Projectile Tracking Chronograph

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ABSTRACT

An electrical, computer, and photonics engineering project, the Projectile Tracking Chronograph is a device that measures a projectile's speed and accumulates data from precise imaging using two global shutter cameras and a Raspberry Pi. It then uses this data to calculate and extrapolate trajectory data of the projectile, presenting this data in an intuitive manner to the end user with three dimensional plots and with a robust and original hardware design.

Keywords: Chronograph, projectile tracking, stereoscopic imaging, global shutter camera, transimpedance amplifier, photodiode, infrared strobing, laser gate, trajectory estimation, embedded systems, image processing

1. INTRODUCTION

The Projectile Tracking Chronograph (PTC) was conceived as a way to make measuring high speed projectiles' velocity and predicting their flight path easier, blending optical lenses and imaging with cheap electronics to deliver accurate readings while also being cost effective. Implemented with two computational units, the PTC accurately measures speed with a dedicated embedded system powered by an ESP32 microcontroller, and this system works in tandem with a Raspberry Pi Model 5 and two Global Shutter cameras to capture still frames of the projectile in motion without blur or shutter distortion, regardless of the projectile's speed. The PTC's custom hardware operates on infrared strobing and imaging, eliminating disorienting bright flashes while still providing crisp images. Additionally, the PTC boasts easily detachable, diagnosable, and replaceable hardware components with quick-disconnect strobe, sensor, and computational modules. With built-in hardware peripherals, the user may easily check the status of any strobe module to assess damage, then easily hot-swap the module. After firing a projectile, the PTC will quickly analyze the projectile's velocity and quickly display information on a touchscreen for easy viewing of statistics and predictive analysis of the projectile's collision with a set target.

2. SYSTEM CONCEPT

At the front end of the device, where a user may launch a projectile into the PTC, lies a laser gate system. When the launched projectile passes through this laser gate, it will occlude part of the laser beam, twice, and a sensor composed of a photodiode and transimpedance amplifier will be able to detect these occlusions, allowing our microcontroller to read these signals and calculate the projectiles speed. It can be noted that the laser source is actually a line laser, which after collimation produces a thin sheet of laser light that can be bounced around the laser gate chamber using mirrors. At the opposite end of the laser gate, the thin laser sheets are then focused back down into a small beam upon the photodiode.

After this laser gate, there lies a dark imaging chamber with two cameras and a number of strobe modules. After the projectile's speed is calculated, the cameras are activated in a long exposure mode and the strobe modules are activated in two separate instances. Since the imaging chamber is dark and non-reflective, the cameras won't be able to see anything until the strobe modules light up the chamber, briefly illuminating the chamber and the projectile for the cameras to see in two separate positions. With these two image frames collected, the PTC can then begin estimating trajectory data and predicting the projectile's point of collision with a target. The concept design of the PTC system can be seen in Fig. 1.

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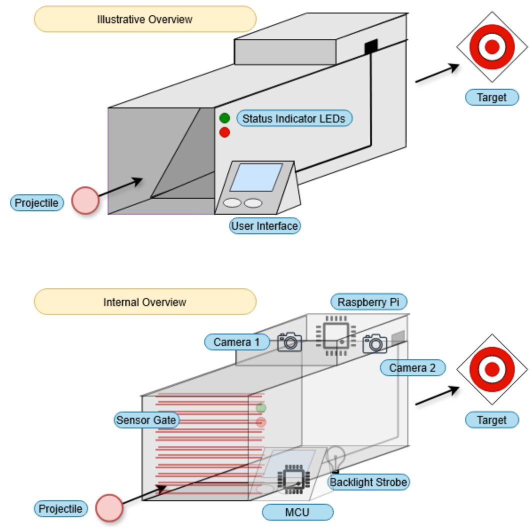

Figure 1. Concept art of device.

3. COMPONENTS

3.1 Microcontroller

The microcontroller is the brains and heart of the PTC, and due to the high speed nature of the PTC, a microcontroller that could operate at even higher speeds was desired to provide significant overhead and allow minimal delays from processes and calculations when measuring a projectile. As such, the ESP32-S3-WROOM-1 was chosen for its easy to incorporate package and significantly higher clock speed compared to similar popular chips. With a {freq} MHz clock frequency, the ESP32 allows the PTC not only to reach its goal of measuring projectile speeds up to 100 m/s, but far exceed it. Additionally, having {# of GPIOS} GPIO pins allows the PTC to fully utilize the ESP32 to control all of its functions without having to incorporate extra ICs. The chip can be programmed using Micropython and the Thonny IDE, allowing fast and easy programming as well as live debugging.

3.2 Image Processing Unit/Graphical User Interface

The Image Processing Unit is responsible for receiving image data from cameras and processing it to extract vital trajectory information. Since the PTC requires two cameras for effective measurements, the Raspberry Pi Model 5 was chosen as its is a Single Board Computer (SBC) with two MIPI ports for cameras, and is fully compatible with Raspberry Pi brand cameras, and can also be programmed with Python. Other considerations introduced the possibility of compatibility issues or simply did not have two MIPI ports for cameras. But with the Raspberry Pi 5, not only can two cameras be interfaced with at the same time, the system can be programmed with a nearly identical programming language as the ESP32.

A Waveshare 2.8 inch Capacitive Touch LCD was chosen as a screen and graphical user interface to display resultant data collected by the PTC to the user, and is driven by SPI and I2C protocols. It can operate with a minimum of 4 wires, and thus allows the PTC to display data without occupying too many GPIO pins on the MCU.

3.3 Trans-Impedance / Signal Amplifier

Trans-Impedance Amplifiers are a special use case of Operational Amplifiers that can convert a photodiode's relatively linear current output to a corresponding voltage, and as such, will be an essential circuit component to making sense of a photodiode's output in conjunction with the PTC's laser gate system to sense when a projectile passes through. The PTC uses an MCP6489 Op-Amp, a quad package amplifier with a 10 MHz Gain Bandwidth Product and a low noise voltage density of 10 nV per root Hertz at 10 kHz. Additionally, with a low operating supply voltage of 1.8V to 5.5V and a slew rate of 20V per microsecond, this chip outperforms similarly priced chips like the TL084 and approaches specifications of higher performance chips. With this quad package, it is also possible to amplify and filter the TIA signal to a level easily readable by the MCU.

3.4 Global Shutter Cameras

Global shutter cameras are capable of high frame rates, and with an externally triggered shutter the micro-controller can precisely control the timing of the exposure. The PTC uses Raspberry Pi brand Global Shutter cameras, and two cameras are used for stereoscopic imaging, allowing the use of parallax to precisely identify in 3 dimensions the location of the projectile.

3.5 Photodiode

The PDB-C171SM photodiode was selected for the transimpedance amplifier (TIA) board. Its surface-mount package supports straightforward PCB integration while maintaining adequate responsivity at 650 nm, specified at approximately 0.4 A/W. A key selection criterion was the photodiode's active area, since larger sensing areas improve optical collection efficiency. The PDB-C171SM provides an active area of 7.5 mm^2, making it appropriate for this system. Additionally, its moderate junction capacitance and low dark current support stable, repeatable detection without requiring excessively complex amplification circuitry.

3.6 Infrared LEDs/Laser Diode

Single wavelength imaging was selected for easier filtering and lens design. Infrared was selected to avoid distracting visible light flashing, and so that even in bright environments, the ambient light can be filtered out easily. AC3535A-YRR-1000ma LEDs were chosen for their high luminosity and ability to handle higher currents. 850 nm LEDs are some of the cheapest and most powerful of the near infrared LEDs, and the camera sensor still had over a 40% responsivity compared to the peak wavelength. 850 nm is used in some consumer applications like 3d face scanning for facial recognition to unlock cell phones, which means that there is a robust ecosystem of components for filtering and lighting with 850 nm light. The Adafruit 1057 laser diode was selected as the light source for the laser gate subsystem. This device is a line laser with an integrated cylindrical lens, operating at a wavelength of 650 nm and producing a 120-degree fan angle with a maximum output power of 5 mW. Its wide beam spread, relatively high optical intensity, and strong detectability by silicon photodiodes made it well suited for this application.

3.7 Mirrors/Cylindrical Lenses/Camera Lenses

A combination of flat and flexible mirrors was used to implement the laser gate geometry. The flat mirrors redirected the laser beam across the designated sensing region, enabling accurate projectile speed measurements. The flexible mirrors were used to shape and direct the incoming and reflected laser paths so that projectile detection could be maintained across the full sensing region. In addition, an external cylindrical lens was used to isolate and expand the central portion of the line-laser output, increasing the effective optical intensity within the measurement zone. All optical components were housed in 3D-printed mounts, which provided a low-cost and accessible solution for mechanical integration and alignment. To allow iterative development, very inexpensive lens elements were selected. By taking what was available and designing around it, workable camera lenses were created using elements costing less than $10 with 3d printed mounts and apertures.

4. ELECTRONIC HARDWARE

4.1 Strobe Module

The Strobe Module serves the essential function of providing the two global shutter cameras the infrared light necessary to capture an image of a projectile at two separate points in a dark chamber, while also being a detachable component of the PTC, which can support up to 9 strobe modules at the same time. To accomplish this, strobe modules are connected to the motherboard with an RJ45 port and a Cat 6 cable. Strobe modules have a local capacitor bank that is charged with a constant current limiter, allowing the strobe modules to flash LEDs by discharging the capacitor bank instead of straining the system's main power supply. With an adjustable voltage regulator after the capacitor bank, the system's 24V power can be turned down to a suitable voltage to power the LEDs and enforce a 1A current output through a 1 Ohm resistor at the end of the signal chain. The LEDs are switched on and off by a MOSFET and gate driver, and their switching signal is received from the MCU and motherboard through an optocoupler to protect them from and transient voltage or current spikes from the strobe modules. An overcurrent detection circuit is included on the module and under fault conditions triggers a latch that prevents the module from strobing until the user manually checks and clears the fault via a GUI. The modules also include connections to sense the voltage on their individual capacitor banks as well as read their fault status.

4.2 Trans-Impedance Amplifier (TIA) Module

The TIA module is responsible for housing the TIA and corresponding gain and filtering stages, as well as filtering power inputs and housing an I2C compatible Ambient Light Sensor (ALS). The MCP6489 op-amp is responsible for the TIA itself, two gain stages with filters in between, as well as a final stage that acts as a comparator. This comparator stage and a trim potentiometer allows a threshold voltage to be set, and when a projectile passing through the laser gate causes a change in signal, the resultant change can be converted into a binary signal that can be read by the MCU with far greater speed than a typical analog to digital conversion, for which the MCU would have to use its onboard ADC that runs at about 20kHz. By using this comparator, the PTC is theoretically able to measure speeds up to 500 m/s.

4.3 Regulator Module/MCU Module

The Regulator Module is responsible for taking the PTC's 24V main power and regulating it down to a stable 3.3V to use with the MCU and other chips and operations that require 3.3V. It uses an LM2576S adjustable switching regulator to fine tune a voltage output and is attached to the PTC's motherboard via two rows of pin header sockets. It includes an input transistor for Under-Voltage Lockout to prevent the LM2576S from outputting voltage until there is a stable input of greater than 3.6V. Additionally, an output schottkey diode is included to prevent backflow without causing a large drop in output voltage.

The ESP32 MCU sits on its own module PCB so that it can be easily removed and replaced with the PTC, which allows for easy programming of the ESP32 outside of the PTC. To support this function, the MCU module also includes its own onboard LDO linear regulator to turn USB 5V power into a usable 3.3V. This regulator also includes an output diode to prevent backflow when not in use while the MCU module is connected to the PTC.

4.4 Motherboard

The Motherboard is responsible for powering every connected module and routing signals between them, and also includes various ICs and detachable components responsible for voltage regulation to 5V and operations related to fault-detection and status indication. Each strobe module's capacitor bank connection is divided down into a safe voltage and sent to an analog multiplexer so that the MCU can select which strobe module to read from with a minimum number of pins. Additionally, another connection is present through an identical analog multiplexer to allow the MCU to send a signal to clear a particular strobe module's fault status. There is also another connection from each strobe module to a priority encoder, so that when a fault status occurs on a strobe module, the priority encoder will be able to translate that signal into an identification code that the MCU can use to pinpoint which strobe module is experiencing a fault condition. Slots for detachable 5V switching regulators are included to power the analog multiplexer and priority encoder ICs, and RJ45 ports are included not only for the maximum 9 strobe modules, but one for the TIA module and another for a Camera Trigger signal that is sent to the global shutter cameras so that their image capture may be solely controlled by the MCU. This allows the MCU to precisely control image capture without relying on the Raspberry Pi 5, ensuring that the PTC will be able to operate fast enough to capture a projectile.

5. OPTICAL HARDWARE

5.1 Laser Gate Overview

The laser gate subsystem's primary goal is to detect a projectile entering the sensing region and calculate the speed of that projectile. For the current prototype of the system, this sensing region is defined as 10×13 cm^2, with 13 cm being the height of the sensing region. The line laser diode emits a beam that has its central portion extended out to the height of our sensing region. This beam is then reflected by a series of mirrors, creating two parallel beams that span the path of the projectile. After moving through the sensing region, the beam is focused by a parabolic mirror onto a photodetector mounted to our TIA board.

As the projectile passes through the system, it sequentially interrupts the two beams, producing two distinct drops in photodetector signal. The time difference between the two beam interruptions is measured, and since the distance separating the beams is known, the projectile's velocity can be calculated using the equation:

$$v = \frac{d}{\Delta t} \tag{1}$$

The arrangement of the mirrors allows the entire optical path to be folded within a compact enclosure while maintaining precise beam alignment across the sensing region.

5.2 Parabolic Cylindrical Mirror

To improve optical collection efficiency at the end of the laser gate subsystem, a 2D parabolic cylindrical mirror was incorporated to focus the reflected rays from the sensing region onto a compact detector plane. Since the laser gate uses an extended source geometry instead of a single collimated beam, the reflected light spans a range of angles and positions. A flat collection surface would be unable to capture the entirety of the outgoing light, reducing both the optical power and total sensing area that the photodetector would be able to detect. The parabolic cylindrical mirror addresses this issue by focusing the reflected light in one-axis while preserving the geometry of the line-based sensing region. Figure 2 illustrates the ray-tracing concept used to guide the mirror design.

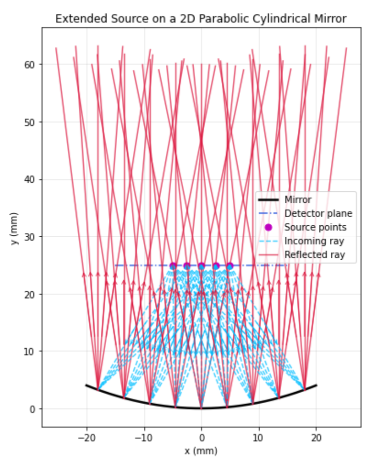

Figure 2. Ray-tracing illustration of the parabolic mirror.

5.3 Projectile Detection Timing Analysis

The temporal response required for reliable projectile detection is determined by the duration for which a projectile blocks each laser beam. If a projectile of diameter D travels with velocity v approximately perpendicular to the laser sheet, the beam interruption time is:

$$t_{\text{int}} = \frac{D}{v} \tag{2}$$

This relationship establishes the minimum signal duration that the photodiode, transimpedance amplifier, comparator stage, and microcontroller must be capable of resolving. Using the current design requirements, projectile diameters are expected to range from 15 mm to 50 mm, while projectile velocities are expected to range from 10 m/s to 50 m/s. Therefore, the analog front end and digital timing system must reliably detect optical interruptions spanning approximately 300 μs to 5.0 ms. This requirement is comfortably within the response capability of the selected photodiode and amplifier chain, while also leaving sufficient timing margin for edge detection by the ESP32-S3. Since projectile velocity is computed from the time difference between two beam interruptions (1), the timing resolution of the microcontroller directly affects measurement accuracy. For a fixed beam spacing d, reducing timestamp uncertainty improves the velocity estimate. As a result, the comparator-based digital output of the TIA stage is preferred over direct ADC sampling, since it enables faster and more repeatable edge timing measurements.

In addition to interruption duration, the spacing between the two laser beams determines the measured time interval Δt. If the beam separation is too small, the interval becomes difficult to measure accurately at high projectile speeds. If it is too large, the optical layout becomes harder to package within the enclosure. The beam spacing must therefore be selected to balance timing accuracy, mechanical compactness, and optical alignment tolerance.

5.4 Photo Chamber Arrangement

The pixel position of the projectile can be converted to an angle from the camera lens, and when done with both cameras, the x,y,z position of the projectile can be calculated. Using strobe photography, there are two exposures of the projectile in each image, one on each side of the image for each strobe flash. By splitting up the image into two halves, the location of the projectile can be determined at two points in time.

5.5 Camera Lenses / Apertures

The camera lenses are designed as using two symmetric plano-convex elements around an aperture and an 850 nm bandpass filter. While there is significant spherical aberration and noticeable blur, the theoretical performance was a spot size between 10 and 40 micrometers depending on the field angle.

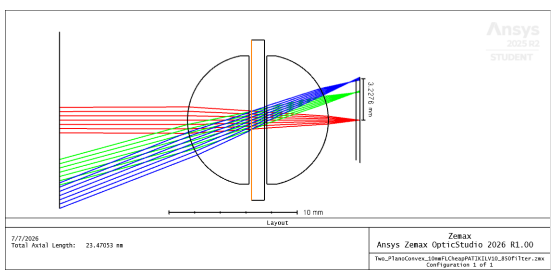

Figure 3. Camera lens layout.

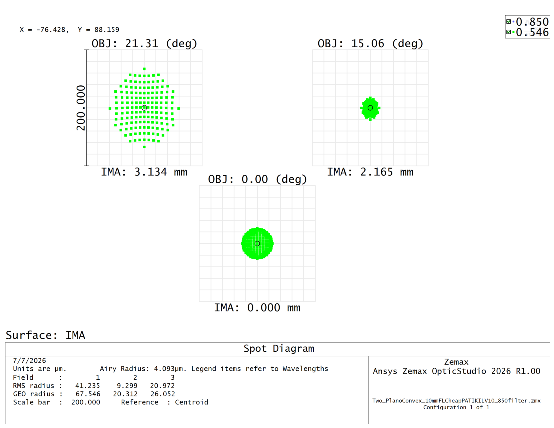

Figure 4. Camera lens spot diagram.

6. SOFTWARE

6.1 Firmware

The firmware portion of the PTC coordinates the timing-sensitive hardware events that occur during a projectile measurement. The ESP32-S3 monitors the photodiode and transimpedance amplifier output from the laser gate circuit. When a projectile interrupts the laser path, the firmware records the timing of the gate events and uses known spacing between laser gates to calculate projectile velocity. This allows the system to determine projectile speed independently from the image processing system. After a valid projectile event is detected, the firmware controls the strobe and camera trigger timing. The strobe modules briefly illuminate the projectile at separate instants while the cameras are actively taking a long exposure shot, creating two visible projectile positions in each camera. The imaging system then provides the calculated projectile coordinates back to the main control system, where they can be combined with the laser-gate velocity measurement to estimate the projectile trajectory.

6.2 Image Analysis Algorithm

The image analysis algorithm converts the stereo camera images into projectile position data. Reference images are first taken of the background without a projectile present. When the stereo images are later captured with a projectile, the projectile images are subtracted from the reference images. This removes much of the static background and makes the illuminated projectile easier to isolate.

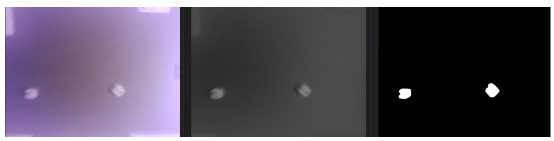

Figure 5. Image analysis pipeline for one camera view, showing the captured long exposure image, the background subtracted result, and the thresholded image used to isolate the projectile regions for centroid detection.

Figure 6. Annotated analysis output of a long exposure image showing the detected projectile spots and centroid markers for the two positions in the top and bottom camera views.

The two halves of each stereo image are separated and treated independently as the two different strobe times. This creates four useful image regions from the two strobe exposures and two cameras: before_camera_1, before_camera_2, after_camera_1, and after_camera_2. For each region, the software thresholds the background subtracted image, detects the projectile contour, and automatically calculates the projectile centroid. The projectile is assumed to move in the positive x direction, with the cameras pointing in the z direction, and the cameras are separated in the y direction. The projectile is projected into cylindrical coordinates with a center axis through the two camera lenses. By taking the y pixel position of the projectile in before_camera_1 and before_camera_2 images and converting those pixels into viewing angles, the intersection of those two vectors gives the cylindrical distance rho from the center axis to the projectile. The x position is also converted into an angle and used to estimate the phi cylindrical coordinate. These cylindrical coordinates can then be converted into cartesian x, y, and z coordinates. This process is repeated for the after-camera images, allowing the two projectile positions to be compared so the projectile trajectory can be calculated.

6.3 User Interface

The user-interface software presents the final measurement results in a format controlled by the MCU. After a projectile event is processed, the MCU receives the velocity measurement from the laser gate timing system and the calculated projectile position data from the imaging system. These values are used to display the projectile's velocity and estimated trajectory to the user. The interface is intended to hide the lower-level sensor and image-processing details, allowing the user to view the final measurement results without needing to interpret raw timing data or camera images.

7. FABRICATION

7.1 PCBs/Mounts

In an effort to preserve system integrity in the event of design errors or malfunctions, every system subset or module as described earlier was fabricated as its own printed circuit board. Using RJ45 connectors and Cat6 cabling, as well as pin headers and sockets, each of these modules is able to connect to the motherboard, whilst remaining fully detachable in the event they must be replaced. The PTC's motherboard, responsible for linking all of these modules together, also includes slots for detachable components like drop-in regulators and the PTC's LCD screen, in addition to the sockets that the regulator module and MCU module would slot into.

As stated earlier in this paper, most of the mounts and housing for the optical components were designed and 3D printed to reduce the overall cost of the project. The external housing will most likely be comprised of wood sheets and beams, increasing the overall sturdiness of the prototype. Future housing may be made of aluminum extrusion, as this would provide both a sturdy and more lightweight frame to the projectile tracking chronograph.

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