Optical Beacon Tracker for Optical Wireless Communications

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Abstract: **The idea of optical wireless communication (OWC) has existed for decades and comes with many advantages. Signals can be driven by light sources across the electromagnetic spectrum, granting a broad range of frequencies to choose from, and the speed of signal transfer is only limited by the pulse width of the light source since the signal travels at the speed of light. Unfortunately, clear signals require precise alignment and are weak to interference from atmospheric loss. Also, if the transmitter or receiver are mobile then maintaining that precise alignment becomes even more difficult, which is the problem we will be solving with this project.**

I. Introduction

This project is sponsored by the Knight Vision Lab, a research group at CREOL with projects involving metasurface aberration correctors to improve performance, size and cost of infrared lenses, vision-based navigation using imagery to determine geolocation, and Sensing technologies from small UASs.

Optical Wireless Communication (OWC) represents a promising frontier in data transmission, harnessing light waves to transfer information with remarkable speed and security. Unlike traditional radio frequency communication, OWC leverages the vast frequency range of the electromagnetic spectrum, providing flexibility in the choice of carrier signals and allowing for high data transfer rates constrained only by the pulse width of the light source. This characteristic makes OWC an appealing solution for applications demanding high-speed data transfer. Additionally, its reliance on line-of-sight propagation adds a natural layer of security, as interception is only possible within the direct path between the transmitter and receiver.

Despite these advantages, OWC faces inherent challenges that must be addressed to ensure reliable performance. Precise alignment between the transmitter and receiver is crucial for clear signal transmission, and the system's vulnerability to atmospheric disturbances can disrupt communication. These issues are exacerbated when either the transmitter or receiver is in motion, as continuous and accurate realignment becomes necessary to maintain the signal path. This project aims to overcome these alignment challenges by developing a system that integrates advanced positioning and tracking mechanisms, enabling robust and stable optical communication even under dynamic conditions.

II. Component Overview

In this section we will be introducing each of our main hardware components along with a summary of why they were chosen and how they will interface with one another in our optical tracking system. In later sections we will be discussing their applications in a more in depth and technical manor relating to our specifications given in section IV.

A. LED Array (SFH-4258S)

An array of Near-Infrared (NIR) LEDs will be employed as the primary light source. These LEDs will be configured and collimated in a manner to ensure a directed and focused beam of light. The Beacon is designed to emit consistent NIR signals over a defined distance. The emitted light will be detected by a quad cell photodiode positioned on the Receiver. We chose the SFH-42582 NIR LEDs for their relatively high power/size ratio, as well as their 30-degree viewing angle.

B. Photodetectors (SPOT-9D-0 and FGA015)

The quadrant photodiode (QPD) on the receiver is critical for capturing the collimated NIR light emitted by the LED array from the beacon. This photodiode is designed to detect the distribution of incoming NIR light across its four quadrants, which helps determine the position of the beam relative to the sensor. The output signals from the individual quadrants of the quad cell are then processed using summing operational amplifiers (op-amps). These op-amps combine the signals from each quadrant to create outputs that represent the light intensity and positional data. The processed signals are then sent to the MCU, where they undergo further analysis to determine the exact position of the beam. This positioning data is crucial for real-time adjustments and maintaining alignment between the beacon and the receiver.

The SPOT-9D-0 is a particularly unique QPD due to a 200um hole in its center, which will enable us to insert an optic fiber. When the light from the 1550nm laser passes through the fiber onto the single-cell SWIR photodiode (the FGA015) we will be able to confirm perfect alignment.

C. IMU and GPS (WWZMDiB, GY-NEO6MV2)

To achieve alignment between the beacon and the receiver, the WWZMDiB IMU and GY-NEO6MV2 GPS modules will be integrated with the ESP32. These modules provide critical data on orientation, positioning, and altitude, serving as a reference for aligning the two components over varying distances. The GPS coordinates, combined with altitude information, enable the calculation of bearing angles required for precise control of the pan and tilt servo motors, ensuring both components are correctly oriented to maintain a line-of-sight connection. This alignment process lays the groundwork for more refined positioning and tracking done by the QPD via the optical signal omitted by the LED array.

D. Telemetry Module (RYLR689)

To facilitate communication between the beacon and the receiver, data from the onboard GPS and IMU modules will be transmitted using LoRa modules. This long-range, low-power wireless communication system is ideal for maintaining reliable data transfer over extended distances. By sending GPS coordinates, altitude, and orientation data from the beacon to the receiver, and vice versa, the system can synchronize alignment and adjust positioning as needed. The RYLR689 module ensures that both components stay updated with each other's real-time positional information, enhancing the accuracy of the bearing calculations and the control of the pan, tilt servo motors and gimbal. This continuous data exchange supports seamless operation and effective alignment for the entire system. Additionally, their compatibility with standard data interfaces, such as SPI, simplifies the integration with our IMU and GPS modules making it an ideal choice for our application.

E. MCU (ESP32 S3 Mini)

The ESP32 S3 Mini was chosen for this project due to its exceptional versatility and broad compatibility with various components and communication protocols. This microcontroller boasts a dual-core Xtensa LX7 processor with a clock speed of up to 240 MHz, providing ample processing power for complex tasks such as data acquisition, signal processing, and real-time control. Its substantial memory capacity, with up to 512 KB of SRAM and support for external flash, enables efficient handling of large data streams and program storage. The integrated support for peripherals like I2C, SPI, and UART further enhances its compatibility with a wide array of sensors and modules, such as IMUs, GPS units, and telemetry devices. This combination of power, connectivity, and flexibility makes the ESP32 S3 Mini an optimal choice for managing the data flow and control functions in our project. Furthermore, the MCU PCB will be equipped with an LDO to allow a 5V input from the PSU while maintaining a 3.3V operating voltage.

F. Servo Motors (FeeTech 35kg FT6335M, Tower Pro Mg995)

Servo motors were chosen due to their reliability, low cost, and ease of integration with the ESP32. Both the FT6335M and the MG995 are metal geared for high wear and tear applications. The 35kg torque rating of the FT6335M ensures that these motors have ample strength to handle the movement of the beacon, which weighs under 3kg. The 360-degree servo is implemented for panning, allowing a full range of motion and broad coverage, while the 180-degree servos will be used for the tilting motion to accommodate a difference in altitude. This combination provides the necessary range of motion for aligning the beacon and receiver. The FT633M will be used for the Beacon because of its' larger weight while the MG995 has a torque rating of 11kg/cm and will be used for the much liter Receiver. The MG955 will have the same range of motion described above for the FT6335M.

G. SWIR Laser Diode (L1550G1)

In this project, while we are not constructing an actual communication device intended for real-world telecommunications, our aim is to create a system that can simulate the core components of such a device. Specifically, we are using a laser diode to replicate the function of a telecommunications laser, which is a critical component in high-speed data transmission. By focusing on the design and operation of this laser diode setup, we intend to provide future users with a foundation they can use to add their own telecommunication-grade lasers if they choose to upgrade the system.

To facilitate this adaptability, we have chosen to integrate the laser diode with an optical fiber, ensuring that the system can handle real communication signals when a compatible laser is introduced. The L1550G1 laser diode was selected due to its high-power output in continuous-wave (CW) mode, which will allow us to pulse the laser at any duty cycle necessary for testing and demonstration purposes.

III. System Integration

Like the previous section, this section will provide a high-level overview of how the software allows the components listed above to interact with one another. There will be two subsections describing how the software allows the Beacon and Receiver to operate in unison.

A. Beacon

The beacon is a bit more simplistic than the receiver when it comes to the software implementation in the sense that the Servo motors being controlled are only to generally align the beacon with the receiver, therefore the GPS, IMU and "Signal Received" data are all that is needed. The ESP32 will be responsible for receiving data from the WWZMDiB and GY-NEO6MV2 locally with its own position along with the positional data received via the telemetry module. Additionally, it will need to calculate the bearing angle and use PWM to reposition the servo motors to their desired angle.

In the case that data via the telemetry module is unavailable the Beacon will enter the "Search Protocol" which will pan and tilt the servos until an optical signal is received. Below is a flow chart showing the high-level process of the beacon.

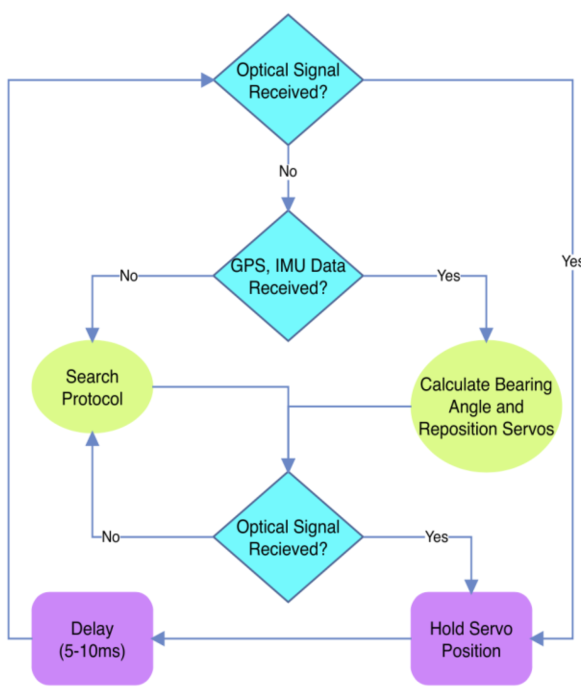


Fig 1: Flowchart of tracking logic for the Beacon

B. Receiver

Unlike the Beacon the receiver will need to be responsible for both general alignment and optical alignment. The flow for general alignment will be like the beacon but after the alignment is established it will need to omit the GPS signals for alignment and solely rely on reading the optical signal. This will be discussed in greater detail in the software section (IV).

IV. Specifications

This section will address the specifications laid out for our project to ensure expected functionality. The specifications that are highlighted in the table below will be elaborated upon further in this section explaining why they are essential and hold more importance over the other. However, in later sections the unhighlighted specifications will be addressed and elaborated on their implementation.

Table 1: Project Specifications

#	Requirement	Spec.
1	Receiver FOV	10-20 degree viewing angle from the Receiver
2	Beacon FOV	35-45 degree viewing angle from the Beacon
3	Stationary Track Accuracy	< 10 mRad
4	Mobile Track Accuracy	< 17.5 mRad
5	Track Loop w/o IMU	10-15 kHz Signal processing loop
6	Track Loop w/ IMU	100-200 Hz
7	Indoor Functional Distance	2-3 meters functional distance indoors (w/o IMU compensation)
8	Outdoor Functional Distance	100-1km functional distance outdoors (w/ IMU compensation)
9	Battery Life	30-60 minutes (requiring power consumption < 500 Wh)
10	GPS Accuracy	2-3 meters
11	Reaction Time	300 – 600 milliseconds

V. Hardware

In this section we detail the technical strategies and component configurations used to meet our project specifications listed in the previous section. To identify which specification is being met in the table above a simple (#) will be given after each statement concerning the specification. Additionally, unlike the previous sections we will also be addressing our power supply and management system.

A. General Alignment

The specifications that will be addressed in this subsection include GPS (10) accuracy and Servo Responsivity (11). To ensure a GPS accuracy of 2-3 meters we have decided to use the GY-NEO6MV2 which is accurate up to 2.5 meters [2] which is suitable for our application of general alignment and within our desired specification range (10). Additionally, the GY-NEO6MV2 features low power consumption and features a built-in ceramic antenna for improved reception even in areas with weaker satellite signals. Its 9600 bps UART interface makes it easy to integrate with our ESP32.

Regarding the Beacon responsiveness, our 35kg servo motors have a speed of up to .197 s per 60-degree rotation [3] well within our spec for responsiveness (11).

B. Optical Alignment/Tracking

The specifications addressed in this subsection will be the stationary and mobile tack accuracies (3,4). To achieve precise optical alignment and tracking of the beacon, we have implemented a trans impedance analog filtering system. This involves a transimpedance amplifier that converts the current signals from the quad cell photodiode into proportional voltage signals. These signals correspond to the light intensity detected by each of the four quadrants (A, B, C, D) of the photodiode. These voltage signals are received by the MCU over the ESP32s analog to digital converter channels. The ESP32 will be responsible for taking the voltage signals and converting them into usable positional data. Specifically, the system computes the quantities (A+D−B−C)/(A+B+C+D) for the X-coordinate, where it takes the difference between the left and right quadrants, and (A+B−C−D)/(A+B+C+D) for the Y-coordinate, where the difference between the top and bottom quadrants are taken. These outputs represent the normalized position of the light spot on the photodiode surface. This data is used to make real-time adjustments to the gimbal's position, ensuring that the system can maintain accurate alignment and tracking of the beacon. Below is a schematic representing the design implemented in achieving positional data.

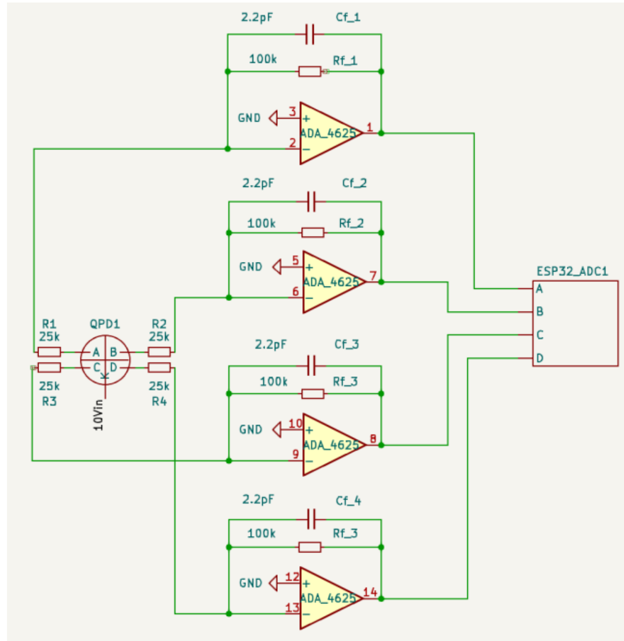


Fig 2: Circuit Diagram for the QPD and tracking.

Once this signal is received and the necessary computations are done by the ESP32 a PWM signal will be sent to the MG995 servo motors to turn to the desired bearing angle used on our Receiver. The MG995 servos can position itself within .15 degrees of its designated angle, which is well below our 10 milliradian specification for tracking accuracy. However, to achieve this level of accuracy using the angle functions in the Servo.h library were changed to use specific pulse widths which are calculated based on the bearing angle as the the write(angle) functions created inaccuracies.

C. PSU

To power both the Beacon and Receiver we will be using the on-board battery used for powering the drone, the Tattu G-Tech 22.8V 23000mAh LiPo Battery. Our PSU will be responsible for stepping down the voltage and distributing power amongst our components. To do this we have two LMQ61460AASRJRR buck regulators and a LT3597 LED Driver. The same PSU board layout will be used for both the beacon and the receiver.

For the beacon side we will need the voltage regulators to output 5V and 7.4V for our MCU and FT6335M. The LED driver will be used to power our array of 25 NIR LEDs at 100mA with PWM dimming from the MCU. This will allow us to modulate the optical signal and distinguish it from ambient/unwanted light.

On the Receiver side the voltage regulators will need to output 5V and 10V. The 5V regulator will be responsible for powering the MCU and operational amplifiers while the 10V regulator will be used in biasing our QPD. The LM2664 switched capacitor voltage converters will be used on the Beacon to provide the op-amps with -5V for the -Vcc pin.

VI. SOFTWARE

The software for the Optical Beacon Tracker is developed to manage the interactions between the GPS, IMU, compass, LoRa modules, and quad-photodiode (QPD) to enable precise, real-time tracking and alignment of the receiver with the transmitted laser signal. The software logic coordinates data from these sensors and determines the necessary motor adjustments to maintain optimal alignment of the QPD. The software will be done entirely in C, and on the Arduino IDE.

The GPS and orientation data acquisition will done by utilizing the 'TinyGPSPlus' and 'QMC5883LCompass' libraries. The reason that GPS library was chosen was that it was compatible with our GPS module, and it was able to parse the GPS data for us. The compass library was a little more complex. The standard compass libraries did not seem to work with our IMU modules, so we had to find this one. We set the mode control, output data rate, full scale range, and sample ratio manually. The x, y, z, azimuth, and bearing all had their own functions in the library and were called. This IMU will also be calibrated occasionally to produce more accurate readouts.

The LoRa communication will be done by LLoRa modules, using the 'LoRa.h' library. Our LoRa module is configured to communicate over SPI connections (SLK, MISO, MOSI, NSS, RST, DIO0 pins). This was important as this library was designed to read data from these pins. S The transmitter and receiver ESP32 units exchange position data and tracking commands, which are crucial for updating real-time alignment and ensuring synchronized positioning.

The QPD will send data through four GPIO ports. Then we will digitally convert using an ADC on ESP32. The Servo motors will be using the 'servo' library that is intrinsic to the ESP32 board. After calculating any angle (0-360 for the pan and 0-180 for the tilt motors), we simply write the angle to the motor.

There will be many calculations used in this code. The first calculation we will be using is the formula to calculate the distance. For that, we will be using the Haversine Formula. We have used a variation of it as I will explain below:

Once the difference of the two coordinates are calculated, these two equations are then calculated:

var1 = (sin(dLat/2) * sin(dLat/2)) + (cos(LatA) * cos(LatB) * sin(dLon/2) * sin(dLon/2)); (eq1)

var2 = 2 * atan2(sqrt(var1), sqrt(1-var1)); (eq2)

The distance is also a factor of the difference; however we do not take the Earths curvature into account since the distances we are working with are short. Next, we need to calculate these X and Y variables and take the arctangent to get our Tbearing:

X = cos(LatB) * sin(dLon); (eq3)

Y = cos(LatA) * (sin(LatB)-sin(LatA)) * cos(LatB) * cos(dLon); (eq4)

Tbearing = atan2(X,Y); (eq5)

The R bearing is then calculated by taking tbearing and subtracting azimuth. The angle of the pan motor is simple the rbearing and the angle of the tilt motor is the arctangent of the distance and the difference in altitude. We can then convert that into degrees from radians and write both numbers to the motors.

All these calculations will be done inside the loop. Once we have saturation detected on the QPD, we no longer waste computational time on the GPS and it is disabled. This makes the response time much faster and our beacon will now rely on the IMU and QPD data. We have already mentioned before how the calculations will be done to find the angle for the motors. If no GPS is detected initially, the code will disable it and rely on the IMU bearing to look for QPD saturation.

The following functions that will be used are: compass.read(), gps.encode(), calculateBearing(), adjustServos(), loraSendAzimuth(), loraReceiveAzimuth(), loraReceiveCoordinates(), loraSendCoordinates(), all the functions for specifically controlling the servos, imulock(), gpsTrack(), gpsSearch(), getQPDangle(), detectCurrent, and all of the various functions to create the GUI.

The GUI was created on an html interface because this project is intended to be used on a GCS such as a computer. Interfacing the system by html would be ideal.

VII. OPTICS

For the beacon end of the project, the array of LEDs and the output of the laser fiber must be directed so that the output beam has a divergence of 35-45 degrees, as is required by specification 2. This will be accomplished by collimating the LED array, reflecting the beam off of a dichroic mirror, and then once again pass the beam through a diverging lens.

We must then expand the output of the SWIR laser so that it matches the size of the LED array before it passes through the diverging lens. Otherwise, if the beams of both the array and the laser are not equal upon reaching the output expander, the divergences will be unequal and reduce the effectiveness of the setup. For a visual aid to the optical design for the beacon, we can reference Fig 3 below

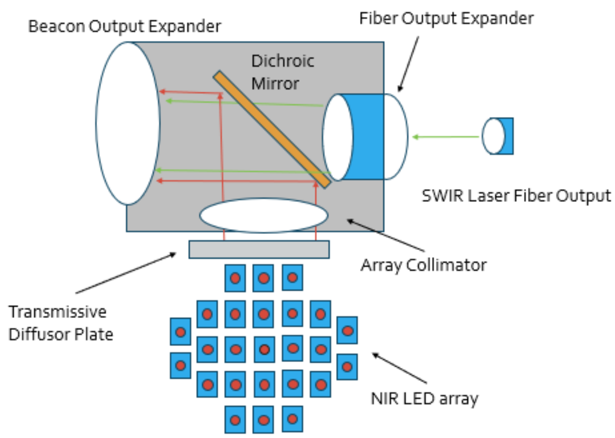


Fig 3: Diagram of the optical layout for the beacon side.

The purpose of the transmissive diffusor plate is to blend the beams of the LEDs together in order to avoid any dark spots where the beam may be incident. Having the LED array in a "circular" shape will enable us to use a smaller lens as a collimator without the risk of losing any power at the corners.

The receiver optics are relatively simple in comparison to the beacon design. They will consist of a single lens for collecting the light and focusing it onto the QPD and into the optic fiber coupled into the center. We will also need a filter with a hole cut into the center so that both the NIR and SWIR light from our beacon can reach their respective detectors. For a visual guide, we can reference Fig 4 below:

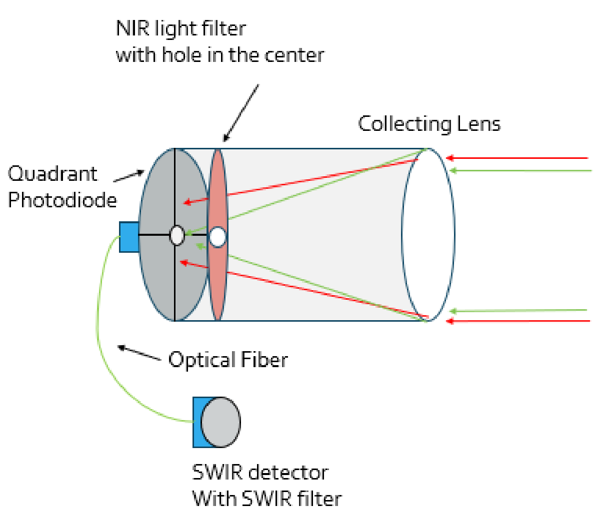


Fig 4: Diagram of the optical layout for the receiver side

By using the filter with a hole cut into the center, we can block out any non-NIR light from the QPD whilst still allowing other wavelengths into the fiber. The SWIR filter on the other end of the fiber will then block out any non-SWIR light from the SWIR photodetector. Due to the size difference between the NIR array and the SWIR fiber output, the beam spot sizes will be different after passing through the collecting lens. The NIR array will be larger and encompass and entire quadrant of the QPD, while the SWIR light will be smaller and can still be focused into the fiber.

VII. Physical Design

Housings for both the Beacon and Receiver will be designed using SolidWorks software and constructed using a 3D printer. The Beacon enclosure will house four PCBs along with the collimators, as shown in Figure 3 in the optics section. The housing needs to be spacious enough to securely fit all components while allowing proper spacing for thermal dissipation and preventing electrical interference between parts. Additionally, the enclosure will feature mounting points for the servo motors used for panning and tilting functions, ensuring stable alignment. Ventilation openings will be incorporated as necessary to manage airflow and maintain optimal operating temperatures for heat-sensitive components. For the Receiver, the enclosure will be designed to hold the quad cell photodiode, MCU, GPS, and related circuitry, with considerations for signal integrity and ease of access for calibration and maintenance. Each enclosure will be constructed from durable, lightweight materials, balancing protection and weight to maintain overall system stability.

Images of the unassembled printed circuit boards (PCBs) are provided below, along with the beacon prototype, to give a general sense of the physical size of the microcontroller units (MCUs) that we plan to enclose in the final apparatus. These images showcase the layout and footprint of the boards, helping to visualize the scale and arrangement within the enclosure. By examining these images, one can gain an understanding of the physical constraints and spatial requirements of the components in the design.

The board has been designed with versatility in mind. It includes pinouts for all general-purpose input/output (GPIO) and power pins, enabling a wide range of configurations and functional changes as needed. This adaptability is crucial, as it allows us to address unforeseen issues or requirements without needing significant redesigns. With easy access to all GPIO and power pins, the board can be repurposed or modified efficiently to suit evolving project needs.

For power, the board relies on a 5V supply, which is provided through a USB-C port. This 5V input is then regulated down to 3.3V using a low dropout (LDO) regulator, ensuring stable operation for the components that require a 3.3V power source. The use of USB-C as the power input not only modernizes the design but also provides a widely accessible power solution, while the LDO regulator ensures that the voltage is consistently maintained within safe operating limits for the device.

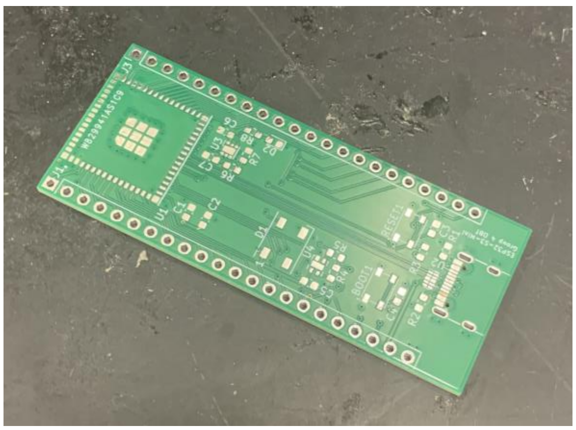


Fig 5: PCB for the MCU

The Receiver board will be responsible for housing the photodetectors and operational amplifiers needed for sending the optical signals to the MCU via five separate ADC channels, four for the quad-cell and one for the single cell photo diodes.

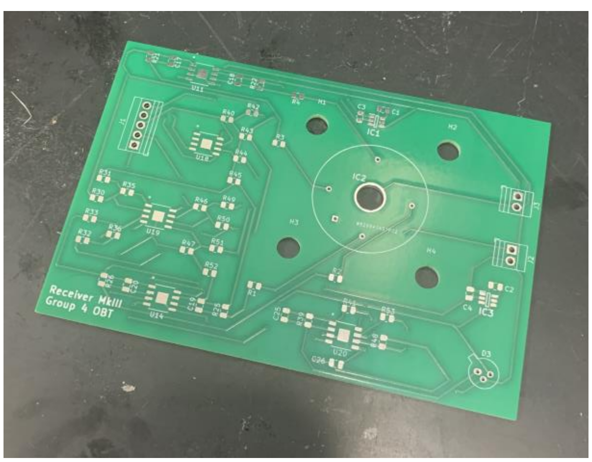


Fig 6: PCB for Receiver

The Beacon prototype shown below includes the collimation lenses and LED array in their fully assembled format. This setup demonstrates how the components work together to focus and direct the light effectively. The lenses ensure that the LED array's output is efficiently focused, optimizing the system's performance.

To secure the structure, enclosures will need to hold the cage rods in place and be mounted directly to the main housing. This ensures stability and proper alignment of each component. For additional clarity, images of both the LED array board and the assembled prototype are provided below, offering a closer look at the design and functionality of the Beacon system.

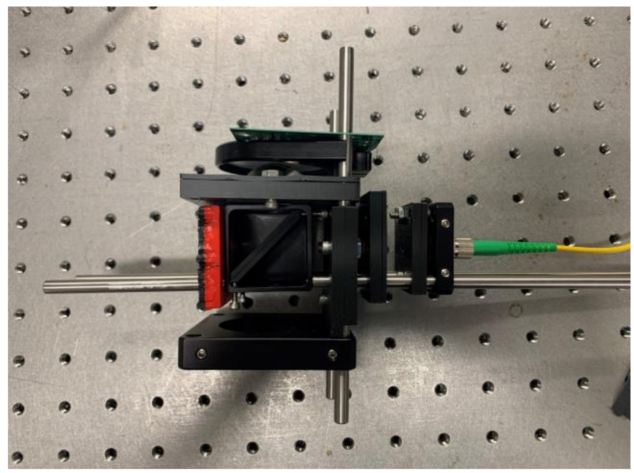


Fig 5: Picture of the initial prototype for the beacon, assembled according to Fig 3 in the optics section.

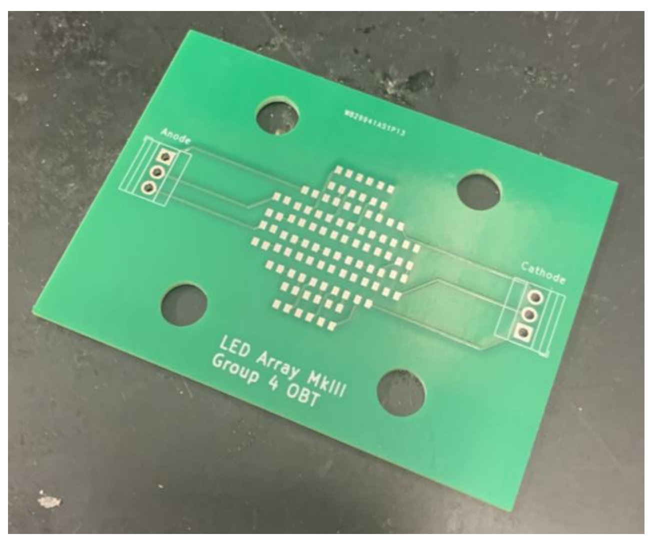
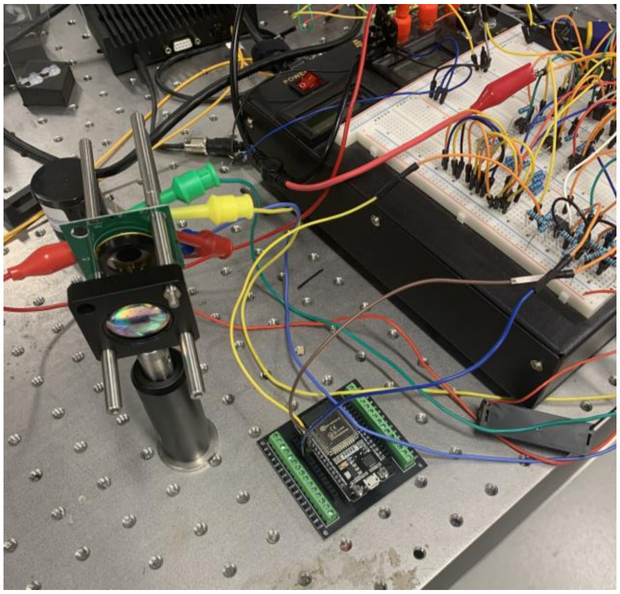


Fig 7: PCB for LED Array

The next picture shows the prototype receiver we assembled to test the responses of our Quadrant Photodetector (QPD). This prototype includes a lens and the QPD, arranged as outlined in Figure 4 in the optics section. Alongside these optical components, we constructed a prototype amplification circuit on a



breadboard to facilitate initial testing. Using this prototype, we simulated the QPD's responses through our amplification circuit, enabling us to conduct preliminary experiments while we wait for the assembly of our PCB.

Fig 8: Picture of the prototype receiver optics, QPD, and circuit used for testing QPD outputs.

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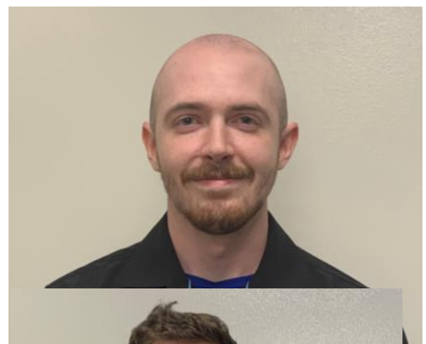
BBIOGRAPHIES



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