in Senior Design 1 was used to create all schematics.

8.3.1 Optical Chamber

The imaging system uses a 3D printed mount, housing the cameras, strobe modules, and Raspberry Pi. The imaging mount is supported by 3 legs to hold it above the imaging area. The 4 PCBs on the bottom are the strobe modules, with two cameras facing down. The Raspberry Pi on top is used to read the cameras and process the images.



Fig. 8.7: Isometric View of Imaging Mount Model (Top)

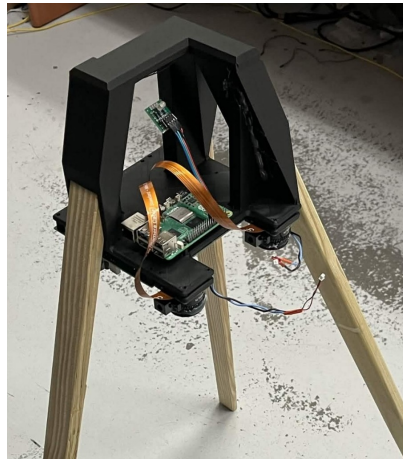


Fig. 8.8: Imaging Mount (Top)

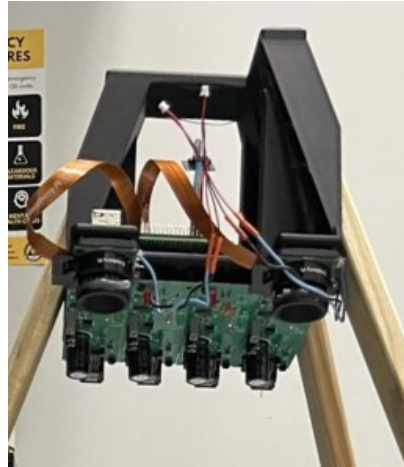


Fig. 8.9: Imaging Mount (Bottom)

8.3.2 Laser Diode and Cylindrical Lens Mount

The laser diode and cylindrical lens are held in a custom mount designed to position both optical elements along a common axis. The taller post incorporates a circular bore sized to friction fit the laser diode. The smaller posts hold end caps that hold the cylindrical lens in place. The cylindrical lens mount was designed to slide over the laser diode base, allowing for adjustable lengths for the line laser. Both pieces contain multiple mounting points that allow for permanent placement, reducing the overall amount of optical alignment necessary for the final product.

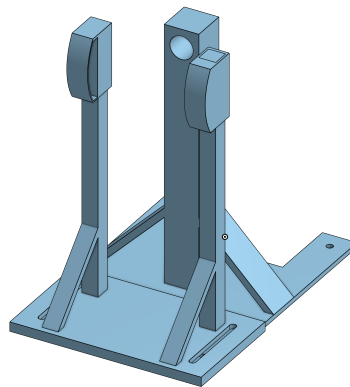


Fig. 8.10: Laser Diode and Cylindrical Lens Mount Model

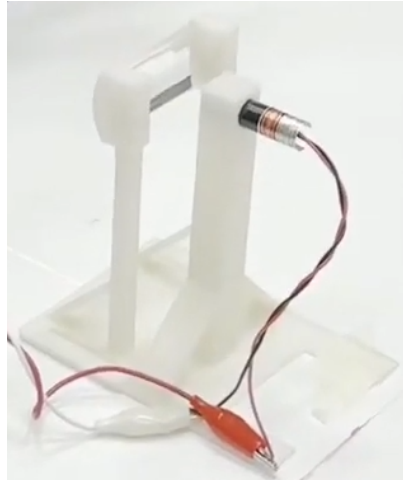


Fig. 8.11: Laser Diode and Cylindrical Lens Mount with Components Mounted

8.3.3 Trans-impedance Amplifier Board Mount

The trans-impedance amplifier mount provides an elevated support structure for the amplifier board housing. A flat base plate anchors the mounting surface using four corner bolt holes, allowing for the mount to be permanently fixed once alignment is achieved. The mount contains 3 adjustable components for precise alignment in both the vertical and horizontal axes. The TIA board slots into the front-most part of the mount.

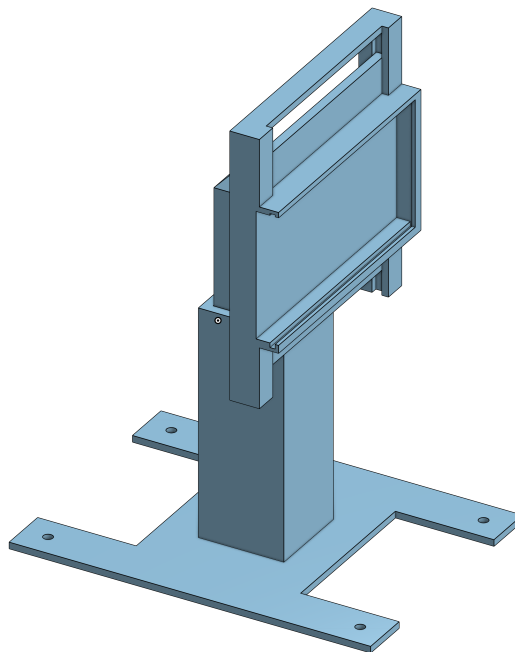


Fig. 8.12: TIA Board Mount Model

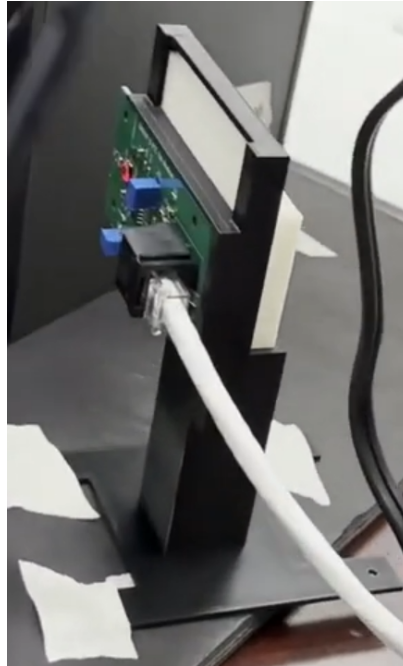


Fig. 8.13: TIA Board Mount with TIA Board Mounted

8.3.4 Parabolic Mirror Mount

The parabolic mirror mount is shaped to hold the bendable acrylic mirror. The design of this mirror mount was specifically made to hold the 8 x 8 inch acrylic mirror previously mentioned. Both a concave and convex piece were designed to form the physical mirror.

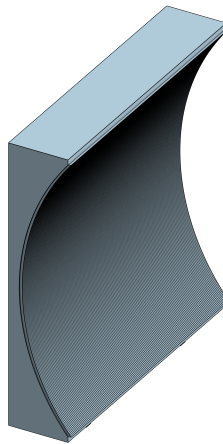


Fig. 8.14: Parabolic Mirror Mount (Concave) Model

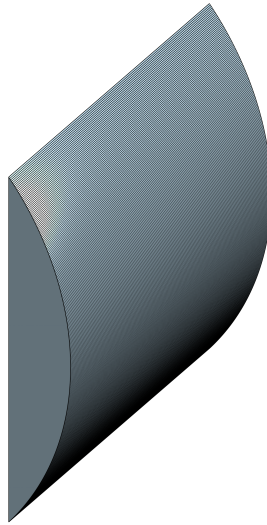


Fig. 8.15: Parabolic Mirror Mount (Convex) Model

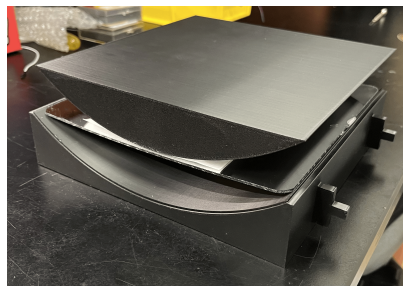


Fig. 8.16: Parabolic Mirror Mount Pieces (Concave and Convex)



Fig. 8.17: Parabolic Mirror Mount with Mirror Attached

8.3.5 Sensor Gate Chamber

The sensor gate chamber is comprised of 6 individual pieces that are fit together to create the entire box. The two largest pieces of the box hold two mirrors each, with slots designed to hold the specific 4 x 8 inch glass mirrors chosen for the project. These slots position the mirror at 45 degree angles, making the formation of the horizontal laser sheets consistent and uniform. Roof pieces were created to contain the stray laser light from escaping the chamber. Side wall pieces were also created with entry/exit points for both the laser light and projectile.

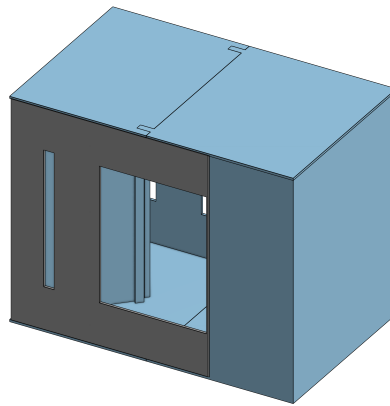


Fig. 8.18: Mirror Box (Top On) Model

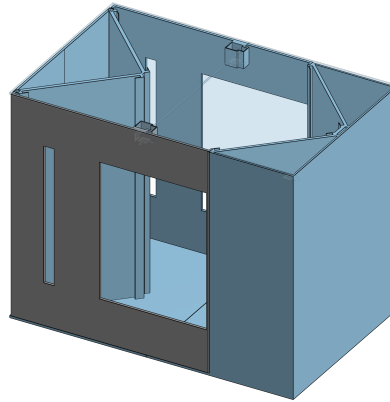


Fig. 8.19: Mirror Box (Top Off) Model

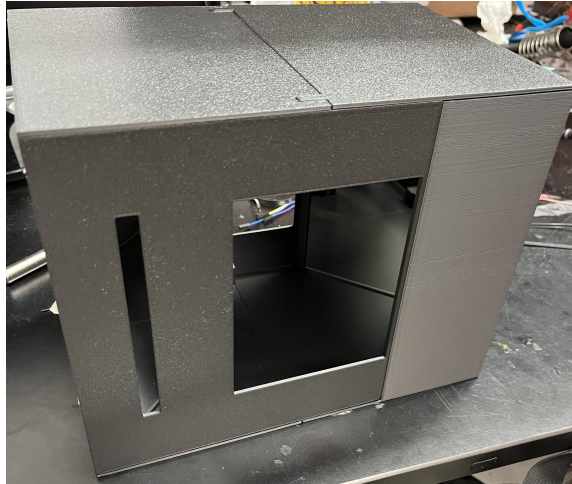


Fig. 8.20: Mirror Box (Top On) with Mirrors Inside

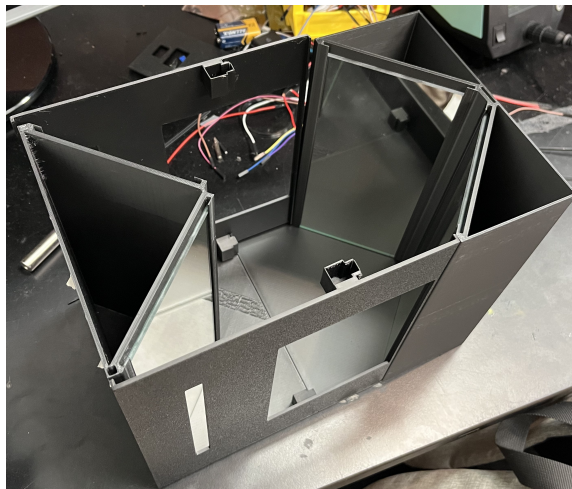


Fig. 8.21: Mirror Box (Top Off) with Mirrors Inside

8.3.6 Motherboard Housing

The diagram shows a lower housing shell modeled as a rectangular tray with a raised perimeter, designed to hold the motherboard for the project. Four corner posts are used to attach the top and bottom pieces of the housing. There are multiple slots in the walls designed to be open to allow for the CAT-6 and other cables to be connected to the board. The top of the housing contains a minor extrusion, which was created to hold the LCD screen mount.

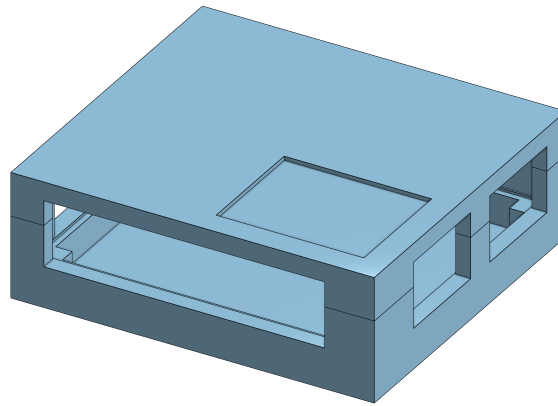


Fig. 8.22: Motherboard Housing (Top On) Model

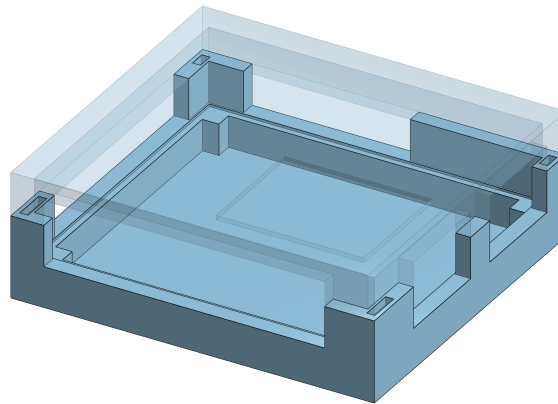


Fig. 8.23: Motherboard Housing (Top Off) Model



Fig. 8.24: Motherboard Housing (Top Off) with Motherboard Inside

8.3.7 LCD Screen Mount

The CAD model depicts an LCD screen mount, designed as a wedge shape. The main body forms a right-triangular ramp with a steep vertical face serving as a mounting surface

for the display. The screen is able to slide in from the right side, with a removable end cap piece that has a slot in the center of it to allow cables to pass through. The mount is shaped to fit into the minor extrusion on the top of the motherboard housing.

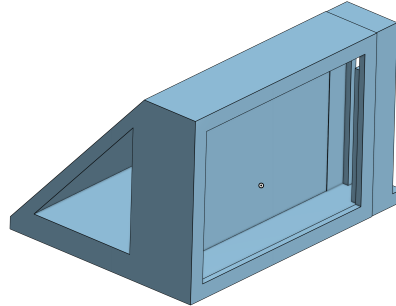


Fig. 8.25: Waveshare Screen Mount Model



Fig. 8.26: Waveshare Screen Mount with Screen Inside

9 System Testing and Evaluation

9.1 Optoelectronics Feasibility - Camera Imaging Subsystem

9.1.1 Strobe Light Intensity

The readout noise of the IMX296 sensor appears to be approximately 5 electrons [89]. Here, the minimum illumination is calculated assuming a readout noise of 5 electrons and having a sufficient SNR to place a 1 [cm] $\times$ 1 [cm] projectile in an image that is on a 29 [cm] $\times$ 22 [cm] background that has a 10% difference in reflectivity than the background to have on average 95% of the time every pixel of the projectile at a different level than every pixel of the background.

We will be assuming a strobe time of $T = 100\mu\text{s}$, that half of the emitted light hits the desired area (efficiency $\eta_{light} = 0.5$), that the wavelength of light is $\lambda = 850[\text{nm}]$, and the camera is $n_{pixels} = 1580000$ or 1.58 megapixels. The formula for photons hitting a pixel given a total light intensity I and these assumptions is

$$N = \frac{I \cdot T \cdot \lambda}{hc} \cdot \frac{\eta_{light}}{n_{pixels}} = \frac{I \cdot 100[\mu\text{s}] \cdot 850[\text{nm}]}{hc} \cdot \frac{0.5}{1580000} = \frac{I}{7.38 \times 10^{-9}[\text{W}]}$$

or 135000 photons per milliwatt.

The projectile would have a size of about 50 pixels by 50 pixels, giving 2500 pixels on the projectile, with about 1,580,000 pixels of background.

Assuming a peak quantum efficiency of 0.69, combined with the 850 [nm] relative efficiency of 0.4, giving a total quantum efficiency of $\eta_{QE} = 0.276$. N is the number of photons that hit the detector, while N_e is the number of electrons that are detected.

$$\sigma_{total} = \sqrt{\sigma_{shot}^2 + \sigma_{readout}^2}$$

If we approximate the shot noise with a gaussian distribution, we can combine the readout noise distributions and the shot noise distributions to approximate the total noise distribution.

$$P_{background < threshold}^{1580000} > 0.5$$

and

$$P_{projectile > threshold}^{2500} > 0.5$$

Which implies

$$P_{background < threshold} > 0.999999561$$

and

$$P_{projectile > threshold} > 0.99972278$$

$$\sigma_{total} = \sqrt{N_e \cdot \sigma_{readout}} = \sqrt{N \cdot 0.276 + 25} = \sqrt{\frac{I \cdot 3.75 \times 10^7}{1[\text{W}]} + 25}$$

While the relative noise is $\frac{\sigma}{N}$ is

$$\frac{\sigma_{total}}{N} = \frac{\sqrt{\frac{I \cdot 3.75 \times 10^7}{1[\text{W}]} + 25} \cdot 7.38 \times 10^{-9}[\text{W}]}{I}$$

We want to select a threshold percentage such that the two probabilities are true. The best threshold seems to be 0.945 given the projectile has a reflectivity of 90%, and the background has a reflectivity of 100%.

Log of probability of overlapping pixel values vs threshold value
with 0.5 [mW] of intensity

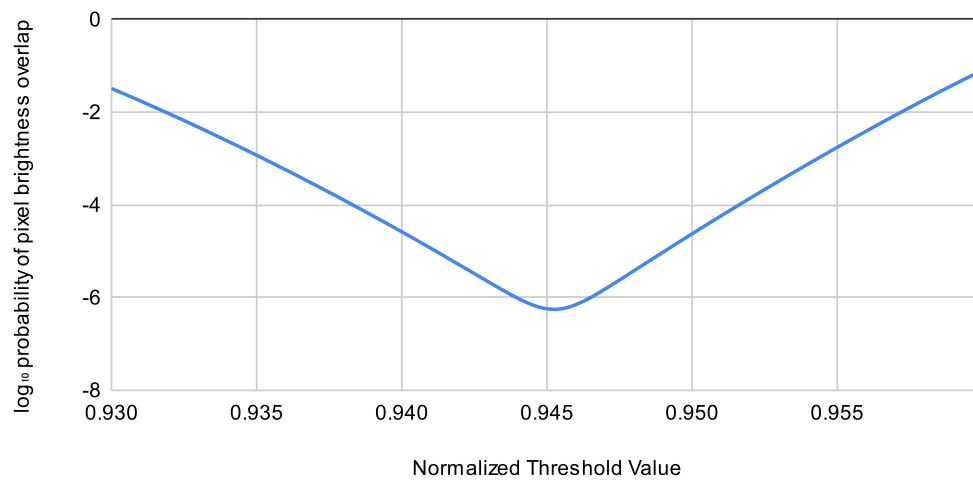


Fig. 9.1: Graph to determine the best threshold value

Spreadsheet calculations give a the value for intensity that creates the probability of a pixel on the projectile having an intensity that overlaps with the intensity of the background of 275 microwatts.

Probability of overlapping pixel values vs light intensity

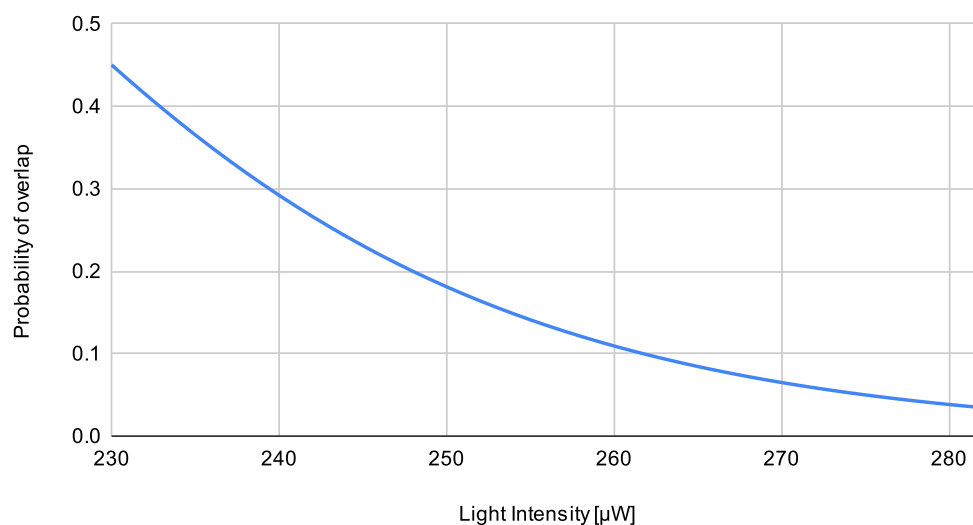


Fig. 9.2: Graph to determine the minimum intensity with no ambient light

If we assume that the camera cannot distinguish pixels with a small difference in the

number of electrons per pixel, that is by discretizing the number of electrons in a pixel into "buckets" of illumination values, the minimum illumination would be higher. If we assume the "buckets" of illumination values are 1000 electrons in size, compared to the approximately 25,000 electrons for "full" illuminance, the minimum illumination value raises to about 0.7 mW.

Probability of overlapping pixel values vs light intensity with discrete bucket sizes

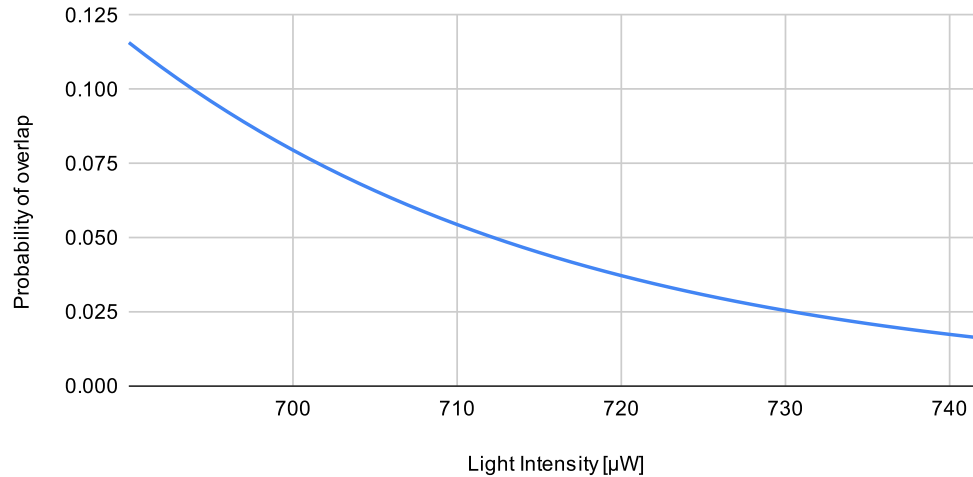


Fig. 9.3: Graph to determine the minimum intensity with no ambient light with discrete illumination bucket sizes of 1000 electrons

Given that the stray illumination from outside the system will likely be far greater than this, the largest source of noise will be stray light.

9.1.2 Outdoor ambient light based minimum intensity

To calculate the minimum intensity based on the light leaked into the strobe chamber, we take the light within the bandwidth of the LEDs filtered out by the bandpass filter, and make sure it is less than 1/2 of the amount of light that is provided by the LEDs.

If we assume a bandwidth $\Delta\lambda = 80[\text{nm}]$, a working environment of sunlight, and having 1/10th of the light from the sun gets into the strobe chamber.

The intensity of the sun between 810 [nm] and 890 [nm] is about $900[\text{W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}]$. This gives about $0.9[\text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}] \cdot 80[\text{nm}] = 72[\text{W} \cdot \text{m}^{-2}]$. There would be about $7.2[\text{W}/\text{m}^2]$ of light incident on the entrances to the strobe chamber. Given 2 openings that are 20 [cm] by 20 [cm], that is 0.58 [W] of light getting into the strobe chamber. Given that our slowest projectile supported is 5 [m/s] within about 0.5 [m] long strobe chamber, that would be an exposure of 100 [ms]. Comparing the strobe on-time to the total exposure time, that is a ratio of about 1000/1, which would mean our total light power

would have about 1000 times the illumination ratio of strobe to ambient, making it 2000 times the ambient illumination level. That makes about 1200 [W] of strobe illumination, which is too much. If we increase the minimum required speed of projectiles outdoors to 50 m/s, therefore reducing the maximum ambient exposure time to $\frac{0.5[m]}{50[m/s]} = 10[ms]$, that takes the strobe intensity requirements down by a factor of 10, which means that 120 [W] of light would be required.

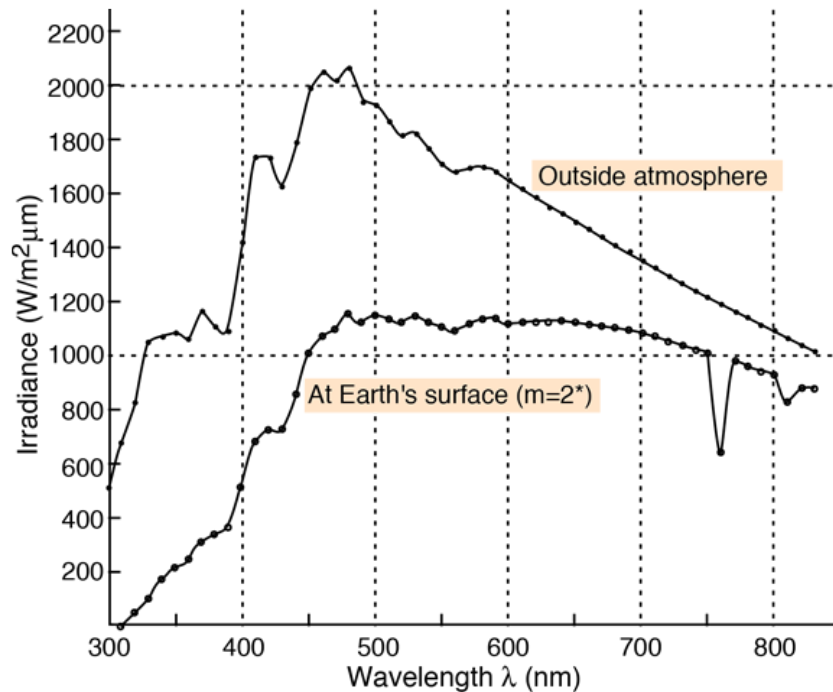


Fig. 9.4: Solar irradiance Credit: NASA via R Nave GSU web page

9.1.3 Indoor ambient light based minimum intensity

Since indoor LED and fluorescent lighting doesn't produce any significant amount of 850 [nm] IR light, we'll simply take the intensity of outdoor sunlight and divide it by the relative intensity of indoor task lighting, which should give a good upper limit of the intensity of indoor lighting. Outdoor noon sunlight can be up to 10,000 lumens per square foot, while indoor task lighting is typically around 100 lumens per square foot. This gives a ratio of 100/1, so that brings our ambient calculations of 1200 [W] down to 12 [W], which is far more affordable. [90]

9.1.4 Alternative non-strobe / stray light resilient approach

Given that we will already have the speed measurement from the light gate, the imaging setup does not need to get the speed of the projectile, only the trajectory direction. If we instead have the illumination constant during the projectile's entire traversal of the imaging area, the projectile will appear as a streak across the image. Taking two intensity profiles across the width of the system near the beginning and end of the imaging area

will allow the angle for two points of the trajectory with respect to the camera to be obtained. These angles can be combined between the two cameras to get a 3D trajectory of the projectile, and combined with the initial speed information to get the direction and velocity.

9.1.5 LED Field of View

The field of view (FOV) of an LED is the angle at which the light comes out of the LED. The FOV of the LED is one point of comparison, since a wider FOV will provide more even lighting within the sensing area of the strobe imaging chamber, while a narrower FOV will provide more light on target, and therefore be more efficient. A good baseline is to have the LED FOV be at least as big as the FOV of the camera, so that it can approximately illuminate the entirety of the sensing area within the FOV of the camera from between the cameras in the same plane as the cameras. Given that the FOV of the cameras will likely be less than 90° , an FOV of the LEDs of between 90° to 120° would be ideal.

9.1.6 Camera

9.1.6.1 Relative Camera Angular Placement

Stereoscopic vision is often done with in-line cameras separated by a known distance. An alternative is to have the cameras facing different directions, which has a few advantages and disadvantages. Cameras at different angles could be tilted to better cover the sensing area within the strobe chamber and make better use of all of the pixels. However the calculations with the cameras at different angles could prove to be more complex and therefore difficult. There are more potential sources of error for differently angled cameras. It could be possible to perform calibration photographs, or include a permanent calibration marking within the strobe chamber to properly calibrate where the cameras are for each shot. Calibration markings at the beginning and end of the strobe chamber would be possible to crop out of the images used for the projectile detection, but could be used for precisely locating the cameras in space.

Due to the decreased complexity, we will be using the same tilt direction for both cameras, separated simply by a distance.

9.1.6.2 Camera Spatial Placement and Field of View

The placement of the cameras and field of view has a significant impact on the overall size and shape of the end product, in addition to having a significant impact on the size of the sensing area.

A larger FOV would allow the cameras to be placed closer to the sensing area, but it would also cause there to be more unused volume in the field of view, since the FOV must include the entire top of the sensing area, and a larger FOV means the viewed area at the bottom of the sensing area would be much larger than the actual sensing area.

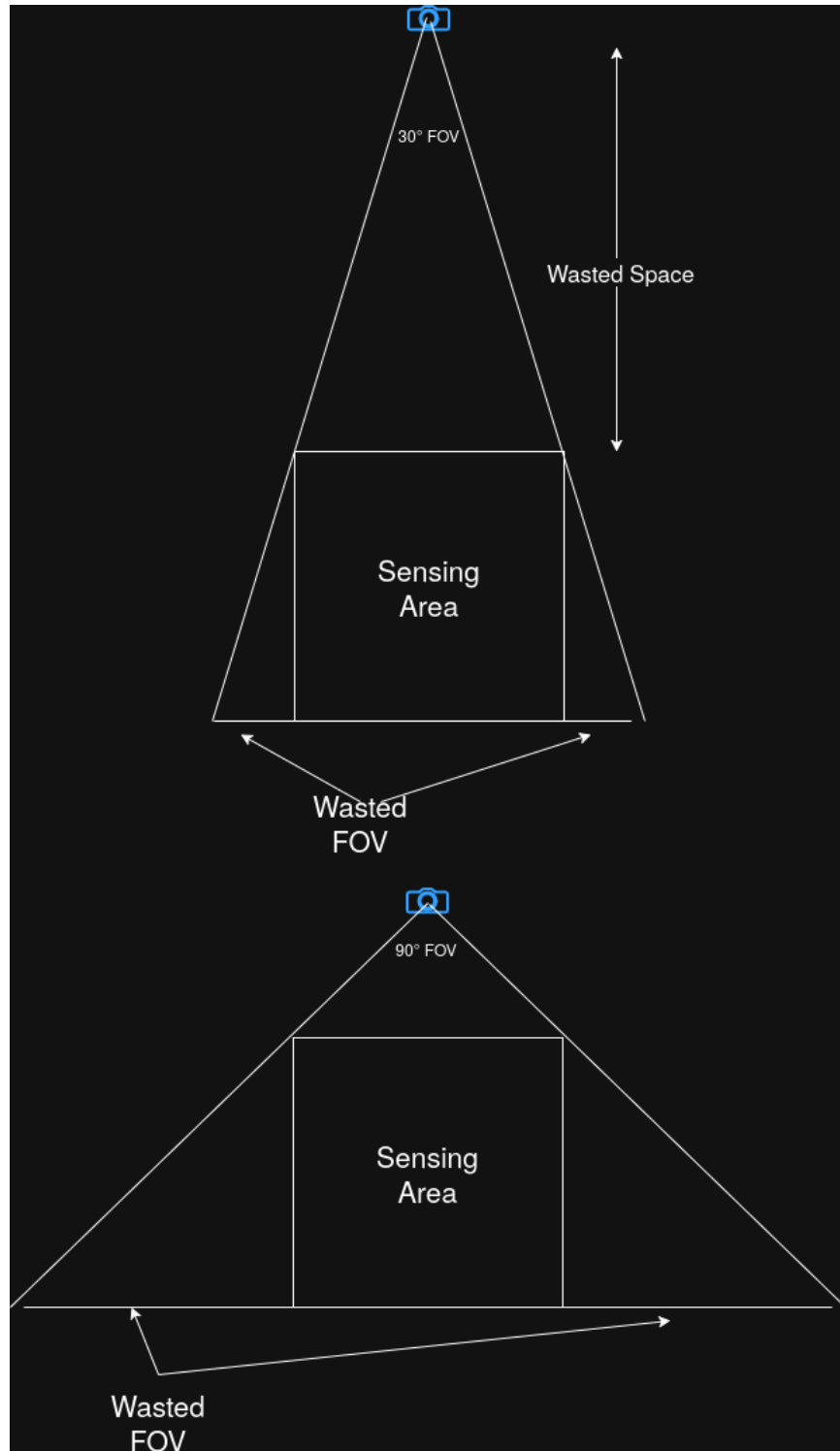


Fig. 9.5: FOV Comparison

Since larger FOVs cause greater spherical aberration and required lenses with focal lengths shorter than was available, we ended up going with a 42.6° FOV lens system.

9.2 Optoelectronics Feasibility - Light Gate Subsystem

9.2.1 Optical Link Analysis

The light gate subsystem serves as the primary trigger mechanism for the PTC, detecting the entry of a projectile into the sensing region and initiating time-of-flight measurements for velocity calculation. This analysis section describes the optical feasibility of using the selected Adafruit 1057 line laser module paired with the PDB-C171SM silicon photodiode to achieve reliable projectile detection.

9.2.1.1 Laser Source Characteristics

The Adafruit 1057 line laser module emits at 650 nm with a maximum optical output power of 5 mW. This module has an integrated cylindrical Fresnel lens that produces a line pattern with a 120° fan angle, distributing the optical power across the illuminated region. For a sensing area width of 100 mm (10 cm) at the target distance, the linear power density can be calculated. The geometric relationship between fan angle and line length are as follows:

$$L = 2d \cdot \tan\left(\frac{\theta}{2}\right) \quad (5)$$

where L is the line length, d is the distance from the aperture of the laser, and θ is the fan angle. Rearranging the equation to solve for d , the source-to-target distance for the laser to achieve a sensing region of 100 mm is approximately 29 mm.

$$d = \frac{L}{2 \cdot \tan(60^\circ)} = \frac{100 \text{ mm}}{2 \cdot \tan(60^\circ)} \approx 29 \text{ mm} \quad (6)$$

With this geometry, the 5 mW output power distributed across the 100 mm sensing region results in a power density of approximately $50 \frac{\mu W}{mm}$:

$$P_{linear} = \frac{5 \text{ mW}}{100 \text{ mm}} = 50 \frac{\mu W}{mm} \quad (7)$$

Due to limited information from the Adafruit data sheet, it is going to be assumed that the intensity profile for this laser is roughly Gaussian in nature, meaning that the central region of the line has a higher radiance than the edges. Additionally, assuming that the distribution of the beam is uniform, the irradiance at the photodetector primarily depends on the efficiency of the collimating/focusing system being used to expand the laser light into sheets. [12]

9.2.1.2 Photodetector Response - Senior Design 1

The PDB-C171SM silicon photodiode exhibits a responsivity of about 0.4 A/W at 650 nm, as seen in the figure below.

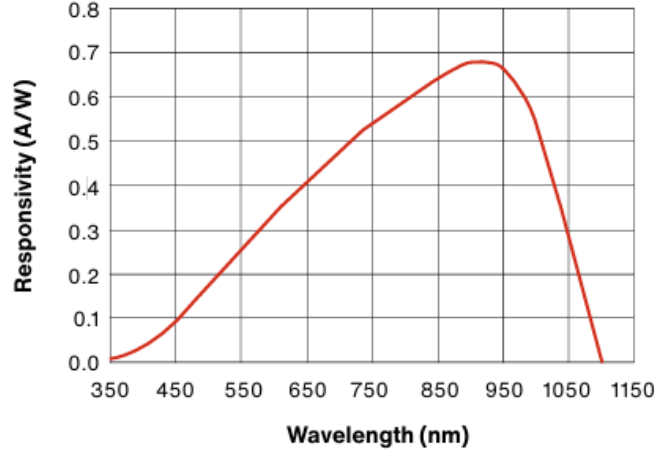


Fig. 9.6: PDB-C171SM Photodiode Spectral Response

The photocurrent generated by the incident optical power is:

$$I_{ph} = R(\lambda) \cdot P_{incident} \quad (8)$$

where $R(\lambda)$ is the wavelength-dependent responsivity and $P_{incident}$ is the optical power reaching the active area. For our laser diode, the ideal photocurrent is 2 mA. In our setup, we are going to use reflective surfaces to collimate the laser beam, bounce it across the sensing region, and focus it back down to a point to be detected by the photodetector. We have decided to use aluminum foil tape on 3D printed structures. The aluminum foil tape provides high reflectivity in the visible spectrum, with values of 88 – 92% for polished aluminum surfaces at 650 nm. [24]

For a photodetector with an active area width of approximately 5-10 mm positioned to capture the reflected beam, the received optical power becomes:

$$P_{received} = P_{incident} \cdot R \cdot \eta_{collection} \quad (9)$$

where R is the reflectivity of the aluminum tape and $\eta_{collection}$ is the collection efficiency of the photodiode. If we are to assume that the reflectivity is $\approx 90\%$ and the collection efficiency is $\approx 10\%$, then the received power becomes:

$$P_{received} = 5 \text{ mW} \cdot 0.9 \cdot 0.1 = 450 \text{ } \mu\text{W} \quad (10)$$

resulting in a corresponding photocurrent of:

$$I_{ph} = 0.4 \frac{\text{A}}{\text{W}} \cdot 450 \text{ } \mu\text{W} = 180 \text{ } \mu\text{A} \quad (11)$$

For the photodiode capacitance values at $V_{bias} = 10 \text{ V}$ and the specified rise time with load resistance $R_L = 1 \text{ k}\Omega$, the bandwidth can be estimated from the RC time constant equation:

$$f_{-3dB} = \frac{1}{2\pi R_L C_d} \quad (12)$$

In the datasheet for the photodetector, the rise time measurements at 820 nm with a $R_L = 1\text{ k}\Omega$ load suggest bandwidth capabilities compatible with the 10-100 kHz carrier frequency. We would have to do more experimental testing to determine the bandwidth capabilities at 650 nm, but we believe that it would still fall into a usable range for our modulated detection scheme. [91]

9.2.1.3 Photodetector Response - Senior Design 2

For the final product of the PTC, the photodiode and method of bouncing the beam remained the same, but the reflectors were swapped out with a more reliable source. Also, the laser diode was measured to be about 3 mW instead of the 5 mW stated by the product website. For our 3 mW laser, the ideal photocurrent would be 1.2 mA. In our setup, the beam is routed through a series of five reflective mirrors before being focused down onto the photodetector's active area. Four of these mirrors have a roughly measured 88% reflectivity, with the fifth having an approximate reflectivity of 85%.

Since the beam passes through these five reflective surfaces sequentially, the cumulative reflectivity is a product of the individual mirror reflectivities:

$$R_{total} = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 = (0.88)^4 \cdot (0.85) \approx 0.51 \quad (13)$$

meaning roughly 51% of the original beam power reaches the photodetector. Using the same equation as before to calculate received optical power (9) and assuming the collection efficiency to be closer to 90% (majority of the light is being focused to a point), we can calculate the optical power to be:

$$P_{received} = 3\text{ mW} \cdot 0.51 \cdot 0.9 \approx 1.38\text{ mW} \quad (14)$$

which results in a corresponding photocurrent of:

$$I_{ph} = 0.4 \frac{A}{W} \cdot 1.38\text{ mW} \approx 552\text{ }\mu A \quad (15)$$

This shows a drastic improvement to the originally calculated photocurrent from Senior Design 1, despite the lower measured power of the actual diode.

9.2.2 Signal-to-Noise Analysis

9.2.2.1 Noise Sources

Shot noise is a type of electronic noise that arises from the discrete nature of electric charge, which causes random fluctuations in steady current flow. It can be expressed by this equation:

$$i_{shot} = \sqrt{2q(I_{ph} + I_d)B} \quad (16)$$

where q is the fundamental charge of an electron ($1.602 \cdot 10^{-19}\text{ C}$), I_d is the dark current, and B is the bandwidth.

Another form of noise is thermal noise, which arises from the random thermal motion of charge carriers in a resistive material. This can cause current fluctuations in a material and can be described as follows:

$$i_{thermal} = \sqrt{\frac{4k_BTB}{R_L}} \quad (17)$$

where k_B is the Boltzmann's constant ($1.381 \cdot 10^{-23} \frac{J}{K}$), T is the temperature, and the other parameters are the same as previously defined. It can be seen from this equation that thermal noise increases as the temperature and/or bandwidth increases and decreases with higher resistance.

Assuming that $T = 300 \text{ K}$ and $B = 100 \text{ kHz}$, the shot and thermal noises can be calculated as such:

$$i_{shot} = \sqrt{2 \cdot 1.602 \cdot 10^{-19} \cdot (180 \cdot 10^{-6}) \cdot 100 \cdot 10^3} = 2.4 \text{ nA} \quad (18)$$

$$i_{thermal} = \sqrt{\frac{4 \cdot 1.381 \cdot 10^{-23} \cdot 300 \cdot 100 \cdot 10^3}{1000}} = 40.7 \text{ nA} \quad (19)$$

The total RMS noise can be calculated by this equation:

$$i_{RMS} = \sqrt{i_{shot}^2 + i_{thermal}^2} \approx 40.8 \text{ nA} \quad (20)$$

9.2.2.2 Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) quantifies how strong a desired signal is compared to the background noise of the received signal. A higher SNR value indicates a strong signal with little background noise, which is desirable for the PTC project. The SNR can be expressed in dB, as seen the the equation below:

$$SNR = \frac{I_{ph}}{i_{RMS}} = \frac{180 \text{ } \mu\text{A}}{40.8 \text{ nA}} \approx 4400 \approx 73 \text{ dB} \quad (21)$$

9.2.3 Projectile Detection Timing Analysis

9.2.3.1 Beam Interruption Geometry

For a projectile of diameter D traveling at a velocity v that is perpendicular to the laser line, the duration of the beam interruption is:

$$t_{interrupt} = \frac{D}{v} \quad (22)$$

For the specified projectile size range (15-50 mm) and velocity range (10-50 m/s), the

upper and lower bounds of the system's temporal resolution requirements can be determined.

TABLE 9.1: Beam Interruption Bounds

Projectile Diameter	Velocity	Interruption Time
15 mm	50 m/s	300 μs
15 mm	10 m/s	1.5 ms
50 mm	50 m/s	1 ms
50 mm	10 m/s	5 ms

This table shows that for our system, our upper bound is a minimum interruption time of 300 μs and our lower bound is 5 ms on the system's temporal resolution requirements.

9.2.3.2 Carrier Frequency Selection

A modulated carrier frequency approach provides a much greater resistance to ambient light interference by shifting the detection signal away from the DC regime. The carrier frequency must satisfy the following:

$$f_{carrier} > \frac{1}{t_{interrupt, min}} \quad (23)$$

where, for our system with a minimum interruption time of 300 μs , the carrier frequency must be greater than 3.3 kHz. To ensure multiple carrier cycles occur during the shortest beam interruption, a carrier frequency of 10-50 kHz should be sufficient. [91]

9.2.3.3 Rise Time Requirements

The laser diode's rise and fall times have a direct impact on the modulation depth that can be achieved at the carrier frequency. For a 50 kHz carrier (period of 20 μs), the rise and fall times should be less than 10% of the half-period in order to maintain a modulation depth greater than 80%.

$$t_{rise, max} < 0.1 \cdot \frac{t_{period}}{2} = 1 \mu s \quad (24)$$

The Adafruit 1057 datasheet does not specify the rise and fall time characteristics. This means that the exact characteristics of this diode will have to be experimentally derived, making theoretical verification more difficult. There is a TTL-modulated variant of this module (Adafruit 1056) that specifies a maximum modulation frequency of 50 kHz, which was the basis for the previous calculations. We believe that the rise times on the order of microseconds for the Adafruit 1057 variant may be achievable as well. [92]

9.2.3.4 Ambient Light Filtering via Modulation

There are many benefits to using a carrier modulation approach to filter out ambient light. By doing this approach (either through a bandpass filter or lock-in detection method), unwanted signals such as the DC components from constant ambient illumination or broadband noise outside of the detection bandwidth are rejected. This type of filtering should be more than enough to achieve the specified ambient light tolerance by a substantial amount. [93]

9.2.4 Velocity Measurement Analysis

9.2.4.1 Time-of-Flight

To measure the velocity of the projectile, there needs to be two spatially separated light gates with a known distance d_{gates} . The velocity can be measured by dividing this known distance by the difference in time between the two disturbances in the gate:

$$v = \frac{d_{gates}}{\Delta t} \quad (25)$$

9.2.4.2 Timing Resolution and Spatial Uncertainty

For the specified maximum speed error of 20%, the timing resolution must satisfy:

$$\frac{\Delta t}{\Delta t_{measured}} < 0.2 \quad (26)$$

For a 50 m/s projectile traversing a 100 mm gate separation:

$$\Delta t_{measured} = \frac{100 \text{ mm}}{50 \text{ m/s}} = 2 \text{ ms} \quad (27)$$

Making the required timing resolution:

$$\Delta t_{timing} = 0.2 \cdot 2 \text{ ms} = 400 \text{ } \mu\text{s} \quad (28)$$

The microcontroller we have chosen (either Raspberry Pi Pico 1 or 2) will have clock speeds that provide timing resolutions that are more than sufficient (133 and 150 MHz respectively for precise measurements).

For a gate separation measurement uncertainty of $\pm 1 \text{ mm}$ over a 100 mm sensing region:

$$\frac{\Delta d}{d_{gates}} = \frac{1 \text{ mm}}{100 \text{ mm}} = 1\% \quad (29)$$

This contributes minimally to the amount of error being contributed to the system, leaving a greater amount of leeway for systematic effects such as non-perpendicular trajectories.

9.2.5 Power Analysis

9.2.5.1 Power Budget

The laser diode module requires a 2.8-5.2 V input at a maximum of 25 mA. Using the maximums for these two metrics, the max power of the laser diode is:

$$P_{laser,max} = 5.2 \text{ V} \cdot 25 \text{ mA} = 130 \text{ mW} \quad (30)$$

This is a very small power draw, making it a very low-power component of the project.

9.2.6 Summary of Feasibility

The analysis of these different aspects of the subsystem indicates that the selected components are capable of meeting the requirements for light gate detection. The primary uncertainties can be attributed to the lack of characterization for the Adafruit 1057 laser module. Testing with this diode should verify the modulation performance, however, other diodes should be considered in case this current module is unable to be modulated within specs.

TABLE 9.2: System Performance Summary

Parameter	Requirement	Calculated	Status
SNR during interruption	$\geq 20 \text{ dB}$	$\sim 73 \text{ dB}$	✓ Exceeds
Photodetector bandwidth	$> 100 \text{ kHz}$	$\sim 100+ \text{ kHz}$	✓ Meets
Detection of 15–50 mm projectiles	Required	$300 \mu\text{s} - 5 \text{ ms}$ events	✓ Feasible
Velocity range 10–50 m/s	Required	Compatible with timing	✓ Feasible
Carrier frequency	10–100 kHz	50 kHz recommended	✓ Meets
Line length	$\geq 100 \text{ mm}$	100 mm at 29 mm distance	✓ Meets
Modulation depth	$\geq 80\%$	Requires verification	△ Uncertain
Rise/fall time	$\leq 1 \mu\text{s}$	Not specified	△ Uncertain

9.3 Hardware Testing - Senior Design 1

9.3.1 Laser Gate Subsystem

9.3.1.1 Laser Diode Power and Beam Spread

The Adafruit 1057 line laser diode was characterized using a Newport 1919-R optical power meter and a standard 12 inch ruler. A digital multimeter (MSR-R500) was used to

verify input voltages for the laser diode received from an FG-200 function generator. The line laser power measurements were made by holding the laser diode directly to the power meter, without any collimation or focusing system. The following power measurements were characterized:

- **At 3.5 V:** Measured power was 1.05 mW.
- **At 4.5 V:** Measured power was 2.5 mW.
- **At 5.1 V:** Measured power was 2.68 mW.

For the spread of the beam, I chose to measure the length of the center-most portion of the beam since this will be the section of laser diode that is being collimated and then focused back down:

- **At 2 cm from table:** Measured line length was 3.31 cm.
- **At 5 cm from table:** Measured line length was 5.33 cm.
- **At 10 cm from table:** Measured line length was 7.58 cm.

9.3.1.2 Parabolic Mirrors

The reflectivity and shape of the parabolic mirrors was tested to ensure that enough light would be present on the photodetector after the collimation, bouncing, and focusing of the laser diode. In the figure below, it can be seen that the aluminum foil allows the laser to maintain a strong, coherent beam when reflecting.



Fig. 9.7: Aluminum Foil Tape Demonstration

When testing using a 3D printed mount for the aluminum foil tape, it could be seen that there were visible striations in the laser beam. This is caused by the actual print of the material, as the 3D printed mounts do not have a completely smooth surface. This

could be correct by sanding down the 3D print, but this means that additional filament will need to be used since there will be some amount lost during the sanding process. Alternatively, sheet metal could be fitted into the mount, but this is a much more intensive process compared to the foil tape.

9.3.1.3 Photodetector Responsiveness

A transimpedance amplifying circuit was assembled on a breadboard to test our selected photodetector. We used a modulated white LED at 10 kHz as an illumination source, and were able to test the responsiveness of the photodetector. In the figures below, the signal on the photodetector is able to be seen using an oscilloscope when the photodetector is blocked vs. unblocked.

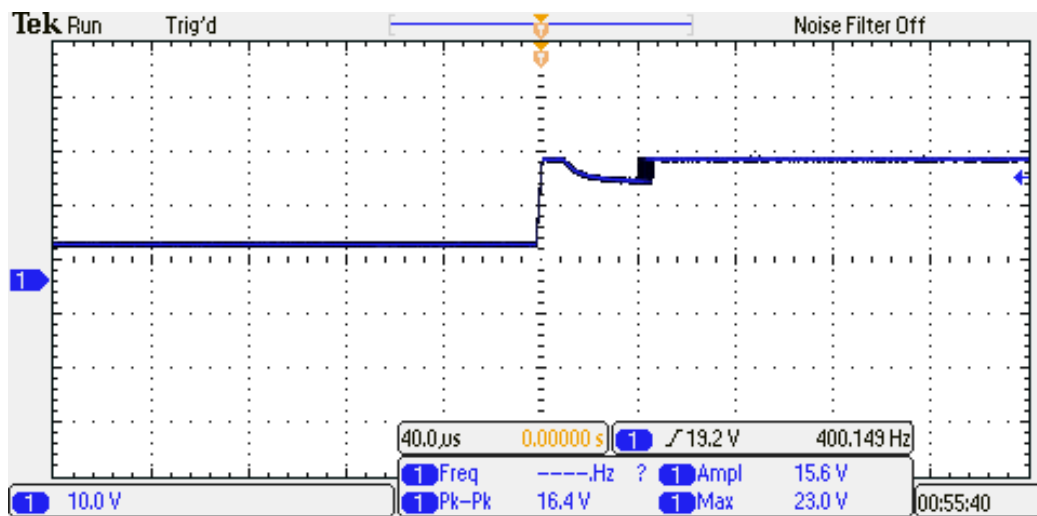


Fig. 9.8: Blocked Photodetector Signal

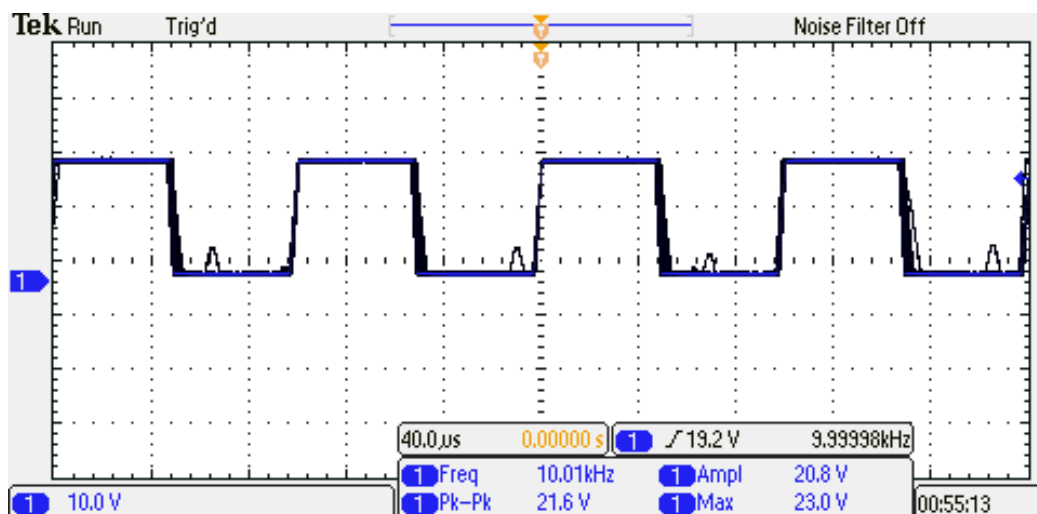


Fig. 9.9: Unblocked Photodetector Signal

There is a noticeable 400 Hz signal still being received when the photodetector is blocked. We believe that this is being caused by our power supply providing a low-frequency noise ripple. Further testing will need to be done to remove this ripple, but we believe that the introduction of a low-pass filter may be able to remove this ripple or minimize the effects of it.

9.3.2 Imaging Subsystem

9.3.2.1 Strobe LED Discharge Circuit

A breadboard setup of the strobe discharge circuit was created, using a function generator as the 3.3 V input signal. With the capacitors charged to 24 V feeding the voltage regulator, the current discharge only had minor ringing at the beginning of the 100 microsecond pulse, which can be seen in the figure below.

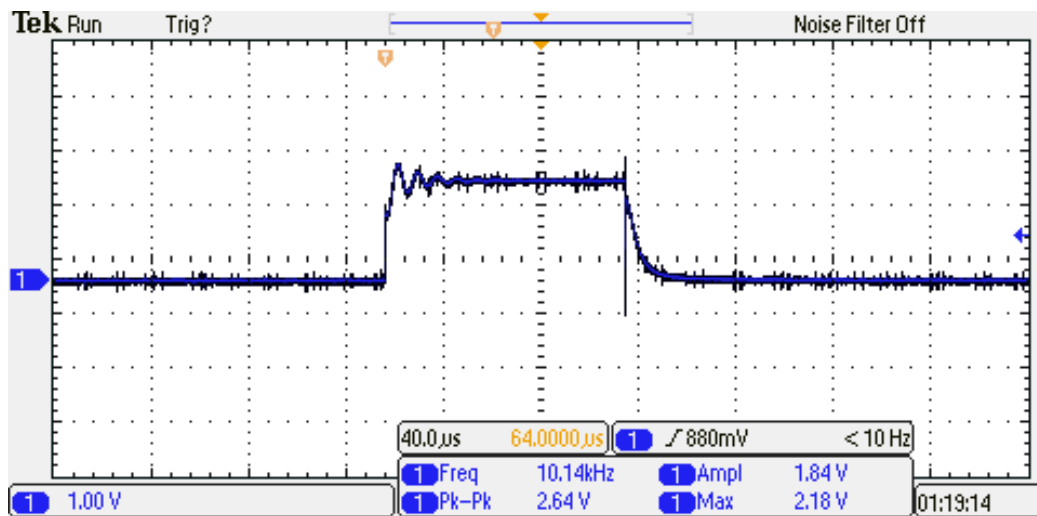


Fig. 9.10: Strobe LED Discharge Pulse Senior Design 1

The current had no noticeable difference between shots, with almost the exact same value and behavior for each pulse. Waveforms between each pulse were indistinguishable from each other. This indicates that the strobe circuitry concept works well, though further testing at higher currents is necessary.

9.3.2.2 Pi Camera Testing

The Raspberry Pi camera subsystem was tested to verify that the Raspberry Pi 5 could properly interface with the selected camera modules and capture images for later processing. Initial testing focused on basic camera recognition, image capture, and display output through the Raspberry Pi. This was done to confirm that the camera hardware and software environment were functioning before integrating the cameras with the full projectile tracking system.

During testing, the Raspberry Pi 5 was able to detect the connected camera modules

and successfully capture still images. These tests confirmed that the camera interface, software drivers, and image capture tools were working correctly. The HDMI output was also used to confirm that the Raspberry Pi could display images locally, which is important for later integration with the user interface and software demo.

Additional testing was done to verify that the Raspberry Pi could support multiple stages of image capture in sequence. While the final system is intended to synchronize the camera with the strobe and light gate, the present testing stage focused only on confirming basic camera operation and software capability. The camera subsystem performed well under these conditions and demonstrated that the Raspberry Pi 5 is capable of supporting the imaging portion of the project.

9.4 Software Testing - Senior Design 1

9.4.1 Image Tracking Software

The software testing performed during Senior Design 1 focused on verifying that the Raspberry Pi 5 could acquire images, process them, and display useful visual output to the user. Since the full projectile tracking hardware has not yet been fully integrated, the software was tested using a simplified demonstration workflow. The main purpose of this testing was to confirm that the software pipeline, display output, and basic image analysis steps were functioning correctly on the intended platform.

The software demonstration was performed on the Raspberry Pi 5 using Python and OpenCV. In the demo, the system first captured a blank reference image and then captured two images that both have a visible test object. The processing software compared the images, identifies the objects within the frame, and displayed the resulting position information on the screen. This demonstrated that the software could successfully perform the basic tasks required for later projectile tracking, including image capture, image comparison, object isolation, and coordinate extraction.

The software also displayed the processed output directly through the Raspberry Pi HDMI interface, confirming that the Pi could support both image processing and user-facing output without requiring an external computer. During testing, the system was able to detect a visible object and overlay useful information on the screen, which serves as an early proof of concept for future trajectory visualization. This is important because the final PTC system will require the Raspberry Pi to process projectile images and then present ballistic results to the user in a simple and understandable format.

Overall, the software testing performed during this phase showed that the basic image tracking pipeline is feasible on the Raspberry Pi 5. While this early demonstration does not yet represent the final projectile-tracking system, it confirms that the selected software tools and processing approach are suitable for continued development in Senior Design 2.

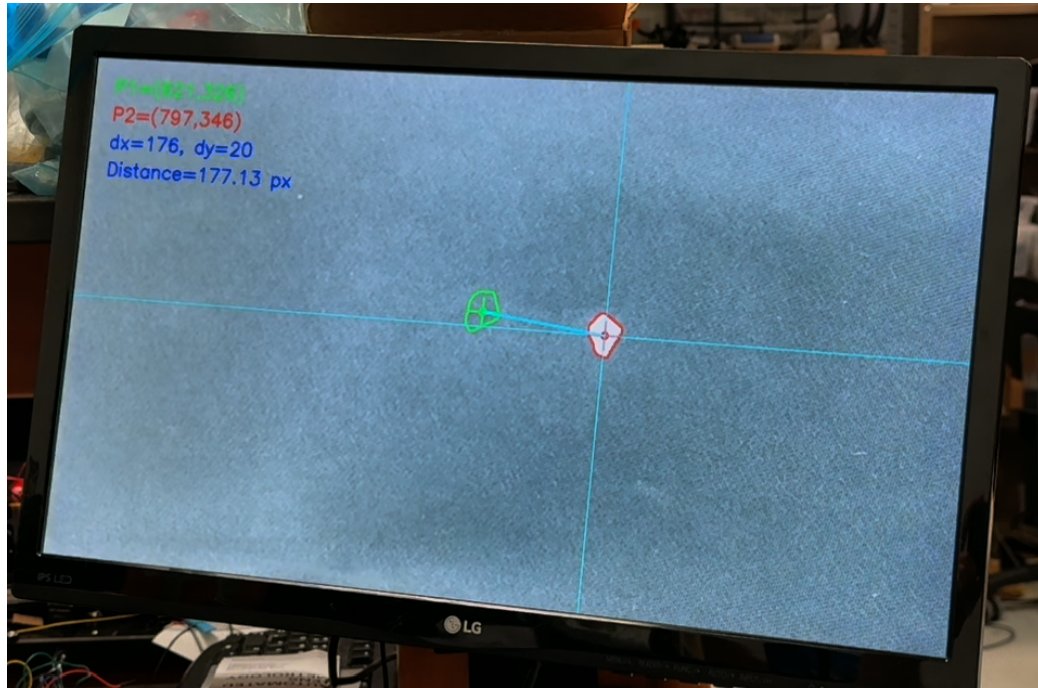


Fig. 9.11: Software Demo Output

9.5 Performance Evaluation - Senior Design 1

9.5.1 Hardware

9.5.1.1 Laser Gate Subsystem

Overall, the components that were tested performed well enough to proceed with further prototyping of the full subsystem. The laser diode produced less optical power than expected, but should still be detectable on the photodiode after being bounced by the mirrors. The parabolic mirrors need to be sanded down if aluminum tape is being used as the uneven surface of the print produces scattering rays coming off of the laser upon contact. The photodetector behaves well under the testing conditions with a white LED source, but development will need to occur using the focused light from the line laser diode. Additional testing will occur once a detectable signal can be received from the line laser on the photodiode after the formation of the actual laser gate, where the voltage drops from an interrupted beam path will be synchronized to the strobe LED discharge circuit.

9.5.1.2 Imaging Subsystem

The parts of the imaging subsystem that was tested demonstrated a stable and repeatable performance. The strobe LED discharge circuit exhibited minimal ringing at the start of the pulse and maintained highly consistent waveforms across repeated pulses. While initial results validate the conceptual design of the circuit, further testing at higher amperage

will be needed to meet performance requirements. The Raspberry Pi camera subsystem also performed as expected, with the camera modules being successfully connected and able to capture consistent images. Although the synchronization with the strobe LEDs and light gate has not been implemented yet, the current testing shows that the imaging system is capable of supporting the required functionality.

9.5.2 Software

The software performed well during the initial demonstration and showed that the Raspberry Pi 5 is capable of running the image-processing pipeline needed for the PTC project. The system was able to capture images, process them in Python using OpenCV, and display the resulting output through the HDMI interface. From a functional standpoint, this confirmed that the software could carry out the main steps needed for later projectile detection and trajectory processing.

One positive aspect of the software performance was that the processing pipeline remained stable during testing. The Raspberry Pi was able to run the demo repeatedly without crashing, and the image analysis logic successfully identified the object used during testing. The displayed output was also clear and useful, which supports the goal of providing a user-friendly visual interface in the final design.

Although the software demonstration was successful, the testing also showed that the current implementation is still an early-stage prototype. The present software was tested on a simple object-detection scenario rather than a true high-speed projectile event. Because of this, the system has not yet been fully evaluated under the timing and image-capture demands expected in the completed design. Future testing in Senior Design 2 will need to measure how well the software performs when synchronized with the light gate, strobe system, and camera imaging setup.

In summary, the software performed well for the scope of testing completed so far. The demonstration confirmed that the selected software environment is capable of supporting image processing and display tasks on the Raspberry Pi 5, while also identifying the need for more advanced integration and timing validation in the next phase of development.

9.6 Overall Integration - Senior Design 1

All of the subsystems and their constituent parts will be combined to create the final product for the PTC. The laser gate subsystem will utilize the collimating, bouncing, and focusing parabolic mirrors to create a uniform light gate that will be able to detect a voltage drop on the photodetector. When there are two interrupts on the photodetector (voltage drops), this means that an object has passed through the laser gate and a velocity measurement can be acquired using the known distance between the two gates and the time between the interrupts.

This velocity measurement is then synchronized with the strobe LED discharge circuit that is a part of the imaging subsystem. The MCU will trigger the strobes to flash at two

specific points in time. These flashes will show the object at two different points spatially, which can be used to determine the positional data of the projectile. A 3D reconstruction can then be made using this data, with all of the gathered information being read out to the user on an external screen.

9.7 Plan for Senior Design 2

For the next part of our project's timeline (Senior Design 2), we plan on accomplishing the following:

- **Individual Subsystem Completion:** We will complete the necessary requirements for each subsystem in preparation for total system integration. This means that every individual requirement necessary for every subsystem (such as achieving the specified sensing region for the laser gate or having a synchronized flash for the strobe LED circuit) will be completed.
- **Subsystem Integration:** Following the completion of every subsystem, we will then combine them to form the prototype version of the PTC. This early prototype should be able to accurately detect the velocity of a projectile and take an image of the projectile as it moves through the box. The physical box for the prototype will also be constructed to house the components for the PTC.
- **Ordering of Additional Components:** Upon testing, it may become clear that additional components need to be ordered to swap or replace already existing parts. This will have to be completed early in senior design 2, as enough time needs to be allocated for receiving and testing these potential parts. Before senior design 2 starts, an order for monochromatic LEDs will be placed due to a design change made in the early stages of system testing.
- **System Testing and Refinement:** After all parts of the project are working, additional testing and refinement will occur to ensure the highest quality work is produced. This means refining aspects such as laser gate mirror design or making software and hardware improvements to ensure smooth user operation, as well as minimize the chance of malfunction.
- **Project Completion:** When all changes have been made and the PTC has been thoroughly tested, it will be demoed to our committee to show that we were able to achieve all of our specifications for the project. Another showcase will also be held where we will demo our project to other faculty and staff.

9.8 Hardware Testing - Senior Design 2

9.8.1 Laser Gate Subsystem

9.8.1.1 Parabolic Mirror

The parabolic mirror was designed to focus down the received output laser light from the exit slit in the mirror box. This mirror is positioned to focus the light onto the photodetector that is mounted on the TIA board. In the figure below, a ray-traced diagram can be seen detailing the theoretical focus of the parabolic mirror for a line with a height of approximately 13 cm.

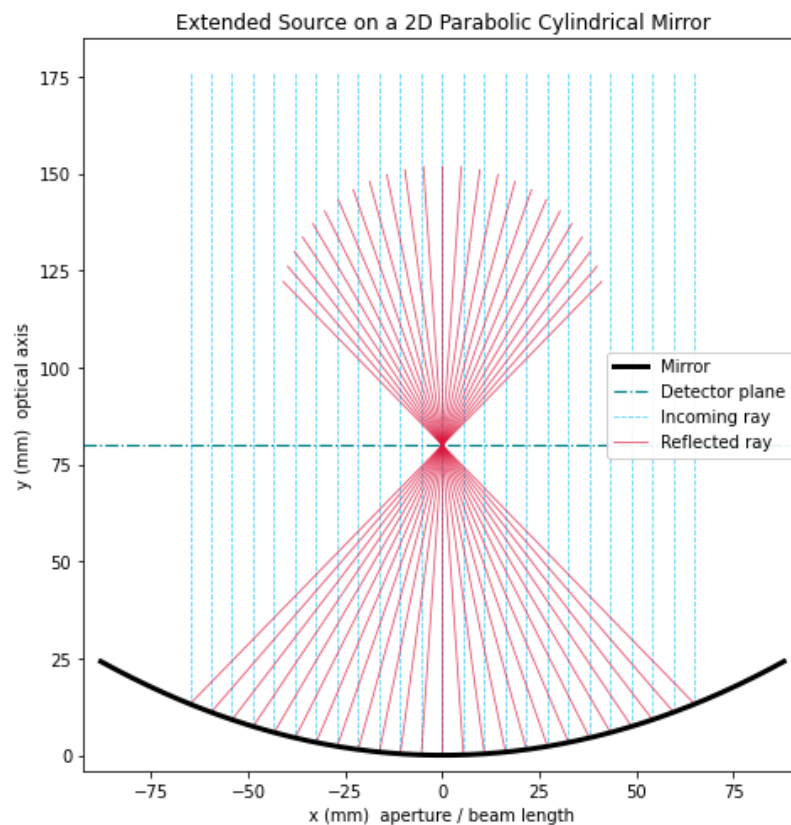


Fig. 9.12: Ray-trace of laser after hitting the parabolic mirror

To create the parabolic mirror (as seen in 8.17), the convex and concave molds (8.16) were used to hold and press the mirror into place. The mirror was first heated with a heat gun to warm the material, followed by a light application of hot glue to the back of the mirror. The mirror was then quickly flipped over and pressed into the convex mold. The accompanying concave piece was applied to the surface of the mirror (cloth was draped over the reflective surface to reduce scratching) with a sufficient amount of weight being used to hold the mirror in place. The mirror was left under this weight for approximately 8 hours to ensure sufficient adhesion to the mount.

After this process was completed, the alignment of the mirror was optimized with the output beam to focus the laser light onto the photodetector. Due to warping caused in the manufacturing process of this mirror, the parabolic mirror was able to focus only about 11 cm out of the 13 cm of the total received laser light onto the photodetector. Additionally, the focused light on the photodetector resembled more of an "S" shape than a dot. This means that there was warping in the mirror, leading to a non-uniform focus. Despite this, the sensor gate subsystem was still able to achieve its goal of a 10 x 10 cm sensing region, with the focused beam being able to be seen below:



Fig. 9.13: Focused laser light onto the photodetector

9.8.1.2 Projectile Speed Detection

To validate the accuracy of the sensor gate subsystem, an experiment was conducted to estimate projectile velocity. For this experiment (named the "Wall Test"), we decided that the Nerf Fortnite BASR-L rifle would be the ideal launch platform due to its high shot-to-shot repeatability. The experimental setup consisted of the rifle mounted at a fixed position at one end of a yard stick (0.9144 meters), oriented toward a target wall. An overhead camera was used to capture each launch event for subsequent frame analysis. Using the previously defined equation for speed (25), the velocity could be calculated for each shot. Seen below is a visual representation (9.14) as well as the recorded results from this experiment:

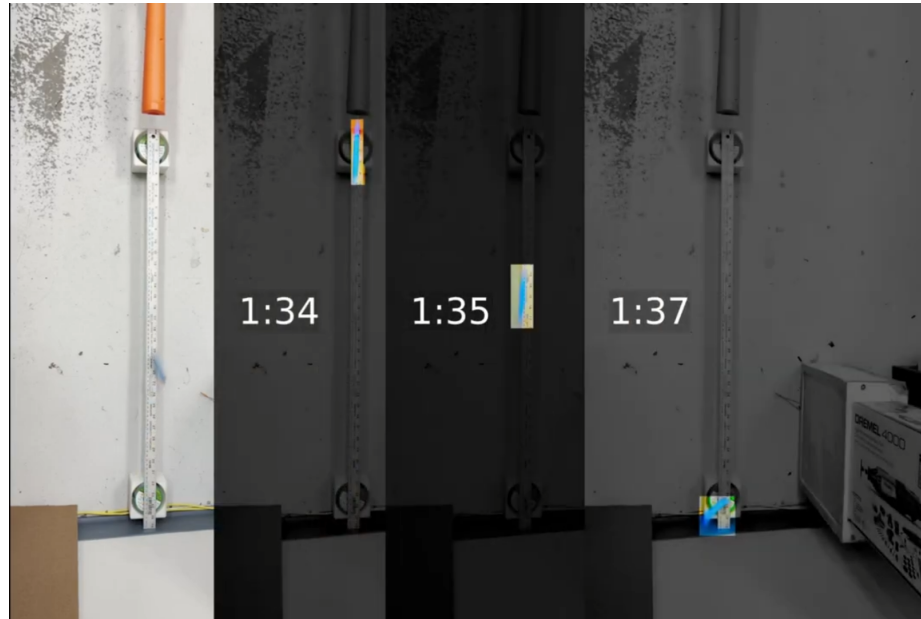


Fig. 9.14: Image displaying the wall test experiment process

TABLE 9.3: Rifle Speed Trials (Wall Test)

Trial	Dart #	t0 (s)	t1 (s)	Speed (m/s)
1	1	1.56	1.62	15.24
1	2	3.84	3.90	15.24
1	3	5.69	5.74	18.29
1	4	7.77	7.82	18.29
1	5	9.61	9.66	18.29
2	1	2.33	2.38	18.29
2	2	4.78	4.82	22.86
2	3	7.23	7.28	18.29
2	4	9.51	9.56	18.29
2	5	11.71	11.75	22.86
Average Speed:				18.59 m/s
Standard Deviation:				2.57 m/s

Using the sensor gate chamber (8.21) and parabolic mirror (8.17), the sensor gate sub-system was able to successfully capture the speeds of incoming projectiles. When the laser is blocked, the trans-impedance amplifier will turn the photo diode resultant drop in current into a resultant drop in voltage, which will then get boosted through two stages of amplification and then pass through a comparator in order to cleanly translate this from analog to digital. Converting to a digital format allows the MCU to quickly identify when the laser has been blocked without having to use the slower ADC. Trimmer potentiometers were used to fine-tune the responsiveness of the TIA. The same Nerf rifle and darts were used in the speed detection experiment to compare with the wall test

results. The table below shows the results from the shots recorded using the sensor gate subsystem:

TABLE 9.4: Rifle Speed Trials (Sensor Gate)

Trial	Speed (m/s)
1	18.111254
2	18.338322
3	18.185192
4	17.199016
5	21.2075316
6	18.791946
7	18.959178
8	19.822006
9	18.77035
10	17.610062
Average Speed:	18.69948576 m/s
Standard Deviation:	1.145550032 m/s

The two measurement methods show similar tendencies but notably different spread and reliability. As seen in figure 9.15, the PTC measured speed has a median of about 18.7 m/s with a fairly tight interquartile range, with its data points clustered closely around the mean. It also has one clear outlier at 21.2 m/s. The hand-calculated speed using the video, by contrast, shows a comparable median at about 18.6 m/s. However, the range of this method is much larger, with a standard deviation of 2.57 m/s compared to the 1.15 m/s captured by the PTC. This suggests that the hand-calculated method is more prone to error while the hardware sensor produces more consistent results. Overall, both methods agree reasonably well on the average speed value, but the hardware measurement appears to be more reliable for repeated trials.

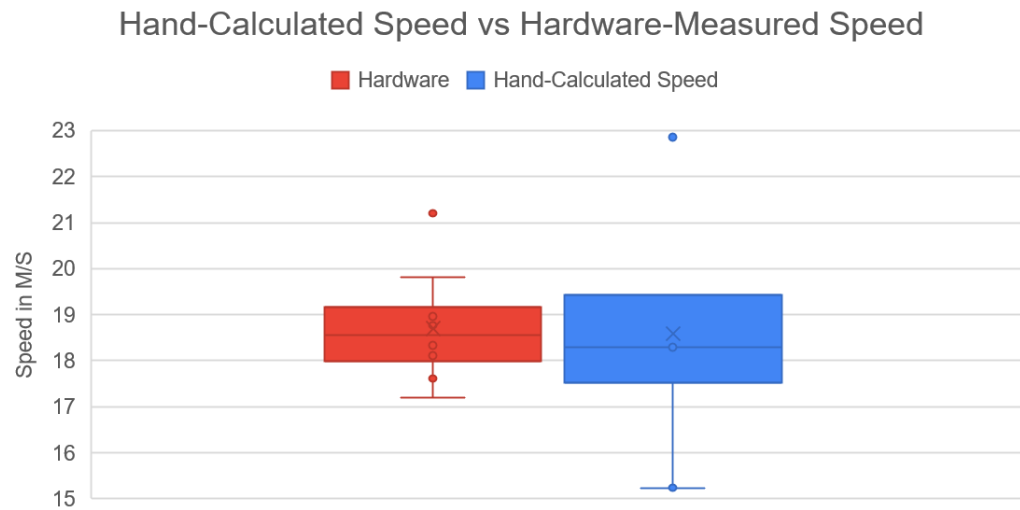


Fig. 9.15: Box and whisker plot comparing the projectile speeds captured using both methods

9.8.2 Imaging Subsystem

9.8.2.1 Strobe LED Discharge Circuit

The strobe discharge circuits were created, and provided good results. While there was slight ringing, strobe pulses under 15 microseconds were achieved, with consistent current. There was less than 4% standard deviation on the maximum current, and less than 0.5% standard deviation on the pulse length.

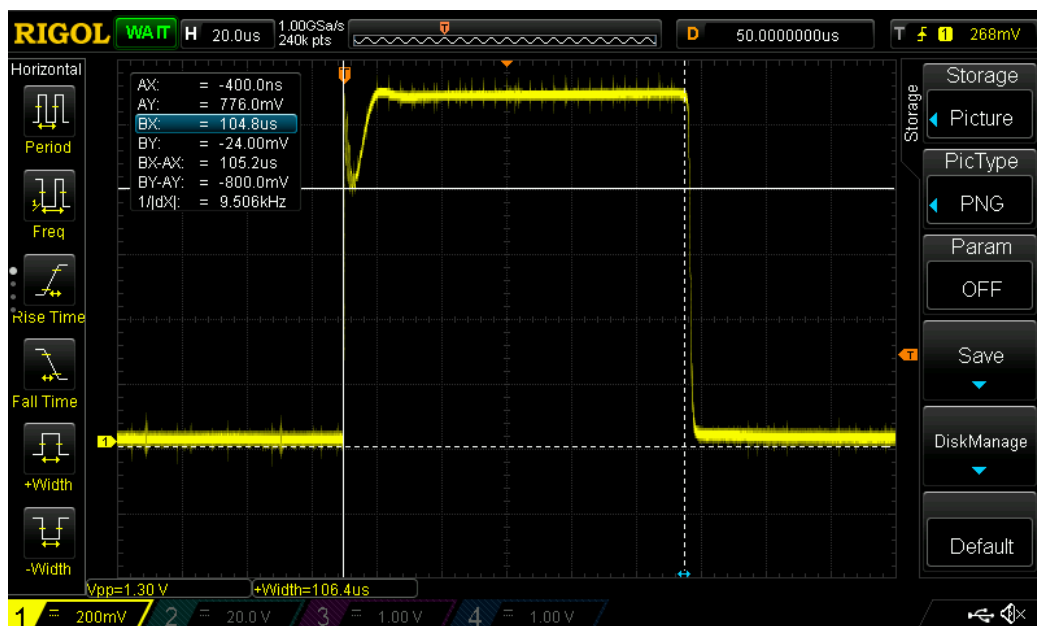


Fig. 9.16: Strobe LED Discharge Pulse Senior Design 2

TABLE 9.5: Strobe Pulse Testing

Trial	Peak Current (A)	Pulse Duration (μs)
1	1.30	106.4
2	1.25	106.0
3	1.26	106.8
4	1.22	106.4
5	1.27	106.4
6	1.25	107.6
7	1.19	106.8
8	1.26	107.6
9	1.15	106.8
10	1.24	106.8
Mean	1.24	106.8
Standard Deviation	0.0428	0.5147
Standard Deviation Ratio	3.45%	0.48%

The current had no noticeable difference between shots except for the beginning peak, otherwise with almost the exact same value and behavior for each pulse. Waveforms between each pulse were nearly indistinguishable from each other. The strobe circuitry was excellent at providing stable, repeatable pulses of light.

9.8.2.2 Camera Testing

During Senior Design 2, the Raspberry Pi Camera Module 2 was replaced with two Raspberry Pi Global Shutter cameras. This eliminated motion distortion that occurred with the rolling shutter cameras and significantly improved centroid accuracy for high-speed projectiles. The cameras operate using synchronized external hardware triggers generated by the ESP32, ensuring both cameras capture images simultaneously. Long-exposure imaging combined with synchronized strobe illumination produces sharp projectile images while allowing reliable background subtraction and centroid detection. Testing demonstrated that this imaging approach consistently produced usable projectile centroids for subsequent three-dimensional trajectory calculations. Removing the IR filter made the cameras pick up the 850 nm IR light used for imaging.

9.8.2.3 Lens Testing

The camera lenses were designed with the express intention of iterative development. To that end, inexpensive lenses were selected so that the initial prototypes could be replaced. The first tested lenses (2x PATIKIL 10 mm focal length 10 mm outer diameter plano-convex) had adequate performance after setting up the correct distances. In the infrared image captured with the custom lens, you can see the shadow cast from the 850 nm IR LED source.

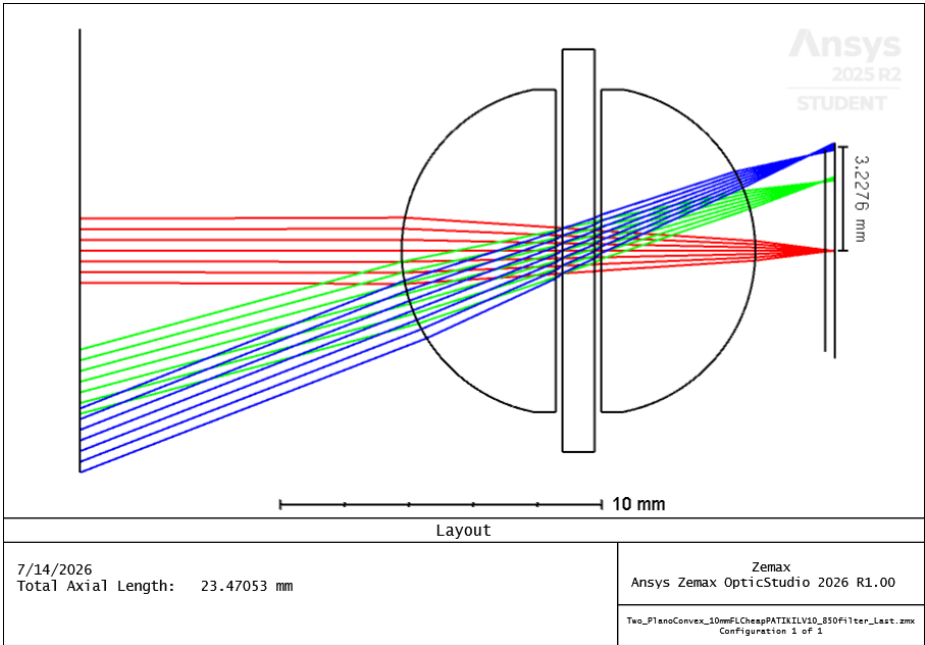


Fig. 9.17: Lens Design Layout

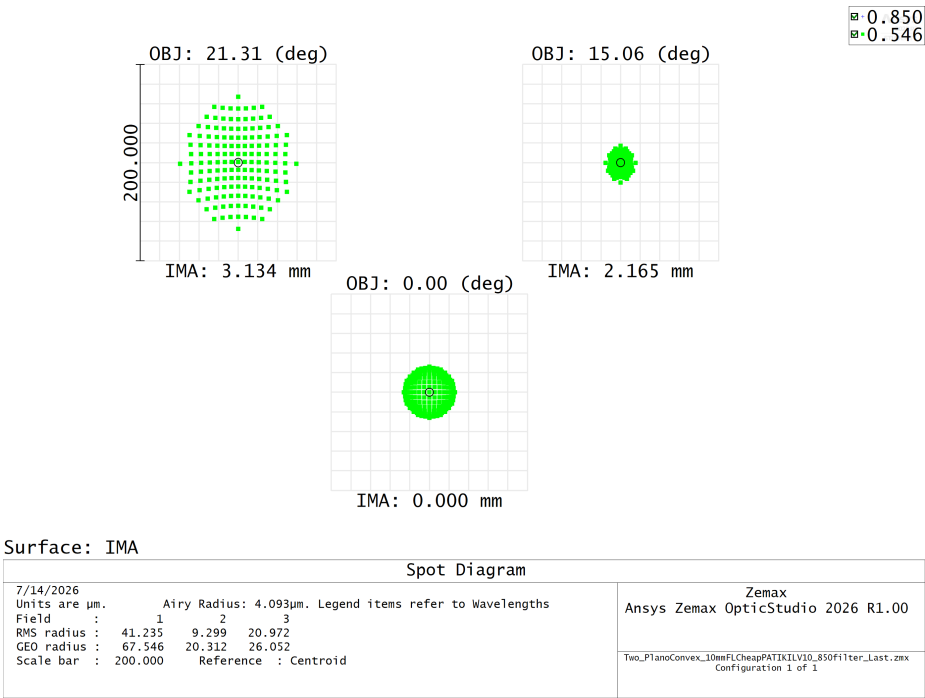


Fig. 9.18: Lens Spot Diagram

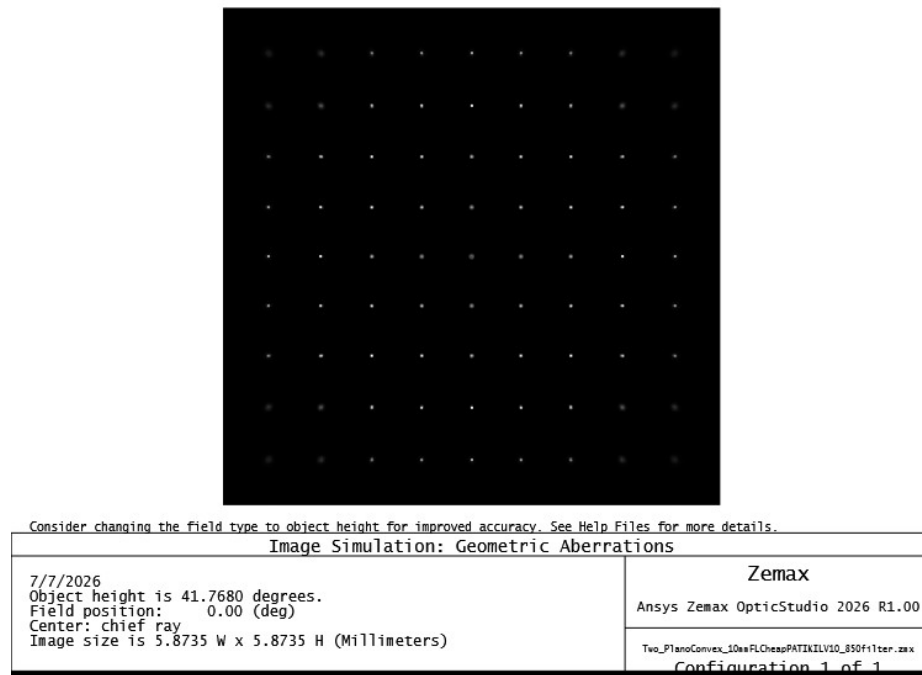


Fig. 9.19: Lens simulated image of a grid of dots



Fig. 9.20: Infrared image captured through custom lens



Fig. 9.21: Setup for IR image (captured with cell phone camera, the global shutter camera and custom lens is visible in the bottom left, and an 850 nm IR LED is visible on the right)

9.9 Software Testing - Senior Design 2

9.9.1 Image Tracking Software

The image processing pipeline was refined during the final implementation of the system. Rather than performing detection directly on raw images, each projectile image is compared against a previously captured reference image taken under identical lighting conditions. The difference between the reference and projectile images is normalized before thresholding is applied to isolate only the moving projectile. Contour detection is then performed on the thresholded image, and the centroid of the largest valid contour is computed using OpenCV image moments.

After centroids are identified in both camera images, stereo triangulation is performed to reconstruct the projectile's three-dimensional position. By repeating this process for two

synchronized strobe exposures, the software determines projectile direction, launch angle, and trajectory while maintaining fast processing times suitable for real-time operation.

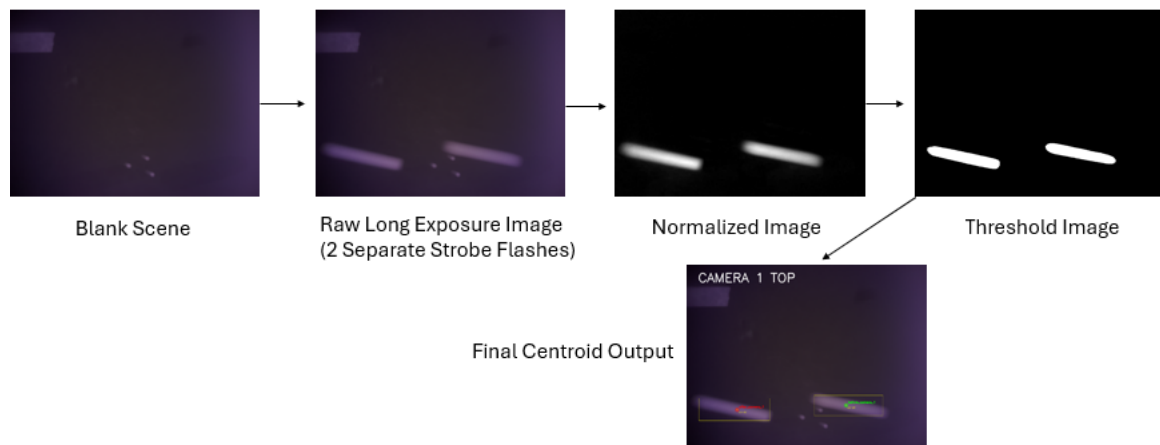


Fig. 9.22: Centroid detection pipeline

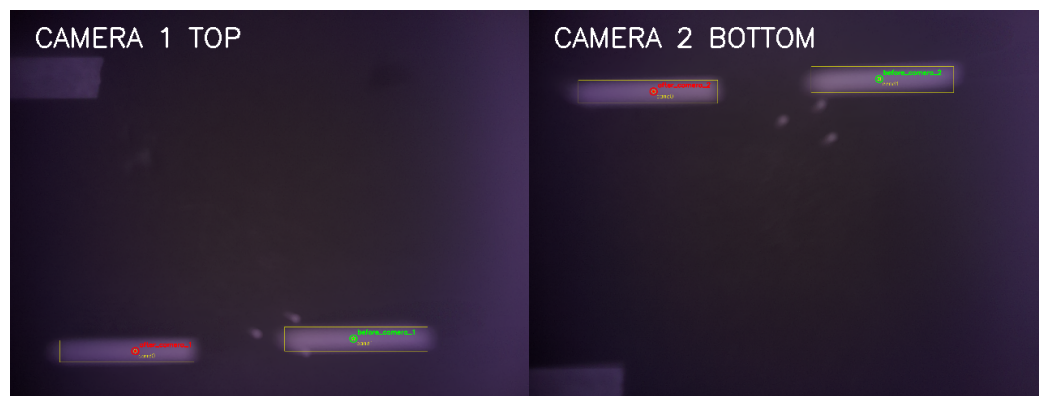


Fig. 9.23: Centroid output of the final demo

9.10 Performance Evaluation - Senior Design 2

9.10.1 Hardware

9.10.1.1 Laser Gate Subsystem

The laser gate subsystem performed well overall, successfully meeting its target of establishing a 10 x 10 cm sensing region despite manufacturing imperfections in the parabolic mirror. The warping introduced during the molding process reduced the effective focal length from the full 13 cm to approximately 11 cm and produced an "S" shaped focal spot rather than a clean point. Despite this, enough of the beam was consistently focused

onto the photodetector to reliably trigger the TIA and comparator stages, confirming that the current mount and molding process is functional.

The system's speed validation further supports the subsystem's reliability and accuracy. Comparing the sensor gate's measured speeds against the independently calculated wall test values showed close agreement in average speed (18.7 m/s vs. 18.58 m/s), giving confidence that the sensor gate is measuring true projectile velocity. More notable, the laser gate produced a much tighter standard deviation (1.15 m/s compared to the hand-calculated 2.57 m/s), suggesting that the hardware-based timing is more precise. This consistency was shown across ten trials, indicating that the TIA, comparator, and MCU timing logic function reliably under realistic firing conditions.

9.10.1.2 Imaging Subsystem

The imaging subsystem successfully took two images of the projectile in flight. With 6 mm airsoft BBs, it was just capable of imaging the projectiles to determine trajectory. With Nerf darts, it consistently got clear images of the projectiles, giving good trajectory information. Strobe performance was good, with excellent consistency and short pulse times. More light would have been advantageous, since there was a trade-off on the light from the strobes reaching the cameras versus the required pulse duration.

There was turn-off delay given by unexpected behavior of the optocoupler in the strobe circuit, that was mostly fixed by reducing the resistance of a pull down resistor from 50 k Ω to 1 k Ω , but it was likely the biggest contributor to the extra 6 microseconds of pulse time the LEDs were on for compared to the time the amount of time the strobe signal was on for.

9.10.2 Software

The software subsystem successfully integrated the laser gate, cameras, strobes, Raspberry Pi 5, micro-controller, and user interface into a single automated system. Throughout testing, the software reliably coordinated communication between the micro-controller and the Raspberry Pi using UART, allowing the laser gate to trigger the image acquisition at the correct time while providing updates throughout the testing process.

The imaging software consistently performed background subtraction, image normalization, thresholding, contour detection, and centroid calculation to identify the projectile in each camera image. Using the centroids detected by both cameras, the software successfully calculated the projectile's three-dimensional position through stereo triangulation. Two strobe exposures produced two independent 3D coordinates, allowing the software to determine the projectile's horizontal angle, vertical angle, and its estimated range. These results were displayed on the display together with the measured projectile speed.

Overall, the software operated reliably during repeated testing and successfully automated the complete measurement process, from trigger detection through image processing and trajectory calculation. The modular software architecture also allowed individual subsystems to be tested independently throughout development, simplifying debugging

and validation. While additional optimization could further reduce processing time, the final implementation met the functional requirements of the prototype and demonstrated successful operation of the Projectile Tracking Chronograph system.

9.11 Overall Integration - Senior Design 2

All of the subsystems have been combined to create the final product of the PTC. The laser gate used a cylindrical lens to expand the central point of the line laser to a height of 13 cm. The laser light was then bounced around the mirror chamber to produce the two horizontal sheets of light, followed by a parabolic mirror that focuses the beam onto the photodetector. Using the same logic as before, the speed is calculated using the beam interruptions. This speed measurement was synchronized with the strobe LED circuits, where the MCU triggers the strobes to flash at two points in time. The cameras and strobes were mounted on a tripod above an absorbent black surface. A visualization was constructed on our UI screen showing the vertical and horizontal angles of the projectile, as well as its speed and estimated range based on the centroid detection algorithm. A secondary screen was also used to display the captured images of the projectile in-flight. The motherboard was housed in a 3D-printed box, with CAT-6 cabling used to connect it to the other boards in the system. The figure below shows the full PTC system.

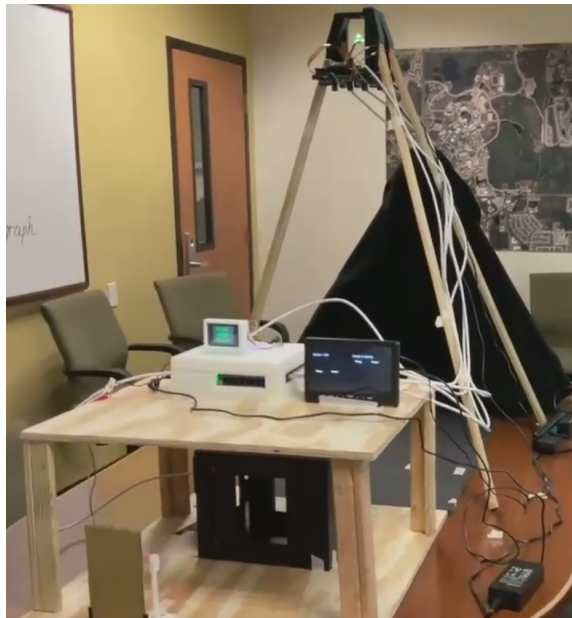


Fig. 9.24: The Fully Assembled PTC System

10 Administrative Content

10.1 Budget

The PTC project is planned with a total expenditure limit of \$1000, as established by the project team to ensure the system can be developed within reasonable cost constraints while still meeting technical objectives. This budget is intended to support the optical, electrical, and computing components that are required for the implementation of the optical projectile measurement system.

10.2 Bill of Materials (BOM)

The BOM provides a comprehensive list of the components that are necessary to design and build the PTC. Maintaining the BOM throughout the project aids in cost awareness and serves as a centralized reference for the various hardware needs of the project. Below is a table containing the components and the costs of each part. The actual cost is the money that was spent for each part, and the budget cost is the estimated amount we were willing to spend for each part.

TABLE 10.1: Bill of Materials

Device	Part #	Distributor	Quantity	Cost (Actual)	Cost (Budget)
Laser Diode	Adafruit 1057	DigiKey	2x	\$17.90	\$50.00
Photodetector	PDB-C171SM	DigiKey	2x	\$8.98	\$50.00
IR LED	AC3535A-YRR-1000 mA	DigiKey	60x	\$60.00	\$100.00
Flat Glass Mirrors	Plymor	Amazon	4x	\$27.94	\$75.00
Acrylic Mirrors	Yuntop	Amazon	1x	\$5.90	\$30.00
Cameras	Global Shutter	Micro Center	2x	\$111.98	\$200.00
Imaging Lenses	PATIKIL 10mm OD 10mm FL Lenses (5)	Amazon	1x	\$5.69	\$100.00
850nm Bandpass Filters	Quanmin 850nm IR Narrow Band-pass Filter (2)	Amazon	1x	\$17.99	\$50.00
Raspberry Pi 5	SC1642	DigiKey	1x	\$65.00	\$100.00
RJ45 Connectors	MTJ-881X1	Mouser	22x	\$8.16	\$25.00
MCU	ESP32-S3-WROOM-1-N8R8	Mouser	1x	\$6.32	\$25.00

Level Shifter	SN74LV8T541-DGSR	Mouser	2x	\$1.10	\$5.00
Analog Multiplexer	CD74HC4067SM	Mouser	2x	\$1.26	\$5.00
Plano-Convex Cylindrical Lens	28X12mm K9 Optical Glass	EBay	1x	\$14.51	\$50.00
Priority Encoder	CD74HC147M96	Mouser	1x	\$0.48	\$5.00
Switching Regulator	LM2576S	Mouser	1x	\$1.59	\$5.00
LDO Linear Regulator	AZ1117	Mouser	2x	\$0.42	\$5.00
Rail-to-Rail Op-Amp	MCP6489	Mouser	1x	\$0.48	\$5.00
Ambient Light Sensor	LTR-329ALS-01	Mouser	1x	\$0.57	\$5.00
Optocoupler	VOM453T	Mouser	10x	\$9.72	\$20.00
SR Latch	CD4043BDR	Mouser	10x	\$5.26	\$15.00
Gate Driver	ZXGD3009DY	Mouser	10x	\$1.68	\$5.00
LDO Linear Regulator	LD1086DTTRY	Mouser	10x	\$13.31	\$20.00
Switching Regulator	R-78K5.0-0.5	Mouser	2x	\$5.70	\$10.00
LCD Display	Waveshare General 2.4inch LCD Display Module	Amazon	1x	\$11.99	\$20.00
3D Print Filament	PLA	Best Buy	3x	\$61.00	\$50.00
Wooden Base Mount	Plywood	Home Depot	1x	\$23.46	\$25.00
Wood Glue	Gorilla Original Wood Glue	Home Depot	1x	\$3.98	\$5.00
Imaging mount tripod legs	1"x2"x8' Wood	Lowe's	3x	\$9.24	\$20.00
PCBs	N/A	JLCPCB	1x	\$89.31	\$100.00
PCB Stencils	N/A	JLCPCB	1x	\$122.70	\$100.00
Sub Total Estimate:				\$713.02	Goal: <\$1000

10.3 Project Milestones

This senior design project involves multiple interconnected technical and documentation tasks, so setting clearly defined milestones with set deadlines is essential for maintaining consistent progress and organization. Clearly scheduled milestones break the project into

manageable phases, helping our team to prioritize either individual or group tasks at any given time. By committing to specific dates, our team is able to ensure that all progress made between each stage of the project is done so in a controlled and predictable manner, thereby minimizing any last-minute risks that may occur. Our project milestone table has a description of each milestone, the start/anticipated end dates, and each milestone's dependencies.

TABLE 10.2: Project Milestones

Milestone Description	Start Date	End Date	Description
Finalize Project Concept and Scope	1/27/26	1/29/26	Define project objectives, requirements, and system boundaries
Divide and Conquer Document Finalization	1/25/26	1/29/26	Complete task allocation and subsystem responsibility documentation
Divide and Conquer Review Meeting	2/3/26	2/3/26	Review and approve task distribution with advisors
Committee Formation and Initial Meeting	1/26/26	1/30/26	Form the advisor committee and discuss project expectations
Find image processing software	2/3/2026	2/13/2026	Research available options
30-Page Draft Development and Revision	2/3/26	2/20/26	Develop an initial technical report and revise based on feedback
Sensor Gate Subsystem Testing	2/6/2026	2/29/2026	Verifying reliable projection detection, timing accuracy, and interrupt behavior
Camera + Strobe Subsystem Testing	2/6/2026	2/29/2026	Validating synchronized strobe activation and image capture during projectile events
60-Page Draft Development and Revision	2/20/26	3/10/26	Expand documentation with detailed design and implementation
Photonic Subsystem Integration	3/1/2026	3/16/2026	Integrating laser, mirrors, and optical sensors into a unified system
Senior Design 1 Midterm Demo	3/3/2026	3/3/2026	Develop a functional photonic subsystem capable of demonstrating one core component of the project

90-Page Draft Development and Revision	3/10/26	3/27/26	Finalize comprehensive system design and analysis documentation
Senior Design 1 Final Report	3/27/26	4/10/26	Submit the completed SD1 design report
Image Processing Program Finalized	4/12/2026	4/21/2026	Completing and validating image-processing algorithms for projectile position and trajectory analysis
Senior Design 1 Final Demo	4/21/2026	4/21/2026	Implement and validate a complete photonic subsystem capable of executing a primary project function
Mini Demonstration Video	4/28/26	4/28/26	Demonstrate early system functionality and progress
CDR Presentation Video	5/15/2026	6/10/2026	Present the finalized design
CDR Presentation Slide	5/15/2026	6/10/2026	Prepare slides summarizing system design and progress
Senior Design 2 Midterm Demonstration Video	5/15/2026	6/27/2026	Show system integration and functional progress
8-Page Conference Paper	6/19/2026	7/7/2026	Prepare a concise conference-style technical paper
Senior Design 2 Final Report	5/15/2026	7/28/2026	Submit the final report covering implementation and testing
Final Presentation Video	6/10/2026	7/20/2026	Present final system design and results
Final Presentation Slide	6/10/2026	7/20/2026	Prepare slides that summarize final project outcomes
Final Demonstration Video	7/22/2026	7/22/2026	Demonstrate completed system functionality

10.4 Hardware Milestones

The hardware portion of this senior design project involves several design and testing steps, making explicitly defined hardware milestones essential for maintaining steady progress. Since there are many interdependent portions of this project, having set deadlines for milestones such as gathering components and prototyping will ensure that

everyone in the group is able to make consistent advancements in their respective portions. Below is the hardware milestone table, with the start/anticipated end dates as well as a description of each milestone.

TABLE 10.3: Hardware Milestones

Hardware Milestone	Start Date	End Date	Description
Component Selection	1/26/2026	2/8/2026	Making a Bill of Materials
Gather Electronic Components (Power Supply, Capacitors, MOSFETs, etc.)	2/6/2026	2/21/2026	Ordering from a manufacturer
Gather Optical Components (Laser Diodes, Photodetectors, Cameras, etc.)	2/6/2026	2/21/2026	Ordering from a manufacturer
System Testing	2/6/2026	2/29/2026	All components are tested and work
Complete Project with Prototype Board	3/16/2026	5/15/2026	Assemble the components for a prototype
PCB Testing	5/15/2026	6/18/2026	Creating and ordering a customized PCB
Test Prototype with PCB	6/18/2026	7/1/2026	Using the customized PCB for the design
Sensor Gate Speed Detection	6/18/2026	7/04/22	Successfully detected the speed of a previously measured projectile using the sensor gate
Projectile Image Capture Using Strobes	6/18/2026	7/02/2026	Capturing images using the designed strobe modules
Optical Subsystems Integration	7/04/2026	7/10/2026	Getting images of the projectile in-flight from the imaging subsystem triggered by the sensor gate subsystem
Centroid Detection Algorithm Completion	6/24/2026	7/15/2026	Accurately detecting of the centroids of the projectiles in the captured images from the optical subsystems to allow for trajectory analysis
User-Interface System Integrated	6/24/2026	7/20/2026	Integrating the graphical user interface with back-end processing for data display
Finalize Prototype	7/10/2026	7/20/2026	Finalize the project using the PCB boards

10.5 Work Distribution

The work distribution table provides an outline of the allocation of responsibilities among the team members of the PTC project. This ensures balanced contributions as well as clear ownership of the project tasks. It identifies the primary roles for members across hardware and software development, testing, and system integration to promote accountability and collaboration.

TABLE 10.4: Work Distribution of Group Members

Name	Major	Responsibilities
Austin Stoetzer	Optical Engineering	Sensor Gate Design and Implementation Project Lead Administrative Documentation Photonic System Integration with Electronics and Software
Blake Rainwater	Optical Engineering	Camera and Strobe System Prototype & Technical Lead Projectile Trajectory Visualization Photonic System Integration with Electronics and Software
Mathew Aranibar	Electrical Engineering	PCB Design MCU Selection and Implementation Component Research Lead Photonic System Integration with Electronics
Gianni Angelone	Computer Engineering	Software and UI Integration Lead Website Design and Management Projectile Trajectory Visualization Photonic System Integration with Software

11 Conclusion

Through the Projectile Tracking Chronograph (PTC) project, four undergraduate students from the ECE/CREOL degree tracks applied and expanded their skills by tackling the complexities of various integrated optical and electronic technologies. In this project, various aspects of their knowledge base were used, such as laser-based optical sensing, high-speed image capturing PCB design, and embedded system programming. The

primary goal of the PTC is to provide comprehensive ballistic measurements that go beyond traditional chronographs by combining precise velocity measurements with real-time trajectory estimation in a single system. This report thoroughly documents the work conducted by the four students across the 2026 Spring and Summer semesters, highlighting their time and dedication spent experimenting with both familiar and unfamiliar technologies to enhance project outcomes. The team confronted many problems throughout the development process, with each challenge requiring careful research, testing, and prototyping to overcome.

11.1 Technical Achievements

The PTC integrates several key subsystems that work together to meet the requirements for its measuring capabilities:

- **Laser Gate Velocity Measurement:** The laser gate subsystem uses a system of collimating and focusing parabolic mirrors to expand a line laser beam into a specified sensing region and then focus the beam down to a point to be detected on a photodetector. This system is used to achieve precise time-of-flight measurements that enables the imaging subsystem to accurately identify the appropriate times to flash the strobe LED circuitry.
- **High-Speed Imaging and Strobe LEDs:** The imaging subsystem captures the projectiles in flight using a synchronized strobe illumination timed to the projectile's passage through the measurement area. The usage of monochrome LEDs for the strobe mixed with a high-contrast background allows for clear images to be taken for position extraction, with this approach enabling the capture of objects traveling at velocities exceeding over a hundred meters per second.
- **Trajectory Reconstruction:** The PTC utilized image processing algorithms running on the embedded platform to extract spatial positional data from the captured images to compute trajectory parameters such as launch angle, flight path, and predicted point of impact. The processing pipeline was optimized to deliver results in a short amount of time to allow for this device to be used consistently and efficiently.
- **User Interface/Visualization:** The graphical interface presents accurate velocity data and a visual trajectory plot to the user, making the system easy to understand. The design of the interface prioritized clarity and accessibility, making the system especially useful for people such as hobbyists or educators.

11.2 Professional Development

The interdisciplinary nature of the PTC required each member to develop not only their own skills related to their major, but also skills related other aspects of engineering and

design. Various aspects of engineering such as circuit design, optical design, and software design were shared among the team members, with each person learning more about each other's proficiencies. Also, many facets of project development and documentation were learned for each member. Several key lessons emerged from this project, such as:

- 1) **Early Testing and Prototyping:** Subsystems that functioned in isolation or in other testing processes sometimes exhibited unexpected behavior in practice. The proper allocation of time for integration and early testing allowed the team to identify and resolve issues that may have otherwise proved detrimental in the long run.
- 2) **Documentation Matters:** Maintaining detailed records throughout the project, whether it be early prototype sketches or an accurate BOM, provided invaluable when revisiting earlier work or troubleshooting unexpected system behavior. The discipline of thorough documentation, while very time-consuming, overall benefited the development process for the PTC.
- 3) **Communication is Key:** Communication, whether it is between team members or advisors/overseers is extremely important. Learning how to set dates for meetings and talk about everyone's needs for a project enables a smoother experience for all of those involved. Good communication has helped those involved with the PTC project fully understand what was expected of them at every point of the project's lifespan, which creates a much more lax, but still productive, environment.

11.3 Future Work

While the PTC will meet the design requirements as documented in this report, there are definitely improvements that can be made to the system, such as:

- **Higher Velocity Sensing:** The current system is optimized for projectiles around or less than 100 meters per second, but with modifications to the strobe timing, optical gate, and image processing algorithms we can surely improve the sensing speed of the system.
- **Multi-shot Analysis:** Our system is currently built to do statistical analysis for one projectile at a time, but further development of the project could allow for the ballistic profiles of multiple objects to be measured in a single measurement window.
- **Wireless Connectivity for Data Exporting:** By enabling the system to be controlled via WiFi, the user could potentially control the system through the use of an app, disregarding the need for the user to manually initialize the system.

11.4 Closing Remarks

The Projectile Tracking Chronograph system demonstrates how optical, electrical, and computer engineering disciplines can be combined to create a practical and useful measurement tool. Throughout its development, the project has pushed the team to apply concepts from their time at the University of Central Florida in a meaningful way. From initial concept development to system design and testing, the PTC has played a significant role in strengthening each member's problem-solving capabilities. Ultimately, this project highlights the professional and technical skills the members of the PTC team have developed and refined in preparation for their future engineering careers.

Appendix A - Citations

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Appendix B - Useful Tools

[1] EdrawMax Online

[2] Draw.io

[3] Microsoft PowerPoint

[4] Google Docs

[5] Digikey

[6] Google Search Engine

[7] Ultra Librarian

[8] Snap Magic Search

[9] OnShape

Appendix C - AI Use Prompts and Outcomes

Case Study 1

[1a] Case Study 1 Prompt

Prompt: “Design a real-time image processing pipeline capable of detecting a high-speed projectile using three sequential images captured with synchronized strobe illumination. The system will run on a Raspberry Pi using Python and OpenCV. Explain the processing stages required to detect the projectile, calculate velocity, estimate trajectory angle, and display a real-time visualization suitable for a user interface.”

[1b] Case Study 1 ChatGPT Outcome

“To implement a real-time projectile tracking system using Python and OpenCV, the processing pipeline should be divided into structured stages. First, synchronized image acquisition must capture three frames illuminated by a short-duration strobe to freeze projectile motion. These frames should be timestamped to preserve accurate timing intervals.

Next, preprocessing should be performed to improve detection reliability. This includes grayscale conversion, Gaussian filtering to reduce sensor noise, and intensity normalization to compensate for lighting variation. Background subtraction or frame differencing can then be used to isolate moving objects between consecutive frames.

After motion isolation, contour detection can identify candidate objects. The projectile position may be estimated by calculating the centroid of the detected contour. Tracking the centroid across the three frames allows displacement measurements to be computed in pixel space. Using calibration data, pixel displacement can be converted into real-world distance.

Velocity is calculated by dividing displacement by the known time interval between frames. The launch angle can be estimated using linear regression or slope calculations between detected projectile positions. Finally, visualization may be implemented using OpenCV drawing functions or a plotting library to animate projectile motion in real time for display on a graphical user interface.

Performance optimization techniques such as region-of-interest cropping, multithreading, and reduced image resolution may be necessary to maintain real-time execution on embedded hardware platforms.”

[1c] Case Study 1 Google AI Outcome “A projectile tracking system using sequential images can be implemented through several computer vision techniques. Motion detection may be achieved using optical flow, frame differencing, or feature-based tracking methods. Each technique provides advantages depending on lighting consistency and object speed.

The system should begin by capturing synchronized images and converting them into grayscale format for computational efficiency. Edge detection or threshold segmentation may then be used to identify moving objects within each frame. Object tracking algorithms such as Kalman filtering or template matching can improve stability across frames.

Velocity estimation can be determined by measuring positional changes over time, while trajectory estimation may involve curve fitting or predictive modeling. Visualization can be implemented through graphical overlays or animation frameworks capable of updating in real time.

While multiple approaches exist, system performance depends heavily on hardware capability, camera synchronization accuracy, and image noise conditions.”

[1d] Case Study 1 DeepSeek Outcome “A practical implementation of projectile tracking should prioritize computational efficiency and robustness against noise. Instead of relying solely on contour detection, adaptive thresholding combined with morphological filtering can improve detection reliability under varying illumination.

The algorithm may store detected projectile coordinates in a buffer and apply predictive tracking methods such as Kalman filtering to estimate motion between frames. Parallel processing techniques and vectorized operations are recommended to maintain real-time performance.

For visualization, a physics-based animation model can simulate projectile motion using calculated velocity and angle parameters. Rendering may be performed using OpenCV drawing routines or a lightweight graphics framework. Optimization strategies such as

GPU acceleration or batch processing can further improve responsiveness.”

Case Study 2

[2a.1] Case study 2 Prompt:

”I would like your assistance in making my document editing in LaTeX more streamlined. I am going to provide you a table that I made that I will call the standard table format (STF for short). Whenever I upload a table going forward, I would like you to convert it to STF. Here is the reference STF:”

TABLE .1: Comparison of IR LEDs - Case Study

Parameter	AG3535C-YRR-1000mA-H1	AC3535B-YRR-1000mA-H1	AC3535L-YRR-1000MA / AC3535A-YRR-1000MA
Manufacturer	Solidlite	Solidlite	Solidlite / Solidlite
Price (\$)	1.1	1	1 / 1
Current - DC Forward (If) (Max)	1 A	1.5 A	1.5 A / 1.5 A
Radiant Intensity (Min @ If)	430 mW/sr @ 1 A	900 mW/sr @ 1.5 A	175 mW/sr @ 1 A / 550 mW/sr @ 1 A
Viewing Angle	120°	60°	150° / 90°
mW/\$	1228.08	757.61	814.97 / 1012.17
mW/\$ (wall-plug)	2454.55	4650	4650 / 4950

[2a.2] Case Study 2 Additional Prompt:

”Convert to STF:”

TABLE .2: Strobe Illumination Wavelength - Original

Feature	UV	Blue	Red	IR
Cost	Moderate	Moderate	High	Low
Longevity	Low	Moderate	High	High
Diffraction-limited Resolution	High	Moderate	Low	Low
High Power Common	Yes	Yes	No	Yes
Visible	No	Yes	Yes	No
IMX296 Responsivity	Low (<0.5)	Moderate (0.5-0.8)	High (0.9-1)	Moderate (0.5-0.9)

[2b] Case Study 2 - ChatGPT’s Response

TABLE .3: Strobe Illumination Wavelength - ChatGPT

Feature	UV	Blue	Red / IR
Cost	Moderate	Moderate	High / Low
Longevity	Low	Moderate	High / High
Diffraction-limited Resolution	High	Moderate	Low / Low
High Power Common	Yes	Yes	No / Yes
Visible	No	Yes	Yes / No
IMX296 Responsivity	Low (< 0.5)	Moderate (0.5–0.8)	High (0.9–1) / Moderate (0.5–0.9)

”Important Note: Your STF only supports 4 columns, but your original table had 5 (UV, Blue, Red, IR). So I combined:

- Red + IR → one column (Red / IR)

If you’d rather:

- Expand STF to 5 columns, or
- Keep all wavelengths separate

I can adjust your standard format accordingly.”

[2c] Case Study 2 - Copilot’s Response

TABLE .4: Strobe Illumination Wavelength - Copilot

Feature	UV	Blue	Red	IR
Cost	Moderate	Moderate	High	Low
Longevity	Low	Moderate	High	High
Diffraction-limited Resolution	High	Moderate	Low	Low
High Power Common	Yes	Yes	No	Yes
Visible	No	Yes	Yes	No
IMX296 Responsivity	Low (<0.5)	Moderate (0.5-0.8)	High (0.9-1)	Moderate (0.5-0.9)

”If you’d like this table to use different column widths or if you want me to standardize captions or labels as well, I can adjust the STF template accordingly.”

Case Study 3: Metaprompt

Prompt 1

Prompt: "My undergraduate senior design project is a combination of optics, photonics, electrical engineering, and software used to measure the speed and trajectory of a projectile. I need to do a case study comparing how well different AI works for my senior design project. What are some uses for AI?"

Used the "Thinking" selection in the drop-down (rather than the "Fast", "Pro", or "Deep Research").

Gemini Response

Integrating AI into a high-speed projectile tracking system offers several ways to enhance precision, especially where traditional mathematical models might struggle with environmental noise or complex aerodynamics. For your case study, you can categorize AI applications into signal processing, computer vision, and predictive modeling. Here are four primary use cases for AI in your project:

1. High-Speed Object Detection and Tracking

If your project uses optical sensors or high-speed cameras, AI can be used to identify the projectile against a cluttered or low-contrast background.

- **The AI Role:** Using Convolutional Neural Networks (CNNs) or "You Only Look Once" (YOLO) architectures to localize the projectile in each frame.
- **Why use AI?** Traditional frame-differencing can fail if the camera shakes or if lighting changes. AI models can be trained to recognize the specific geometry of your projectile, ignoring "noise" like shadows or debris.
- **Comparison Point:** You could compare a **heavyweight model** (e.g., YOLOv8) against a **lightweight model** (e.g., MobileNet) to see which balances accuracy and processing latency better for real-time tracking.

2. Trajectory Prediction and Extrapolation

Projectiles often follow a parabolic path, but variables like air resistance (drag), wind, and spin create non-linear deviations.

- **The AI Role:** Recurrent Neural Networks (RNNs) or Long Short-Term Memory (LSTM) networks are designed for sequential data. They can "learn" the flight characteristics of the projectile.
- **The Math:** While a standard kinematic equation might look like $y = y_0 + v_{0y}t - \frac{1}{2}gt^2$, an AI model can account for the drag coefficient C_d which

changes dynamically with speed.

- **Comparison Point:** Compare the accuracy of a **Linear Regression** model against a **Deep Neural Network (DNN)** when predicting the final impact point based on the first 10% of the flight path.

3. Sensor Fusion (Optics + Electrical)

In a system using both photonics (like laser gates) and electrical sensors (like acoustic or Hall effect sensors), the data often arrives at different rates and with different error margins.

- **The AI Role:** A Neural Network can act as an advanced “Kalman Filter.” It learns which sensor is more reliable at specific segments of the trajectory.
- **Why use AI?** It can resolve conflicts. For example, if an optical sensor is blinded by a flash, the AI can weigh the electrical sensor data more heavily for that millisecond.
- **Comparison Point:** Compare a **Traditional Kalman Filter** (mathematical) against a **Gated Recurrent Unit (GRU)** for multi-sensor data integration.

4. Signal Denoising in Photonics

Photonics sensors can be incredibly sensitive but prone to “shot noise” or thermal interference in the electrical components.

- **The AI Role: Autoencoders** can be used to “clean” the raw signal. By training a network on “clean” vs. “noisy” signal pairs, the AI learns to reconstruct the true pulse of the projectile passing a sensor.
- **The Benefit:** This allows you to use lower-cost hardware because the software (AI) compensates for the lack of hardware shielding or high-end filtering.
- **Comparison Point:** Compare **Wavelet Transforms** (traditional) against **1D Convolutional Neural Networks** for signal-to-noise ratio (SNR) improvement.

Suggested Case Study Framework

To make your case study robust, I recommend comparing these models across three specific metrics:

1. **Inference Latency:** How many milliseconds does it take to process one data point? (Critical for high-speed projectiles).
2. **Computational Cost:** Can the AI run on an edge device (like a Raspberry Pi or Jetson Nano) or does it require a desktop GPU?

3. **Robustness:** How does the accuracy drop when you introduce artificial “noise” (e.g., dimmed lighting or simulated wind)?

Would you like me to help you draft a specific comparison table for two of these architectures (e.g., YOLO vs. a standard Kalman Filter)?

Grok Response

AI has numerous practical applications in your senior design project for measuring projectile speed and trajectory. Your system—integrating optics/photonics (e.g., high-speed cameras, lasers, or interferometric sensors), electrical engineering (sensors, data acquisition), and software—already generates rich data like image sequences or time-series sensor readings. AI excels at handling noise, sparse/occluded data, real-time processing, and fusing multi-modal inputs (e.g., video + IMU), which classical methods often struggle with in dynamic, real-world conditions like varying lighting, high speeds, or environmental interference.

Here are some targeted, implementable uses for AI in your project. These are drawn from established applications in ballistics, sports analytics, robotics, and defense systems, making them suitable for an undergraduate case study. You can compare different AI approaches (e.g., traditional computer vision vs. machine learning vs. deep learning vs. physics-informed models) on metrics like accuracy (position/velocity error), latency (for real-time use), robustness (to noise/lighting), computational cost (CPU/GPU/embedded), and data efficiency.

1. Object Detection and Tracking in Optical/Video Data

- **How it works:** Use computer vision AI to automatically locate the projectile in each frame from your high-speed camera(s) or photonic sensors. Models like YOLO (You Only Look Once) series detect the projectile as a bounding box or keypoint, then pair with trackers (e.g., DeepSORT or ByteTrack) to follow it across frames.
- **Benefits for your project:** Replaces manual or threshold-based detection (which fails under blur, glare, or background clutter). Enables precise 2D/3D position extraction for velocity calculation via frame timestamps.
- **Real-world examples:** Applied to ball tracking in sports broadcasts (e.g., via AWS deep learning pipelines) and high-speed cannon projectile video analysis for 3D pose/velocity.
- **Case study angle:** Compare YOLOv8/v11 (fast, real-time on edge devices) vs. classical OpenCV (background subtraction + contour detection) vs. older detectors like Faster R-CNN. Measure mAP (mean average precision) and FPS.

2. Trajectory Prediction and Smoothing from Noisy/Sparse Data

- **How it works:** Feed detected positions (or raw sensor data) into recurrent networks like LSTM/GRU or transformers to predict future positions and smooth noisy measurements. Physics-Informed Neural Networks (PINNs) add physical constraints (e.g., projectile motion equations with drag/Magnus effects) directly into the loss

function.

- **Benefits for your project:** Handles gaps in optical data (e.g., projectile exiting frame or sensor occlusion) and predicts full trajectories even from partial observations. Improves speed/trajectory estimates beyond simple least-squares fitting.
- **Real-world examples:** LSTM for GNSS-denied mortar trajectory estimation from IMU data; PINNs for 3D table tennis ball kinematics from video; hybrid physics-ML for non-rigid projectile launch modeling.
- **Case study angle:** Compare LSTM/PINNs (data-efficient, physics-aware) vs. pure data-driven neural nets vs. traditional Kalman filters. Test on simulated + real projectile data for RMSE in position/velocity.

3. Velocity/Speed Estimation and Sensor Fusion

- **How it works:** AI processes time-stamped positions or optical flow from your photonics setup (e.g., combining camera frames with laser Doppler or high-speed video). Regression models or optical flow + deep learning estimate instantaneous speed; multi-sensor fusion (e.g., via neural networks) integrates EE sensor data.
- **Benefits for your project:** More accurate than manual frame differencing, especially at high velocities where blur occurs. Real-time edge AI can output speed on-device.
- **Real-world examples:** Vision AI for ball speed/direction in sports; deep learning + optical flow for velocity in high-speed scenarios; automated CV for cannon projectile initial velocity/orientation.
- **Case study angle:** Benchmark CNN-based optical flow vs. traditional Lucas-Kanade vs. hybrid ML (e.g., Random Forest on physics features). Evaluate error vs. ground-truth chronograph data.

4. 3D Trajectory Reconstruction from 2D Optical Views

- **How it works:** Monocular or stereo camera setups use AI (e.g., CNNs or PINNs) to lift 2D image coordinates to 3D space, incorporating camera calibration and projectile dynamics.
- **Benefits for your project:** Reduces hardware needs (no multi-camera rig required) while leveraging your existing optics. Corrects for perspective/distortion in photonic imaging.
- **Real-world examples:** Monocular 3D projectile localization from video; patent methods for golf/baseball trajectories from single-camera 2D images.
- **Case study angle:** Compare PINN-based 3D lifting vs. geometric triangulation + ML refinement. Assess reconstruction error in lab tests.

5. Image Enhancement, Denoising, and Anomaly Detection (Photonics-Focused)

- **How it works:** Generative or convolutional models denoise low-light/high-speed photonic images, enhance contrast, or flag anomalies (e.g., projectile wobble or sensor failure).
- **Benefits for your project:** Improves data quality from optical/EE sensors before downstream processing, especially in outdoor or variable conditions.

- **Real-world examples:** AI super-resolution and denoising in electro-optical systems for embedded tracking.
- **Case study angle:** Compare autoencoders or diffusion models vs. classical filters (e.g., Gaussian). Quantify PSNR improvement and downstream tracking accuracy.

6. Optimization, Simulation, and Post-Processing (Software Layer)

- **How it works:** Train ML models on your collected dataset to optimize launch parameters, simulate trajectories (hybrid physics + ML), or generate ballistic tables/reports.
- **Benefits for your project:** Extends the system beyond measurement to predictive analytics (e.g., “what-if” trajectory adjustments).
- **Real-world examples:** Neural nets for optimal launch angle prediction; extreme learning machines for impact point forecasting; hybrid ODE solvers + Random Forest for bullet velocity.
- **Case study angle:** Compare data-driven ML vs. physics-only simulation vs. hybrid approaches on prediction error and training data needs.

Suggestions for Your AI Case Study

- **AIs to compare:**
 - Baseline: Non-AI (OpenCV classical CV + Kalman filter).
 - Traditional ML: SVM/random forests for detection/regression.
 - Deep learning: YOLO + LSTM (end-to-end).
 - Advanced: PINNs or transformer-based (physics-aware).
 - Edge vs. cloud: TensorFlow Lite/PyTorch Mobile vs. full models.
- **Implementation tips:** Use open-source tools (Ultralytics YOLO, PyTorch for PINNs/LSTM, OpenCV). Generate synthetic data via physics simulators (e.g., projectile motion equations in Python) to augment limited real shots. Test in your lab with a safe projectile launcher (e.g., air cannon or slingshot).
- **Evaluation framework:** Collect ground-truth via high-precision sensors or multiple synchronized cameras. Metrics: MAE/RMSE for speed/trajectory, inference time (ms/frame), power consumption (for embedded EE), generalization (different lighting/speeds).
- **Feasibility for undergrad:** Start small—prototype detection/tracking on your existing video data. Many models train in hours on a laptop GPU. This adds strong “AI integration” value to your report/presentation.

These uses can make your system more accurate, autonomous, and scalable while providing excellent material for a comparative case study (e.g., “AI boosts velocity accuracy by X% with Y ms latency”). If you share more details (e.g., specific sensors, data format, or hardware constraints), I can refine these further or suggest code starters!

Case Study 4

UART

To get more information on UART, I queried: "UART Standard".

I then queried: "is UART a standard like USB"

Responses

UART, response 1

UART, or Universal Asynchronous Receiver-Transmitter, is a hardware communication protocol used for asynchronous serial communication, allowing data to be transmitted one bit at a time over two wires. It requires both the transmitting and receiving devices to be configured with the same baud rate, data bits, parity bits, and stop bits for successful communication. [Links to: [Analog.com \(UART\)](https://www.analog.com/en/products/uart.html), and [Wikipedia.org \(UART\)](https://en.wikipedia.org/wiki/UART)]

UART, response 2

UART is not a standard like USB; rather, it is a hardware communication protocol used for asynchronous serial communication. USB, on the other hand, is a standardized protocol that manages data transfer between devices and includes features like device detection and hot-plugging.