

# UCF Senior Design I

## *Optical Beacon Tracker for Optical Wireless Communication*

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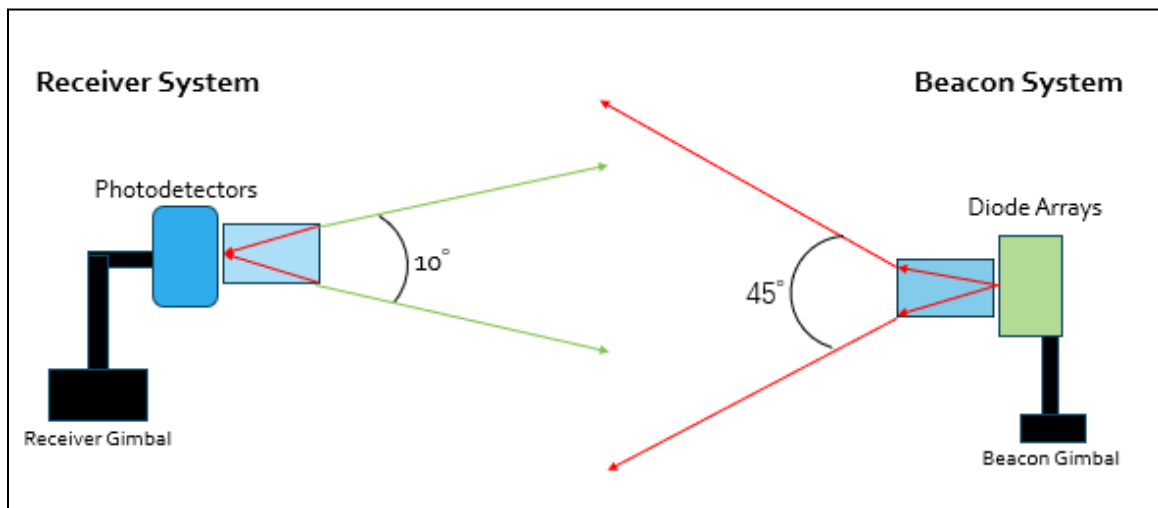
**\*Chapters 1, 6, 7, and 9 will not be in this document version**

## 2 Project Description

### 2.1 Motivation and Background

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 large 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. Signals also cannot be intercepted unless the potential spy is within the line of sight of the transmitter, which makes OWC one of the most secure ways to send communications. Unfortunately, clear signals require precise alignment and are weak to interference from atmospheric loss [4]. Also, if the transmitter or receiver are mobile then maintaining that precise alignment becomes even more difficult, which is the problem we will try to solve.

The goal of this project is to build a device that can track an optical beacon while both the receiver and the beacon are mobile. When it comes to position tracking, one of the most obvious solutions would be GPS, and in fact we'll even be including GPS in the design for general alignment. However, most GPS systems are only accurate down to a few meters, while optical communications require precision down the centimeter. With a quadrant photodiode (QPD) we can accurately track the position of any light source at a certain wavelength as long as the receiver optics are properly designed. With an array of laser diodes, we can transmit light over long distances with enough optical power to be detected by the QPD and align both the receiver and the beacon. We'll be using a QPD sensitive to 850nm for alignment, and a standard photodiode sensitive to 1550nm to confirm perfect alignment of the system.



*Figure 2.1-1: System diagram of the optical beacon tracker.*

Using two separate wavelengths is essential. If we only used one wavelength, the beacon and the transmitted signal would interfere with each other. By using laser diodes that emit 850nm and 1550nm infrared light, we can avoid loss due to atmospheric interference.

The lack of susceptibility to atmospheric loss is also one of the reasons that 1550nm is the most common wavelength for OWC, which is why it's the wavelength we'll use to confirm alignment. We'd like to stress that we are not building a communication system, only a tracker that can be easily integrated into a communication system.

## 2.2 Goals and Objectives

The goals we have for this project span from immediate basic goals, to advanced and stretch goals. The basic goals define the bare minimum for the project to be successful, and can easily be accomplished by our project deadline. The basic goals for this project can be summarized as follows:

- Create a beacon with enough power and divergence to be detected up to 3 meters away whilst indoors
- Create a receiver that can actively track the beacon whilst mobile, up to 3 meters away when indoors

The advance goals for the project will be more difficult and still need to be completed before our allotted time for the project is up, but they are still reasonably achievable. The advance goals are:

- Capable of tracking up to 1 km away whilst outdoors.
- Tracking the beacon with the accuracy stated in the requirements and specifications section.

The stretch goals would only be attainable if we stay very far ahead on this project. Since we only have 3 team members, the second stretch goal in particular would be difficult to achieve during our allotted time. The stretch goals are:

- Capable of tracking up to 10 km away in ideal weather conditions.
- Capable of transmitting and decoding a simple signal (like an SOS) from the beacon.

For now, the goal is simply to be capable of tracking a beacon attached to the object transmitting the signals. To be able to send and decode actual signals from the beacon would reasonably require an extra team member, which makes it a far stretching goal. Tracking the beacon at 10 km should be possible in theory, however proving it in any way other than mathematically would be nearly impossible without the use of drones.

The objectives for this project will all add up to help us accomplish our goals.

- Perform safety calculations so that the 850 nm laser diodes can be safely used indoors.
- Calculate the required optical output power for the beacon to be detectable by the receiver at a given distance.
- Design the focusing, diverging, and collimating lens systems on the beacon and receiver.
- Design a PCB for the beacon and receiver.
- Design a power supply for the beacon and receiver respectively, capable of driving the laser diodes and gimbals/dc motor, as well as biasing the photodiodes.

- Create an algorithm that enables the gimbals/dc motor to use outputs from the QPD, GPS, and IMU as inputs for positioning.

## 2.3 Requirements and Specifications

Like any engineering project, we'll have to meet certain design specifications by the end of the year. This is a sponsored project, so certain specifications such as outdoor functional distance and track accuracy are set by the sponsor. Other specifications were set by ourselves to ensure we can meet our goals for the project.

#:	Requirement	Specification	Description	Priority
1	Receiver FOV	10-20 degrees	The viewing angle from the receiver	Mid
2	Beacon FOV	40-50 degrees	The divergence angle of the beacon	Mid
3	Stationary track accuracy	10-20 $\mu$ Rad	The accuracy of the system when stationary	High
4	Mobile track accuracy	500-600 $\mu$ Rad	The accuracy of the system when mobile	High
5	Track loop without IMU compensation	10-15 kHz	Signal processing loop without using an IMU	Mid
6	Track loop with IMU compensation	100-200 Hz	Signal processing loop while using an IMU	Mid
7	Receiver and Beacon weight	Less than 5kg Each	The receiver and beacon must weigh less than 5kg respectively	Low
8	Indoor functional distance	2-3 meters	Functional distance while indoors	High
9	Outdoor functional distance	1-1.5 kilometers	Functional distance while outdoors	Mid
10	Battery life	30-60 minutes	How long the system will be able to run on battery supply	High
11	Power Consumption	Less than 500 <u>Wh</u>	Power consumed by the beacon and receiver systems respectively	Mid
12	GPS accuracy	2-3 meters	Accuracy of the GPS systems	Mid
13	Budget	Less than \$5k	Total cost of the project	Low

Figure 2.3-1: Table of engineering specifications.

## 2.4 House of Quality

The house of quality diagram is essential for making sure our engineering specifications meet the needs of our clients or sponsors. Our house of quality is shown below.

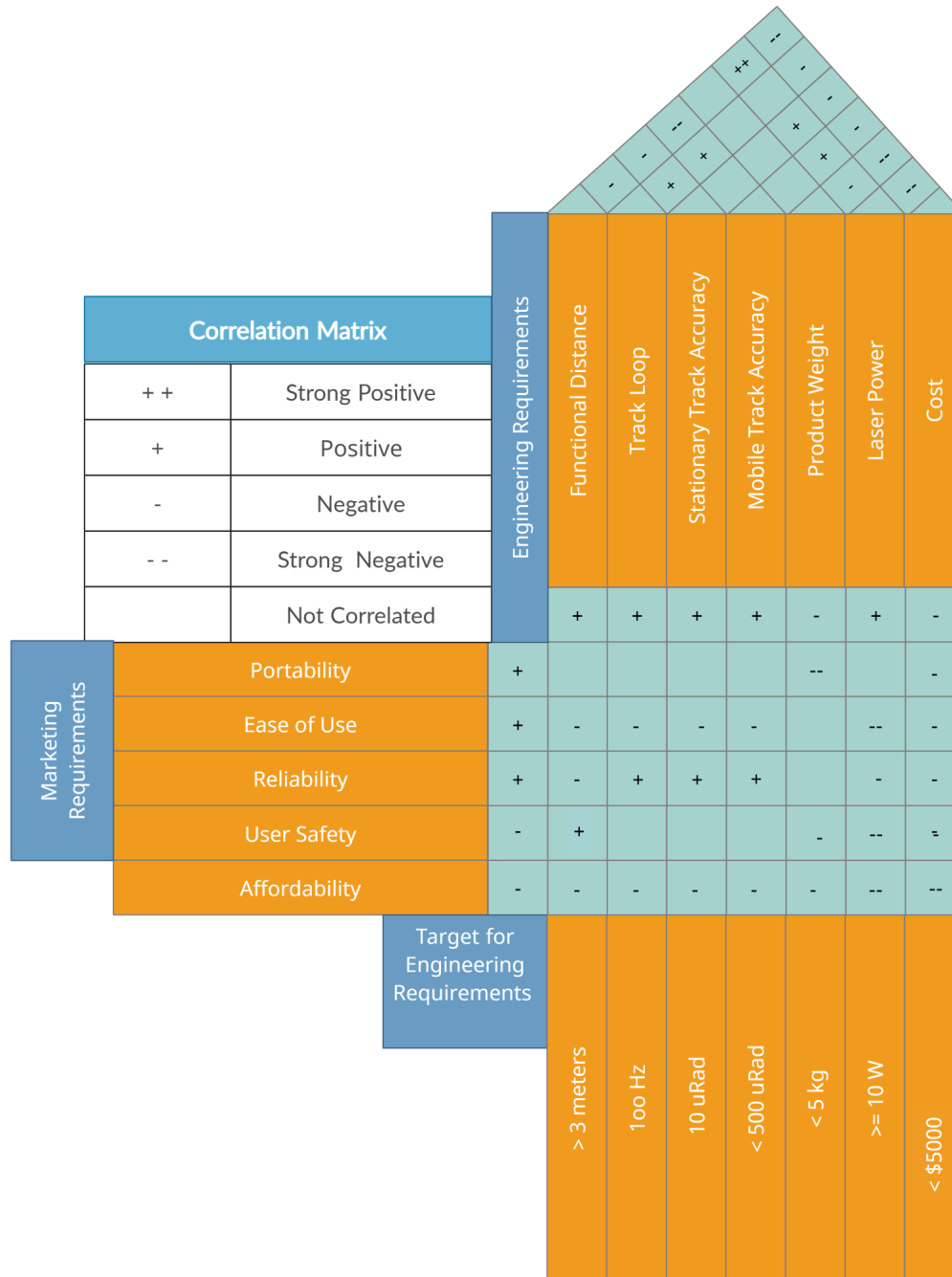


Figure 2.4-1: House of quality diagram

## 2.5 Hardware and Software

## 2.5.1 Hardware

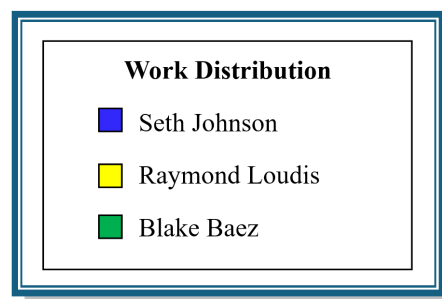
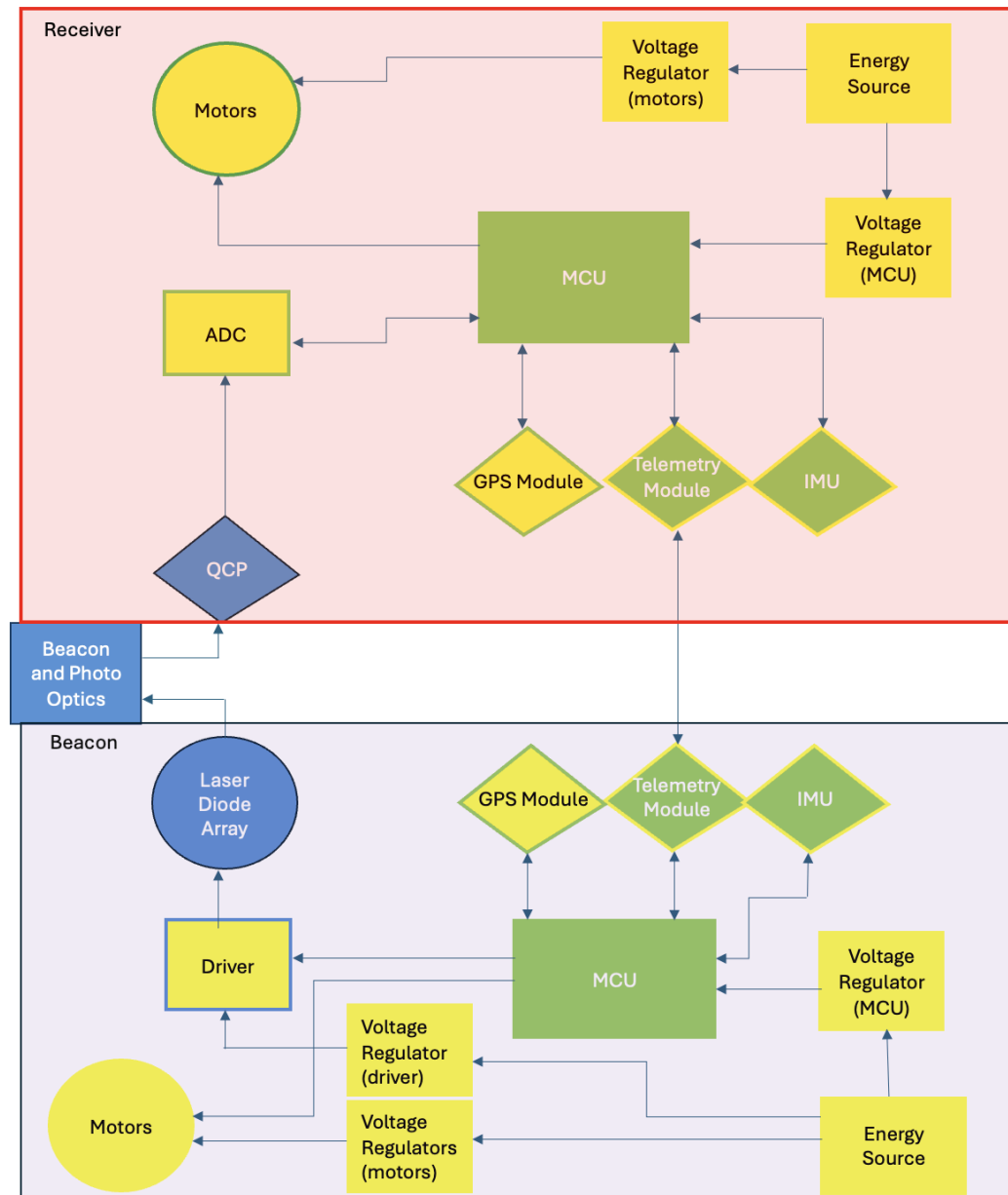


Figure 2.5.1-1: Hardware block diagram.

A quadrant photodiode consists of four separate photodiode segments or quadrants. When the light source of the beacon illuminates the photodiode each segment generates a current proportional to the light received. By comparing these currents, we hope to determine the position of the light source relative to the photodiode and align it with the beacon's transmitter/laser diode array.

However, to generally align the QPD on the receiver with the laser diodes on the beacon we have two plans of attack, the first and most simple option is to have the receiver gimbal rotate slowly at around 10 RPM while angling the lens up and down until a signal is received from the beacon. Simultaneously, the beacon will be pulsating its laser diodes and be rotating in the opposite direction at half the speed. Once the two intersect the receiver will stop its automatic rotation and via LoRa send a signal to the beacon stopping its rotation as well. The receiver's gimbal will then be controlled by the inputs given by the QPD.

The second solution to general alignment is a bit more complicated but preferable to long range target acquisition. Rather than having the beacon and receiver enter a sort of "search mode" as described above with both gimbals rotating until a signal is received, we propose that both the beacon and the receiver be outfitted with GPS and IMU modules to relay exact position and orientation over LoRa communication (assuming IMU has magnetometer). Although more complicated, having GPS and IMU modules can increase the amount of usable tracking data in addition to quicker alignment. As we continue to conduct more research and price out components, we will reassess which method is better suited for this design project. For now both options are being considered, the first option, which will be called "spin protocol" in the flowchart, will be initiated when neither GPS or light signals are received, acting as a sort of fail safe.

The reason that we are currently researching and leaning towards implementing LoRa communication for positional data is that it yields low power consumption and can transmit over long distances. However, the major drawback is the trade off between power efficiency and throughput. Currently we are in the process of calculating the necessary throughput to relay accurate positional data within 90 seconds.

In regards to the laser diode drivers, one of our stretch goals is to implement digital modulation drivers on the transmitter so that the user can modulate the laser diodes output via digital signal, which would be useful for pulsating or changing intensity based on user control. As of now we are considering three different forms of modulation, pulse-width, DAC to convert digital signals from the MCU into analog voltages to regulate current flowing through the diodes, and the third and most promising is direct digital control through the GPIO pins to the drivers. While we consider these options there are some drawbacks and potential problems with high speed modulation. The first being the obvious need for timing accuracy, our current goal is to modulate the lasers at a minimum speed of 1kHz. Another thing to consider is the power supply, if we were to use direct digital control or PWM the GPIO pins and the board must be able to handle the current necessary to power the diodes. Lastly, thermal management could be troublesome as rapid modulation can cause thermal cycling in the laser diode. With these



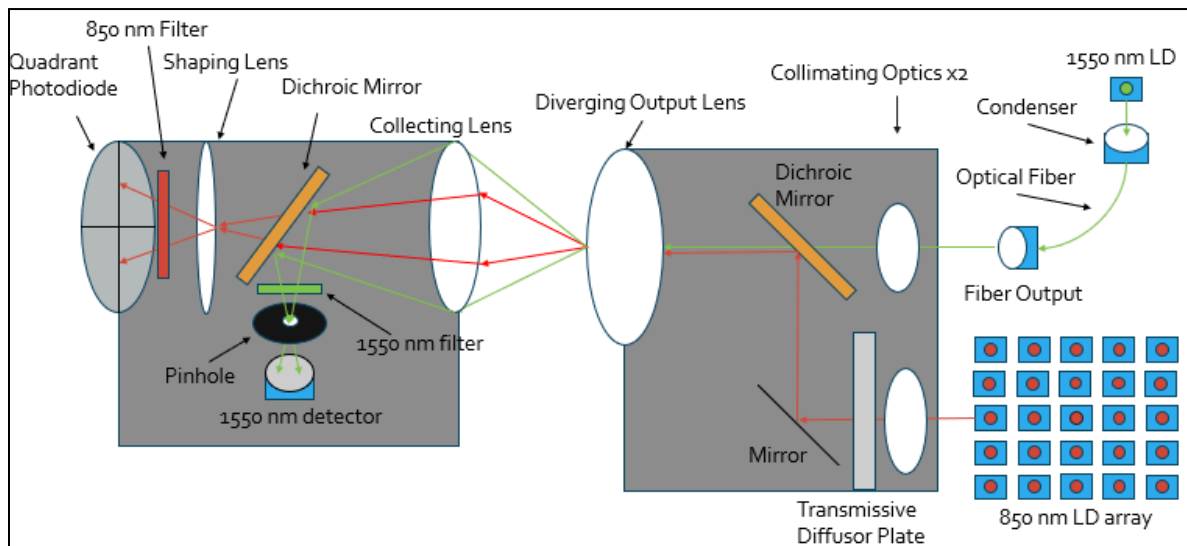
considerations and more we will for now keep modulation as a stretch goal, the assumed drivers in the diagram above are controlled by the MCU and are constant current drivers while we make part selections and weigh our modulation options.

Additionally, in regards to the laser diode and driver layout, the transmitter/beacon will be outfitted with a custom PCB to accommodate the surface mounted laser diodes on one side and the necessary drivers on the other side in an attempt to save space. Depending on modulation capabilities the power source will be either directed through a separate board housing the MCU or directly from the main 22.8V battery supply.

## 2.5.2 Optical Diagram

The optical design is crucial to this project. We must be able to project the light of our beacon with enough divergence to cover a significant area. We must then be able to collect the light from the beacon so that it illuminates the active cell of our QPD while also focusing onto a separate detector.

Laser diodes naturally diverge unevenly on the horizontal and vertical axis, so both arrays will have to be collimated into smaller, more evenly dispersed beams. They will then both pass through a dichroic mirror and a diffuser plate so that the arrays appear as a single spatially coherent beam, and then diverged upon exiting the beacon aperture. Upon reaching the receiver, the two wavelengths must be separated again so that they can be focused onto their own respective detectors. The diagram below illustrates the necessary optical setup for the beacon and receiver system.



*Figure 2.5.2-1: Diagram of the intended optical design*

## 2.5.3 Software

There will be two programmable MCU's controlling both the beacon side and the receiver side. This will be the bulk of the programmable software in this project. The first

step is to initialize all system components, including the microcontroller (MCU), the laser diodes, quadrant photodiode (QPD), gimbals, and communication interfaces. To do this, we need to set up communication protocols (e.g., I2C, SPI), configure the QPD for signal detection, and set up control parameters for the gimbals. The next step is detecting the signals from the 25 laser diodes (850 nm) and the telecom tracking lasers (1550 nm).

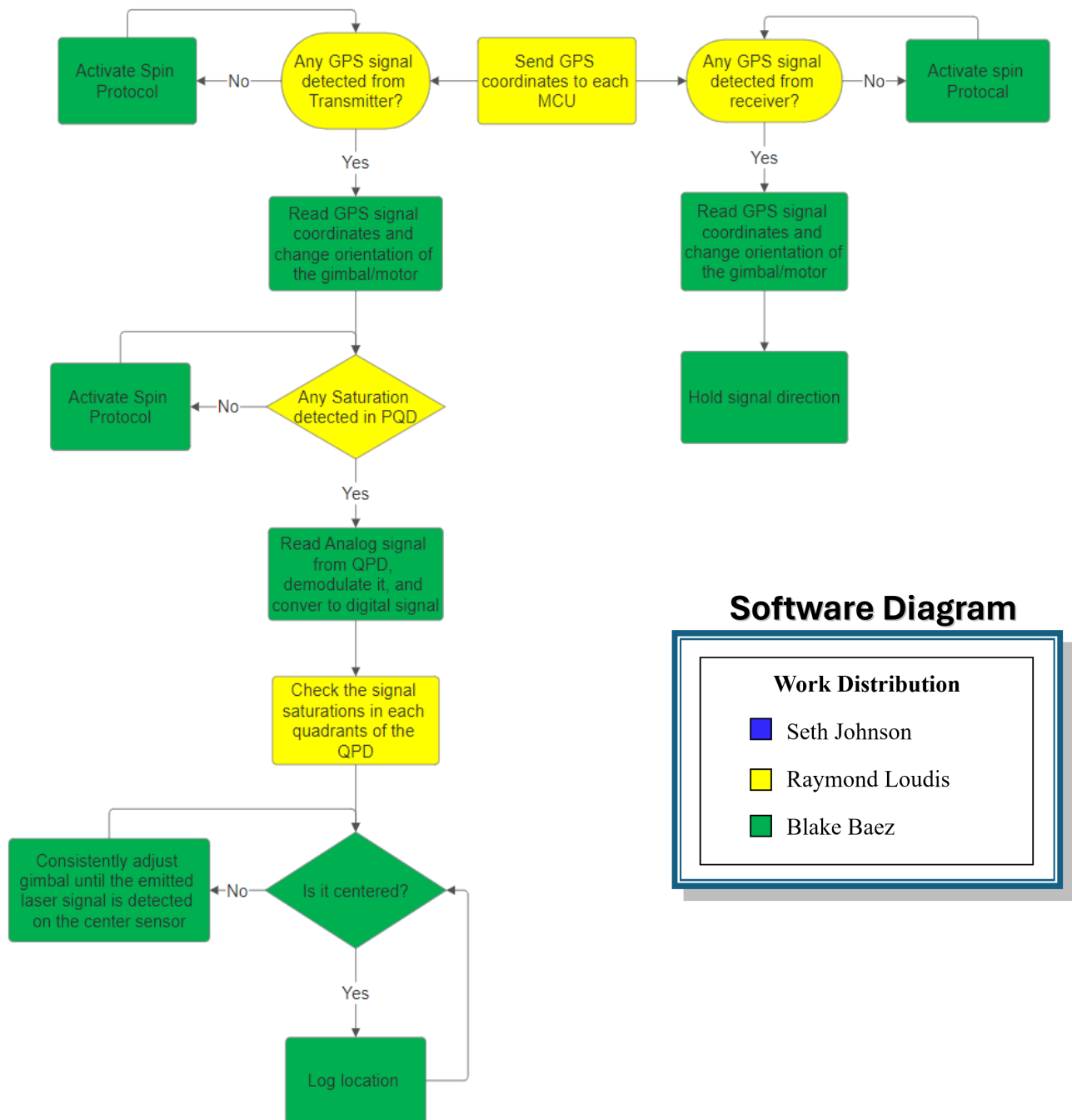


Figure 2.5.3-1: Software flowchart

To accomplish this, the MCU must take the analog signals from the QPD and use ADCs to convert analog signals to digital format. One must implement demodulation techniques to extract the pulsed signals from the noise. Then filter out ambient infrared sources. The software side of that is to apply digital filtering to eliminate remaining ambient IR interference. The tracking algorithm must also only accept the 1550nm, while the 850nm laser input is used for centering from a general location. The way it will be done is by computing the position of the laser beam on the QPD using the differences in signal intensities from the four quadrants. To move the gimbal, The MCU will contain a PID control algorithm to generate gimbal movement commands based on the position data. This PID control algorithm will be done using Ardupilot. It is important that the movement is smooth and precise to avoid signal loss.

As this project goes on, it's important that the code logs critical data and ensures reliable communication. This means logging position data, signal strength, gimbal movements, and system status for debugging and analysis. The system must be able to handle faults effectively to ensure its reliability. This can be done by implementing self-check routines to verify the functionality of all components at startup. It is also somewhat important to efficiently manage power consumption. This system can be used with a battery.

As for the software that will be used in this project, several languages have been considered. These languages are C, C++, Java, VHDL/Verilog (for FPGA-based systems), Python, and MicroPython. Some aspects of this system will be a hard real-time system. That means that making the deadline is very important, as well as making the correct calculations. To do this, one would need a deterministic and stable code. Object-oriented code tends to not be predictable, despite this, a large part of the industry still uses JAVA in a lot of microcontroller applications. Despite the use of C for important real-time tasks, the group has considered other options.

Below is a brief comparison (pros and cons) of each language:

## 1. C

- **Pros:**
  - High performance and low-level memory control, essential for real-time systems.
  - Extensive support for embedded systems and microcontrollers.
  - Well-established for use with real-time operating systems (RTOS).
- **Cons:**
  - More complex and error-prone due to manual memory management.
  - Less abstraction, which can increase development time.

## 2. Java

- **Pros:**
  - High-level language with built-in memory management and garbage collection, reducing memory leaks.

- Object-oriented programming (OOP) features for better code organization and reuse.
- Extensive libraries and frameworks.
- **Cons:**
  - Higher overhead and slower performance compared to C due to the Java Virtual Machine (JVM).
  - Less common in embedded systems and real-time applications, though possible with technologies like Real-Time Specification for Java (RTSJ).
  - Increased latency and unpredictable garbage collection times can be problematic in hard real-time systems.

### 3. C++

- **Pros:**
  - Combines the performance and low-level control of C with object-oriented features.
  - Supports both procedural and object-oriented programming, offering greater flexibility.
  - Extensive libraries and support for embedded systems.
- **Cons:**
  - Manual memory management, similar to C, which can be error-prone.
  - May introduce performance overhead compared to pure C.

### 4. Python

- **Pros:**
  - High-level language with simple syntax, making it easy to write and maintain code.
  - Extensive standard library and third-party modules.
  - Strong community support and rapid development capabilities.
- **Cons:**
  - Interpreted language with significant performance overhead, unsuitable for hard real-time requirements.
  - Limited support for low-level hardware interaction.
  - Not typically used for real-time systems due to garbage collection and interpreter overhead.

### 5. MicroPython

- **Pros:**
  - Python implementation optimized for microcontrollers.
  - Easy to write and understand, with rapid development capabilities.
  - Good for prototyping and educational purposes.
- **Cons:**
  - Performance limitations due to being an interpreted language.
  - Not suitable for hard real-time systems due to garbage collection.

- Limited functionality compared to full Python and other compiled languages.

## 6. VHDL/Verilog (for FPGA-based systems)

- **Pros:**
  - Allows designing custom hardware circuits for real-time performance.
  - Deterministic and highly predictable timing behavior.
- **Cons:**
  - Requires hardware design knowledge and is complex to learn.
  - Longer development cycles compared to software-based solutions.
  - Limited to FPGA-based systems and not applicable to general-purpose microcontrollers.

It is important to note that VHDL/Verilog has an entirely different application than our traditional functional programming language, and especially object-oriented programming. It is based on C but its job is to help design our PCB.

If this group wanted to use object-oriented language for a certain application, it would not use Python. It has very little support for low-level hardware interaction. Even compared to Java, there is way too much performance overhead that the easier coding would go to waste. It also has garbage collection just like microPython. Both of these languages are almost never used and for good reason.

The top three languages that are used in the industry for real-time systems and microcontrollers are C, C++, and JAVA. C++ and JAVA are less ideal because of the fact that they are object-oriented, however they do have support for microcontrollers. Out of these two, JAVA would be the top choice since there is indeed more support on top of Real-Time Specification for Java.

C was already the top choice for many reasons. If one could manage memory well with proper code, one of the major downsides to using C would be fixed. It also has the most support of any language by far for embedded systems and microcontrollers (this includes Real-Time Operating Systems (RTOS) Support). It has the one of highest performance and efficiency, with minimal overhead and deterministic execution. It also has low-level access to memory and hardware.

## 3 Research and Part Selections

### 3.1 Similar Projects

There are a total of 3 comparative projects that will be addressed in this section. The first two share likeness in optical alignment using a QPD while the last one focuses on real time tracking using a 2-axis gimbal such as the Gremsy T3V3 proposed to be used on our receiver.

The first related project that we will be addressing is a study conducted for Free-Space Optical (FSO) communication between a Ground Control Station (GCS) and a UAV [1]. I bring this study up first because it shares likeness in both optical tracking and using a 2-axis gimbal for tracking in real-time. This study proposes, much like our own, that we will be able to use a QPD to align the laser diodes on our beacon. Additionally, the proposal of a circular search pattern to obtain line of sight is similar to our “spin-protocol” listed above in the software flow chart. The experiments conducted in this study show that by using a laser generator, QPD sensor and driving actuators it is possible to control each side of their GCS and UAV independently to achieve perfect optical alignment for FSO communication [1]. However, there are some differences between our approach and the one used in this study. The first key difference is that their design is focused on a communication between a GCS and UAV where our project hopes to be able to achieve this alignment between two UAVs. Another key difference is that we are hoping to reduce the time and increase the range of target acquisition using GPS and LoRa modules. Furthermore, where this study transmitted the positional information received from the GCS photo diode to the UAV, we believe that positioning the beacon with the GPS and IMU will be sufficient for optical alignment and tracking. It should be noted that if our approach lacks the necessary accuracy we may consider a similar solution in both the beacon and receiver utilizing the data obtained from the QPD. Additionally, the distance between the transmitter and receiver for this study were only a distance of 100m, about a tenth of what we hope to demonstrate on our finished product.

The next comparative project that will be addressed is a study to construct a linear closed loop feedback system that compensates for beam wander in medium-range optical link applications or a Laser Beam Stabilization (LBS) system [2]. Unlike the previous study, the distance implemented here is 10km, a bit closer to our desired distance. Issues of longer distance transmission are brought to attention such as beam wander, which is caused as the optical beam propagates through free space and encounters atmospheric interference or turbulence. The turbulent medium consists of large and small scale eddies that act as prisms of varying refractive nature. The LBS system is to compensate for beam wander in a closed loop fashion, the methodology used in their optical alignment are of note and may need to be implemented into later designs for our own project given further testing. This case study shows the implementation of fast steering mirrors mounted onto actuators that reflects the focused beam onto a QPD. Essentially the technique of actuating a mirror for fine tune adjustments could be promising for our attempt of obtaining and maintaining line of sight between our beacon and receiver.

Moving on to our last comparative project, a paper on the development of a gimbal control algorithm for real-time object tracking and location acquisition from a UAV [3]. The algorithm proposed by this paper deals with two scenarios, one offering gimbal pointing at a given coordinate and the other is to align an optically with a certain point in an image plane. This paper covers the implementation of GPS systems with an IMU for position orientation for their first scenario, similar to our own, however their algorithm for tracking is designed around user target selection. Essentially the gimbal is rotated and moved into position until the user has determined line of sight, once the object of interest is selected it is able to control the gimbal to keep the object within a designated camera

frame. Although our project aims to be a bit more autonomous, the algorithms used for gimbal tracking control and the use of GPS systems for positional approximation, provide us insight into what lies ahead for our own project.

## 3.2 Constraints Due to Engineering Specifications

The first minor constraint this project must deal with is keeping the receiver and the transmitter each under 5kg. This was more of a soft constraint that was mentioned by this project's sponsor. All the components including the power supply, gimbal or encoders with dc motor, MCU/IMU, laser diode array, GPS and telemetry modules, and lenses must be 5kg for the transmitter side and 5kg for the receiver side.

Although not a strict requirement, this constraint drives the selection of lightweight materials and components. The Gremsy T3V3 for example is one of the more lightweight gimbals while also meeting our other design requirements. The downside of picking a gimbal in general is that it itself has its own weight requirement. This became a concern for the transmitter side since the group decided more of the budget would go to moving the receiver QPD and lenses.

Most of the weight will be reserved for the mounting components, lenses, and laser diodes for the transmitter and receiver. The reason is that the rest of these parts will not reach 1kg for the receiver or transmitter side. To give a part selection example for the transmitter side:

- **Micro-Controller:** Cube Orange+
- **GPS module:** Here 4
- **telemetry module:** RFD900x for the receiver

As for the receiver side part selection:

- **Micro-Controller:** ESP 32 Arduino board
- **GPS Receiver module:** Here + base
- **GPS Receiver module:** Here + base antenna
- **Telemetry module:** RFD900x for the receiver

The total weight for the receiver side is 73g for the Cube Orange + standard set, 60g for the Here 4, and 18g for the RFD900x (with attached antennas), giving us a total weight of 151g. The total weight for the transmitter side is 9.3g for the typically ESP 32 Arduino board, 18.6g for the Here + base, 60g (with cable), and 18g for the RFD900x (with attached antennas), giving us a total weight of 105.9g. This leaves us with 4.849kg for the receiver side and 4.894kg for the transmitter side.

With the weight limit in mind, the system must be robust. It will be constantly moving around, and it must be able to consistently keep the same precision. It is imperative that mounting parts for the receiver and transmitter contain lightweight alloys or composite materials that can help meet the weight constraint without compromising strength.

Another minor constraint is power consumption. The employer did not give this project a restriction on power limits. It was only mentioned in passing that this system will never be used for more than half an hour. It was also stated that running the system for half an hour was not an actual requirement either. Regardless, the battery must be large enough to run the system for a couple of minutes. The bigger the battery, the more it could take out of our budget. The battery is not factored into our weight limit however, as the power supply will be changed around for this system when in use for certain applications as stated by our employer.

Efficiency is also important. While the system must have a moderate amount of power usage so that a battery with a huge amount of Watt-hours is not needed, the system must also operate within the power limits of available batteries or power supplies. Components must be chosen for their energy efficiency. Low-power microcontrollers, energy-efficient sensors, and optimized firmware can help reduce overall power consumption.

For that reason, we have chosen Arduino boards as our micro controllers, such as the Cube Orange and ESP 32, which not only consume little power, but they also both offer power-efficient modes as well. On average, the Cube Orange + operates at a maximum of 5v at 0.5A giving us 2.5 Watts without using power-efficient modes. This means it only consumes 2.5W hours on average. The ESP 32 uses even less voltage and current: 3.3v and 0.2A, giving use 0.66 W and 0.66 Watt-hours.

One of the most important parts in terms of power usage is the laser diode array. Unlike the motors/gimbals, GPS, microcontroller, etc., the laser diodes will constantly be running. The average consumption of a one-watt 850nm laser diode is 1 Watt-hour. There will be an array of 25 of these diodes so that is 25 Watt-hour on top of the 1 Watt-hour 1550nm laser diode. This power consumption is subject to much change as it is difficult to find lasers that meet our requirements at just one watt. It is also important to note that these laser diodes will have 10 kHz track loop (without IMU compensation) and 100 Hz track loop (with IMU compensation). This changes the average power consumption to as much as 10% from the given numbers above. This is based on the duty cycle of the laser diodes for both cases.

The most important constraint that this group had to work with is the precision and accuracy of the system. This is the focal point of the project. The receiver side must be able to accurately track the transmitter side up to 10 microrad track accuracy (stationary), 500 microrad track accuracy (moving), and capable of tracking to within 5-degrees of the solar corridor. The 850nm laser signal must evenly saturate the QPD and the 1550nm laser signal must go through a center pinhole and onto the 1550 nm detector. This will drastically raise the costs of the parts.

Since the parts of the system must not only be precise, but accurate as well, the mounting parts must be fast, smooth, and stable. It will mean nothing if the receiver can accurately track the laser signal stationary but cannot hold onto that signal because it isn't stable, or the signal is moving around. This meant that the encoders with dc motors and or gimbals



must have brushless dc motors or servo motors. This limits a lot of potential motors and gimbals and raises the price.

To meet the 10 microrad track accuracy (stationary), 500 microrad track accuracy (moving), and capable of tracking to within 5-degrees of the solar corridor, the resolution of the encoders must be around 4096 pulses per revolution on the receiver side. It is not feasible to have an encoder with dc motors or gimbals of this level on both the receiver and transmitter as it would exceed our budget. This is why the group decided to have the receiver mount very accurate enough to compensate for the less accurate transmitter, thus the reason for such a high resolution for the encoders.

It has not been worked out yet but we hypothesize that a less accurate encoder with a dc motor or gimbal as low as 256 pulses per revolution could work. In case this impeded the accuracy of the system, a cheap 4000 pulse per revolution mount was given as an option that could still fit within the project budget.

Signal processing was also important and even factored into the precision and accuracy of the system. The MCU must process the signals accurately and quickly. The telemetry module was to be also able to properly send the signal out, so the microcontroller can achieve this. For this reason, the module should be rated above distances that the project is aiming to do. This will give the system insurance that it can successfully send signals despite interference. As for the MCU/IMU, it must be able to handle real-time signal processing, requiring efficient coding practices and possibly the use of hardware accelerators. All the while filtering algorithms must distinguish the laser signal from noise with precision. This aspect of the project must be hard real-time. Failure could mean incorrect tracking and no signal, making the system a failure.

For the optical design, the main constraints we'll have to work around are the divergence angle of the beacon, the field of view of the receiver, and the optical path length of the receiver. The respective values for these constraints are:

- 45-degree divergence angle of the beacon.
- 10-degree field of view angle of the receiver.
- 2 inch optical path length of the receiver optics.

These constraints are necessary for the success of the project, even if they seem arbitrary. For the beacon, the divergence angle is such that there's a wide angle where the light source is visible, but not so wide that the output power is spread too far. If the divergence were 30-degrees, it would be too narrow for practical detection. If the divergence were 60-degrees, the power would be spread too much and would be too difficult to detect. A divergence angle of 45-degrees is a good in-between so that the beacon is visible and detectable. Similarly, for the field of view of the receiver, 5-degrees would be too narrow, and 15 or 20-degrees would be too broad for accurate tracking, which makes 10-degrees a good in-between for accurate tracking.

The optical path length for the receiver is arguably the most arbitrary, however keeping

the path length short allows for more portability and smaller focused spot sizes for the beam, which lead to more accurate tracking and more efficient product.

### **3.3 Technology Investigation and Selection**

#### **3.3.1 Exploring Motion Control Solutions**

One of the first and biggest considerations that group had to make is how to move the QPD and the laser diode array. There are many ways we can practically move objects in the x and y plane but there are many complex-mirror based options as well. Some of the options we look at are galvanometer-based systems, voice coil actuators, MEMS (Micro-Electro-mechanical Systems) mirrors, stepper motor systems with precision stages, piezoelectric actuators, electro-optical deflectors (EOD), rotary encoders with DC motors, and gimbals.

The Galvanometer-based system, although highly precise with extremely fast response times, was immediately out due to complexity and cost. We believed it would put us over budget when looking up parts. Even if we could fit it into our budget, the online support and complexity of these would hinder the development of our project. Even without the high cost, they would not be practical. They work based on mirrors, motors, and the servo. The problem is if one wants to have a wider range of motion, you must have more motors and mirrors. This would just be impractical. The electro-optical deflector is similar in the sense that it uses mirrors as well. However, it uses electro-optic effects instead to deflect the light beam without moving parts. This cannot work because of several reasons: it is too expensive, complex, and it can only move the laser from specific predetermined angles.

Voice coil actuators are used for other applications besides sound. They provide high precision and fast response times as well. Their biggest downside is limited range of motion. The average range of motion for a small VCA is in the millimeter range. That will not work for this project. Somewhat similar is the Piezoelectric actuator. Piezoelectric actuators are a device that use piezoelectric effect to provide small, precise movements. These are also in the microscopic effective range and would not meet the needs of this project.

Another mirror-based system is the MEMS. This was another method that was immediately dismissed. The degree of motion was exceedingly small and for much more precise movement that was what we needed. There are no ways for the average person to even build this machine for an application such as this.

The last two options are the ones this group has settled on, gimbals and rotary encoder with DC motors. They both meet the requirements for this project. They are both affordable, have the right amount of precision we need, and are far less complex than most of these options. The gimbal would be ready as is, but the difficult part would be coding the algorithm to use it. DC motors are simpler in nature, but they would need some work. They only spin on one axis so two are needed. It is a matter of hooking them up together and being able to maintain that precision.

Receiver Mount Options					
	AVG Precision	AVG Power needed	AVG range of motion	Cost	AVG Weight
<b>Galvanometer-based system</b>	±0.5 mm	around 10-50 watts	Can cover 360 degrees in a 2D plane.	\$2,000 - \$10,000	1kg - 3 kg
<b>Voice coil actuator</b>	Sub-micron to micron-level precision	Around 10-100 watts	Limited to a few millimeters to centimeters in linear motion.	\$1,000 - \$5,000	0.5 kg - 2kg
<b>Piezoelectric actuator</b>	Nanometer to sub-micron precision	less than 10 watts	Limited to a few micrometers in linear motion.	\$500 - \$2,000	0.1kg - 0.5kg
<b>MEMS</b>	Sub-micron to micron-level accuracy	less than 1 watt	Limited range, usually a few degrees of rotation or micrometers of linear travel.	\$10 - \$500	Less than 0.1 kg
<b>Gimbals</b>	Around 0.01 degrees	5-100 watts	360 degrees in yaw, pitch, and roll	\$500 - \$5,000	1kg - 5 kg
<b>Rotary encoder with DC motors</b>	Around 0.01 degrees	5-100 watts	360 degrees in one 2D plane.	\$100 - \$1,000	0.5kg - 2 kg

*Table 3.3.1-1: Comparison of mounts for the receiver.*

For the receiver rotary encoder with DC motor, the group came up with several different brands that could work with this project. The brands are as follows: Maxon Motor, Faulhaber, Oriental Motor, Dynamotion, Pololu, and US Digital. We have chosen two options: the Maxon Motor and the Faulhaber. The reason we didn't pick US digital is because they generally don't sell motors on the level of precision we need for the receiver, just the encoders that they can be paired with. We have picked two brushless DC motors from the Maxon motor and Faulhaber Motor companies that we think would suit our needs. The rotary encoder with motor we picked from Maxon Motor is the DCX series with encoder (specifically the Maxon DCX 22 S with Encoder (High Precision Version)). Below is a graph comparison of the receiver side motors and encoders:

Receiver Side DC Motor/Encoder Consideration	
Brand/Type	Brand/Type
Maxon Motor <ul style="list-style-type: none"> <li>• <b>Motor Type:</b> DCX 22 S</li> <li>• <b>Encoder Type:</b> ENX 16 EASY Absolute</li> </ul>	Faulhaber Motor <ul style="list-style-type: none"> <li>• <b>Motor Type:</b> 3242 BX4</li> <li>• <b>Encoder Type:</b> IE3-1024</li> </ul>
Voltage	Voltage
<ul style="list-style-type: none"> <li>• <b>Nominal Voltage (motor):</b> 12 V</li> <li>• <b>Supply Voltage (encoder):</b> 3.3 V or 5 V</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Nominal Voltage (motor):</b> 12 V</li> <li>• <b>Supply Voltage (encoder):</b> 3.3 V or 5.5 V</li> </ul>
Resolution	Resolution
<ul style="list-style-type: none"> <li>• 4096 pulses per revolution (12-bit)</li> </ul>	<ul style="list-style-type: none"> <li>• 4096 pulses per revolution with quadrature encoding</li> </ul>
Operating Temperature	Operating Temperature
<ul style="list-style-type: none"> <li>• -40°C to +100°C</li> </ul>	<ul style="list-style-type: none"> <li>• -40°C to +100°C</li> </ul>
Weight	Weight
<ul style="list-style-type: none"> <li>• Motor: 66g</li> <li>• Encoder: 9g</li> </ul>	<ul style="list-style-type: none"> <li>• Motor: 179g</li> <li>• Encoder: 13.5g</li> </ul>
Current	Current
<ul style="list-style-type: none"> <li>• No load current (motor): 19.6 mA</li> <li>• Stall current (motor): 3.25 A</li> <li>• Supply current (encoder): 22 mA</li> </ul>	<ul style="list-style-type: none"> <li>• No load current (motor): 179 mA</li> <li>• Stall current (motor): N/A</li> <li>• Supply current (encoder): 20 mA</li> </ul>
Cost	Cost
<ul style="list-style-type: none"> <li>• Around \$190 (subject to add-ons)</li> </ul>	<ul style="list-style-type: none"> <li>• Around \$500 (exact cost is not certain as you must contact them for purchase it seems)</li> </ul>

*Table 3.3.1-2: Comparison of DC motors/encoders for the receiver.*

These are the two brands that had one of the highest resolutions that met within our budget, met within our loose weight requirement, and consumed a reasonable amount of power. The battery (our main power source) has not been decided but motors that consume an over 100 watts may have to be reconsidered. For reference, the max the Maxon motor can use is 39 watts, but with a typical usage being around 10 watts.

It is important to note that this project needs two of these motors since it needs to be able to rotate in the x-plane and y-plane. It is highly unlikely that these motors need anything but the base configurations so they are both within our budget. Another problem is availability for motors with these levels of precision. Many brands only allow purchase after contacting them. Price is also wildly subject to change.

The transmitter rotary encoder with a DC motor could be much cheaper and less precise. This means we had a much wider market and much more brands to choose from. We also had the option of stepper motors, dc motors, and servo motors instead of just brushless since high precision is not as required. Many of the initial brands we looked at were: NEMA Motors, Pololu Motors, Oriental Motor, Hitec, Adafruit Motors, Odrive, StepperOnline, TowerPro, TT Motor, and Seeed Studio Motors.

The encoders with DC motors that were picked are from Pololu and Oriental Motor. These brands are the most widely available for precise applications (they both offer brushless DC motors or servo motors). Although some of the other motor options are for precise applications such as TT Motor, Stepper Online, and TowerPro. The motors they offer are more geared towards other applications, eg. robotics. Pololu and Oriental Motor also support a wide range of connectors so the motors can be mounted onto each other as well as other objects.

The rotary encoder with motor that we pick from Pololu is the 37D gearmotor with encoder (specifically the Pololu 37D 12V 50:1 Metal Gearmotor with Encoder). It has a gear reduction already equipped for higher precision than the base model. Relative to the transmitter motors, the precision is fairly low but that should not be a problem. With further testing, it will be known for sure if this is sufficient or not over long distances. The rotary encoder with motor we chose from Oriental Motor is the BMU series with encoder (specifically the Oriental Motor BMU Series (BMU60-A2) with Encoder). The price range is \$200 to \$400 considerably more expensive, however much more precise. If it is found that the Pololu motor is not sufficient enough precision wise, we will switch to this motor.

Bellow is a comparison of the specifications of the two encoders with dc motors that we chose:

Transmitter Side DC Motor/Encoder Consideration	
Brand/Type	Brand/Type
Pololu <ul style="list-style-type: none"> <li>• <b>Motor Type:</b> 37D 12V 50:1 Metal Gearmotor</li> <li>• <b>Encoder Type:</b> Magnetic Encoder</li> </ul>	Oriental Motor <ul style="list-style-type: none"> <li>• <b>Motor Type:</b> BMU Series BMUD60-A2</li> <li>• <b>Encoder Type:</b> Incremental Encoder</li> </ul>
Voltage	Voltage
<ul style="list-style-type: none"> <li>• <b>Nominal Voltage (motor):</b> 12 V</li> <li>• <b>Supply Voltage (encoder):</b> 3.3 V or 5 V</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Nominal Voltage (motor):</b> 12 V</li> <li>• <b>Supply Voltage (encoder):</b> 5 V</li> </ul>
Resolution	Resolution
<ul style="list-style-type: none"> <li>• 64 pulses per revolution (CPR) (256 counts per revolution with quadrature encoding)</li> </ul>	<ul style="list-style-type: none"> <li>• 1000 pulses per revolution (PPR) (4000 counts per revolution with quadrature encoding)</li> </ul>
Operating Temperature	Operating Temperature
<ul style="list-style-type: none"> <li>• -40°C to +100°C</li> </ul>	<ul style="list-style-type: none"> <li>• -0°C to +40°C</li> </ul>
Weight	Weight
<ul style="list-style-type: none"> <li>• Motor: 205g</li> </ul>	<ul style="list-style-type: none"> <li>• Motor: 1.3kg</li> </ul>
Current	Current
<ul style="list-style-type: none"> <li>• No load current (motor): 200 mA</li> <li>• Stall current (motor): 5.5 A</li> <li>• Supply current (encoder): 22 mA</li> </ul>	<ul style="list-style-type: none"> <li>• No load current (motor): 179 mA</li> <li>• Stall current (motor): 3.4 A</li> <li>• Supply current (encoder): 50 mA</li> </ul>
Cost	Cost
<ul style="list-style-type: none"> <li>• \$50 to \$70</li> </ul>	<ul style="list-style-type: none"> <li>• \$200 to \$400</li> </ul>

*Table 3.3.1-3: Comparison of DC motors/encoders for the transmitter.*

The receiver gimbal is one of the more practical options that we are considering in order to reach our specifications. It's important that the gimbal has high precision and stability. It also needs to have the necessary connections to support the microcontroller and other necessary parts. The top 6 viable brands that came up were: Gremsy, DJI, Freefly Systems, Moza Zhiyun, and FreiyuTech.

<b>Receiver Gimbal Consideration Part 1</b>					
<b>Brand/Type</b>	<b>Precision</b>	<b>Tilt Range</b>	<b>Operating Temp</b>	<b>Cost</b>	<b>Payload capacity</b>
Gremsy T3V3	±0.01 degrees	±90°	-20°C to 50°C	About \$2500	1.45kg
DJI Ronin-S	±0.02 degrees	-95° to +180°	-20°C to 45°C	About \$750	3.6 kg
Freefly Movi Pro	±0.02 degrees	±105°	-20°C to 50°C	About \$6,500	6.8 kg
Zhiyun Crane 3S	±0.02 degrees	-135° to +185°	-10°C to 45°C	About \$750	6.5 kg
FeiyuTech AK4500	±0.05 degrees	-230° to +175°	-10°C to 45°C	About \$700	4.6 kg
Moza Air 2	±0.02 degrees	-95° to +180°	-10°C to 45°C	About \$600	4.2 kg

*Table 3.3.1-4: Comparison of gimbal options for the receiver*

Precision was the first thing that was looked at first for these brands to be considered for this project. The next most important was cost. The only one of these options that was outside of the project's budget was the Freefly Movi Pro. All of these brands are within the expected payload capacity (below 1kg). The operating temp for each gimbal is well above the temperatures that Florida reaches on a hot day and anything 45 degrees and above is plenty of headroom for any potential overheating issues. As far as the weight is concerned, some of the heavier models can pose a future problem when mounting but it is not a current concern as the heaviest model does not exceed 3kg (the employer gave a non-strict limit of 5kg for the receiver and transmitter side each). This next graph lists some additional specifications that can contribute to the consideration; however most of them are features that should be known in order to work with them. The rest of the specifications and additional notes on each gimbal are listed below:

Receiver Gimbal Consideration Part 2				
Brand/Type	Input Power	Communication Protocol	Weight	Additional Notes
Gremsy T3V3	12-52V	PWM, S.BUS, CAN, PPM, UART, and Bluetooth	1.7 kg	The Gremsy has a lot of mounting points compared to the other gimbals. It also has its own power source.
DJI Ronin-S	12-16V	Bluetooth, USB	1.85 kg	It is hand-held and is not designed to be mounted to anything.
Freefly Movi Pro	14-25V	Bluetooth, Wi-Fi	2.65 kg	The mounting points are clips that attach to tubes.
Zhiyun Crane 3S	24-30V	Bluetooth, USB	2.47 kg	Has a stand but also cannot be mounted to anything.
FeiyuTech AK4500	7.4V	Bluetooth, USB	1.6 kg	It is hand-held and is not designed to be mounted to anything.
Moza Air 2	16.8V	Bluetooth, USB	1.6 kg	Poor mounting support for non-cameras

*Table 3.3.1-5: Comparison of gimbal options for the receiver*

The Gremsy not only had the most precise control, but it was also compact. It comes with direct drive motors, high-resolution encoders, and many attachment points. These features contribute to the gimbal's ability to quickly and accurately adjust its orientation in response to commands derived from the QPD data. It also comes with various software support and control connectivity. This gives us several options to work on in case one option is more ideal. It has not been fully decided on which gimbal would suit this project the most but the Gremsy T3V3 is this group's top pick.

For the transmitter gimbal, the top picks at most several hundred dollars. Here's the top 6 picks we found: Zhiyun Smooth 4, Hohem iSteady Multi, Feiyu G6 Max, MOZA Mini-MI, DJI OM 4 SE, and Zhiyun CRANE M2S. The gimbal on the transmitter side does not have to be accurate, unlike the receiver side. It just needs to be able to have good mounting and be able to steadily hold a position. The following options and their specifications are listed below:



Transmitter Gimbal Consideration Part 1					
Brand/Type	Input Power	Tilt Range	Operating Temp	Cost	Payload capacity
DJI OM 4	7.2V	-106.54° to 235.5°	0°C to 40°C	\$150	230g
Hohem iSteady Multi	3.7V	±160°	-10°C to 45°C	\$140	400g
Feiyu G6 Max	7.4V	±140°	-10°C to 45°C	\$180	1.2 kg
Zhiyun CRANE M2S	7.4V	±160°	-10°C to 45°C	\$180	About 1kg
Moza Mini-MI	7.4V	±155°	0°C to 50°C	About \$110	300g
Zhiyun Smooth 4	7.4V	±120°	-10°C to 45°C	About \$100	210g

*Table 3.3.1-6: Comparison of gimbal options for the transmitter.*

All of these options were well within the project budget so that was not a concern. The biggest concern was the payload capacity. The expected weight for the laser diode array and lenses should be no more than a couple hundred grams at maximum. The issue is that two of these models are below 300g so they will likely not be chosen. The operating temps were still well above the temps experienced in the hot Florida sun.

As far as control connectivity goes, they all have bluetooth, to which our esp 32 arduino board has support for. The only issue is some of the software compatibility and driver access for these gimbals. A lot of these gimbals such as the DJI OM 4 and the Zhiyun Smooth 4 are known not to be very customizable and sometimes struggle to work with android apps. It is also important to note that none of these brands published their accuracy ratings.

Out of these picks, it was decided that the Hohem iSteady Multi and the Feiyu G6 Max were the most suitable transmitter gimbals for this project. Not only did it meet our weight constraints, both of these gimbals are well known for its 3-axis stabilization system. The rest of the specs and additional notes are available below:

Transmitter Gimbal Consideration Part 2			
Brand/Type	Communication Protocol	Weight	Additional Notes
DJI OM 4	Bluetooth	390g	It only has a small magnetic attachment.
Hohem iSteady Multi	Bluetooth	400g	Has multiple attachment points on a large mount.
Feiyu G6 Max	Bluetooth, Wi-Fi	1.2 kg	Has two decent attachment points. One horizontal and one vertical.
Zhiyun CRANE M2S	Bluetooth, Wi-Fi	About 1kg	Has two decent attachment points and comes with a stand.
Moza Mini-MI	Bluetooth	543g	Comes with a stand but the attachment points are not the best. It is only designed for a phone.
Zhiyun Smooth 4	Bluetooth	547g	Poor attachment points that are only designed for a phone.

*Table 3.3.1-7: Comparison of gimbal options for the transmitter.*

### 3.3.2 Exploring MCU and IMU Solutions

The next step for this project was to find a suitable MCU and IMU. Our employer wanted a reliable setup. Some of the models that were considered are as follows: the Pixhawk 4, Holybro Durandal, and the Cube Orange+ Standard Set ADS-B. All three of these brands and their corresponding products are an MCU and IMU combination. All of these brands contain a magnetometer, CAN, I2C, UART, SPI, USB, as well as a barometer chip. The main consideration that this group has to take into account is what standards and software would be ideal choices to accomplish the requirements of this project. This is important because each of these IMU/MCU combos uses different software and standards. The Pixhawk 4 uses that hardware platform PX4 with the NuttX OS. We would have to choose the QGroundControl software to work with as well. It is unknown at this point whether this is the ideal software to work with. Meanwhile, the Cube Orange+ can work with both the PX4 hardware platform and Ardupilot. This flexibility makes it an enticing candidate. Here are the specs of the Pixhawk 4, Holybro Durandal, and Cube Orange+ Standard Set below:

Receiver MCU/IMU Consideration		
Brand/Type	Brand/Type	Brand/Type
Pixhawk 4 <ul style="list-style-type: none"> <li>• <b>MCU:</b> STM32F765 (ARM Cortex-M7, 216MHz)</li> </ul>	Holybro Durandal <ul style="list-style-type: none"> <li>• <b>MCU:</b> STM32H743 (ARM Cortex-M7, 400MHz)</li> </ul>	Cube Orange+ Standard Set <ul style="list-style-type: none"> <li>• <b>MCU:</b> SSTM32H743 (ARM Cortex-M7, 400MHz)</li> </ul>
RAM	RAM	RAM
<ul style="list-style-type: none"> <li>• 512KB</li> </ul>	1MB	1MB
Flash Memory	Flash Memory	Flash Memory
<ul style="list-style-type: none"> <li>• 2MB</li> </ul>	<ul style="list-style-type: none"> <li>• 2MB</li> </ul>	<ul style="list-style-type: none"> <li>• 2MB</li> </ul>
IMU	IMU	IMU
<ul style="list-style-type: none"> <li>• Dual IMU (ICM-20689, BMI055)</li> </ul>	<ul style="list-style-type: none"> <li>• Dual IMU (ICM-20689, BMI055)</li> </ul>	<ul style="list-style-type: none"> <li>• Triple Redundant IMUs (ICM-20948, BMI055, LSM303D)</li> </ul>
Barometer	Barometer	Barometer
<ul style="list-style-type: none"> <li>• MS5611</li> </ul>	<ul style="list-style-type: none"> <li>• MS5611</li> </ul>	<ul style="list-style-type: none"> <li>• MS5611</li> </ul>
Magnetometer	Magnetometer	Magnetometer
<ul style="list-style-type: none"> <li>• IST8310</li> </ul>	<ul style="list-style-type: none"> <li>• IST8310</li> </ul>	<ul style="list-style-type: none"> <li>• IST8310</li> </ul>
Communication Protocol	Communication Protocol	Communication Protocol
<ul style="list-style-type: none"> <li>• CAN, I2C, UART, SPI, USB</li> </ul>	<ul style="list-style-type: none"> <li>• CAN, I2C, UART, SPI, USB</li> </ul>	<ul style="list-style-type: none"> <li>• CAN, I2C, UART, SPI, USB</li> </ul>
Cost	Cost	Cost
<ul style="list-style-type: none"> <li>• About \$200</li> </ul>	<ul style="list-style-type: none"> <li>• About \$200</li> </ul>	<ul style="list-style-type: none"> <li>• About \$350</li> </ul>

Table 3.3.2-1: Comparison of Receiver MCU/IMU modules

It is important to note that the IMU that comes in the Pixhawk 4 and the Holybro Durandal do not come with an accelerometer, gyroscope, or GNSS. It is highly likely that an accelerometer and gyroscope would be needed in these micro controllers (The GNSS may not be required because we are using a GPS). The Cube Orange+ however does have all of these features built in, making it the most convenient package by far. The downside is that it is the most expensive at \$350.

If it is decided either the Pixhawk 4 or Holybro Durandal MCU/IMU combo will be used, the group has decided on two possible IMU chip additions that come with a gyroscope, accelerometer, and magnetometer (the Droteck Sirius having a GNSS as well). The specs are listed in the graph below:

IMU Chip	
Brand/Type	Brand/Type
InvenSense • IMU: MPU-9250	Drotek Sirius • IMU: RTK GNSS
Gyroscope	Gyroscope
• 3-axis	• 3-axis
Accelerometer	Accelerometer
• 3-axis	• 3-axis
Magnetometer	Magnetometer
• -3-axis	• -3-axis
GNSS	GNSS
• N/A	• RTK-enabled GNSS
Cost	Cost
• \$45	• \$275

*Table 3.3.2-2: Comparison of IMU chips.*

It should be noted that both of these are just a chip. They do not have an accompanying pcb to go along with them. A PCB would need to be designed and created in order to incorporate said chips. Then they would need to be set up to communicate with the MCU. The group is worried this might hold the project back if so much time is spent on troubleshooting something to save some money, despite being within our budget. That is

why our main choice is the Cube Orange+ for the MCU/IMU combo for the GCS (ground control station).

The receiver microcontroller must be robust and powerful. The reason is that the group decided that it would be most efficient if it did the heavy lifting in terms of precision. It needs to accurately track the laser signal, which includes fine motor control as well as quick and accurate reading of the QPD.

The transmitter microcontroller is different. It does need the same level of communication protocol, processing speed, or robustness. This does not mean that our choices can have slow processors or low flash memory. The good news is that the cheap microcontroller market is saturated, and innovation is booming. This allows the project to much more easily reach budget goals.

The brands that got consideration had to be easily bought, like the transmitter, had to be Arduino compatible (this means that we are using C code for this microcontroller as well), and compatible with all of the communication protocols the group will be using. Luckily, most microcontrollers under \$50 dollars use UART, USB, and I2C. All of the chosen ones use relatively low power and contain SRAM. The following microcontrollers are the types that the group has decided on: ESP 32, Arduino Due, Teensy 4.0, and Raspberry Pi Pico. Their specifications are listed below:

<b>Transmitter Microcontroller Consideration Part 1</b>					
<b>Brand/Type</b>	<b>Processor</b>	<b>Flash Memory</b>	<b>SRAM</b>	<b>Communication Protocol</b>	<b>Average Cost</b>
ESP 32	Dual-core Tensilica LX6 microprocessor, up to 240 MHz	4 MB	520 KB	3 UART, 3 SPI, 2 I2S, 2 I2C, 1 USB	\$10 - \$20
Arduino Due	Atmel SAM3X8E ARM Cortex-M3, 84 MHz	512 KB	96 KB	4 UART, 2 SPI, 2 I2C, 1 CAN, 1 USB	\$35 - \$50
Teensy 4.0	ARM Cortex-M7, 600 MHz	2 MB	1 MB	7 UART, 3 SPI, 3 I2C, 1 I2S, 1 CAN, 1 USB	\$20 - \$25
Raspberry Pi Pico	Dual-core ARM Cortex-M0+, up to 133 MHz	2 MB	264 KB	2 UART, 2 SPI, 2 I2C, 1 USB	\$4 - \$6

*Table 3.3.2-3: Comparison of transmitter microcontrollers Part 1.*

In terms of CPU performance, all the microcontrollers seem sufficient, even the Arduino Due. The issue comes when looking at flash memory and SRAM. With so little at 512 KB of Flash Memory and 96 KB of SRAM, the group is not confident it could complete its necessary calculations or algorithms before overflowing and having to reboot. For unknown reasons as well, it is by far the highest in price among the options. For these main two reasons, it's the least likely to be chosen.

In terms of communication protocol, all the microcontrollers are excellent except the Raspberry Pi Pico. Two UART connections do not leave much in terms of headroom. It also only has 26 GPIO and 3 channels of 12-bit ADC. Although it is unlikely this group will use all of these pins and channels, it is important to note it has much less than its competitors. As this project is further developed. It may be necessary to attach parts that require analog connections or GPIO pins.

One standout specification to note is that there is only one microcontroller type that has wireless connectivity built in: the ESP 32. This is important because it allows for future possible connectivity options. Some of the parts this group already selected can use Wi-Fi and or Bluetooth. The remaining specs on the microcontrollers are listed in the graph below:

Receiver Gimbal Consideration Part 2				
Brand/Type	Input Power	Communication Protocol	Weight	Additional Notes
Gremsy T3V3	12-52V	PWM, S.BUS, CAN, PPM, UART, and Bluetooth	1.7 kg	The Gremsy has a lot of mounting points compared to the other gimbals. It also has its own power source.
DJI Ronin-S	12-16V	Bluetooth, USB	1.85 kg	It is hand-held and is not designed to be mounted to anything.
Freefly Movi Pro	14-25V	Bluetooth, Wi-Fi	2.65 kg	The mounting points are clips that attach to tubes.
Zhiyun Crane 3S	24-30V	Bluetooth, USB	2.47 kg	Has a stand but also cannot be mounted to anything.
FeiyuTech AK4500	7.4V	Bluetooth, USB	1.6 kg	It is hand-held and is not designed to be mounted to anything.
Moza Air 2	16.8V	Bluetooth, USB	1.6 kg	Poor mounting support for non-cameras

*Table 3.3.2-4: Comparison of transmitter microcontrollers Part 2.*

The operating temperature is also extremely high on the ESP 32. It can reach 125 degrees Celsius. This is a cut above the other microcontrollers. This is all rolled in a package cheaper than almost every other microcontroller except the Raspberry Pi Pico.

### 3.3.3 Exploring GPS Solutions

GPS was another secondary addition as it will be used to support the precise tracking. Nonetheless, the GPS must be accurate enough so that the receiver side does not have trouble locating the laser signal. Any module that has accuracy within meters or above will not be sufficient. The GPS should allow the laser diode array to reliably contact the QPD so that the receiver does not have to search for a signal in the general area that the GPS reported. A more accurate GPS also means that it could calculate the position quicker. The group decided that highly reliable positioning and accuracy within centimeters was required.

Update rate was another important consideration. The update rate of the GPS module determines how frequently it provides position updates. Higher update rates are required in this project because the transmitter can be moving as well as said application requiring real-time position data. The ability for the system to reliably transmit between microcontrollers while they are being moved also requires a module with great sensitivity.

The project description notes that not only is the system a real-time system, it must be secure and ideally encrypted. With accuracy and stability in mind, these GPS modules will need to have their own suitable GNSS module. This means that it can work anywhere in the world as GPS only includes the US satellites. GNSS includes the satellites from other countries such as Russia, China, and the EU. Having access to multiple satellites improves accuracy, redundancy, and availability. This comes at a cost however as it drastically raises the price of the GPS module.

GNSS RTK (Real-Time Kinematic) products seem to be ideal for this purpose. Some of the products the group considered were Emlid Reach RS2 and Reach M2, Ublox C099-F9P Application Board, ArduSimple SimpleRTK2B, Here3+ & Here+ RTK Base (M8P) Combo, and Tersus GNSS BX306. The biggest problem the group ran into with some of these selections is price. If the budget is there, it would be nice to have them, but at a price of the Emlid Reach RS2 (not the M2 model) and Tersus GNSS are expensive (at around \$1000+). If the budget were higher, a better GPS module would be chosen. This would make the system much more reliable and increase the speed at which the exact location of the receiver is established. This would also greatly improve the moving accuracy of the system. The Emlid Reach M2, at a cheaper price of \$500 to \$600 compared to some of its adversaries is a great deal. Below is a graph of specifications for the GPS modules considered:

GPS Module Consideration						
Brand/Type	Communication Protocol	Channels	RTK Accuracy	Constellations Supported	Update Rate	Cost
Emlid Reach M2	UART, USB, Bluetooth 4.0, Wi-Fi 802.11 b/g/n	184 channels	Horizontal 7 mm + 1 ppm, Vertical 14 mm + 1 ppm	GPS/QZSS L1C/A, L2C; GLONASS L1OF, L2OF; Bei Dou B1I, B2I; Galileo E1-B/C, E5b; SBAS L1C/A	1 Hz, 5 Hz, 10 Hz, 14 Hz, 20 Hz	\$500 - \$600
Ublox C099-F9P	USB, UART, I2C, SPI	184 channels	Horizontal 10 mm + 1 ppm, Vertical 20 mm + 1 ppm	GPS L1C/A, L2C; GLONASS L1OF, L2OF; Galileo E1-B/C, E5b; BeiDou B1I, B2I; QZSS L1C/A, L2C; SBAS L1C/A	Up to 20 Hz	Around \$300
ArduSimple SimpleRTK2B	UART, USB, Bluetooth, Wi-Fi (via expansion)	184 channels	Horizontal 10 mm + 1 ppm, Vertical 20 mm + 1 ppm	GPS L1C/A, L2C; GLONASS L1OF, L2OF; Galileo E1-B/C, E5b; BeiDou B1I, B2I; QZSS L1C/A, L2C	Up to 20 Hz	Around \$200
Tersus GNSS BX306	RS-232, USB, CAN	384 channels	Horizontal 8 mm + 1 ppm, Vertical 15 mm + 1 ppm	GPS L1/L2, GLONASS G1/G2, BeiDou B1/B2, Galileo E1/E5b	Up to 20 Hz	Around \$1000
Here3+ & Here+ RTK Base (M8P) Combo	CAN, UART, USB	184 channels	Horizontal: 10 mm + 1 ppm, Vertical: 20 mm + 1 ppm	GPS L1C/A, L2C, GLONASS L1OF, L2OF Galileo, E1-B/C, E5b, BeiDou B1I, B2I, QZSS L1C/A, L2C, SBAS L1C/A	Up to 10 Hz	\$350

Table 3.3.3-1: Comparison of GPS modules.

With only a significant addition of weight (as far as this project is considered it should not matter). We believe the Here3+ & Here+ RTK Base (M8P) Combo is ideal. It is considerably cheaper than most of the options (it is priced at \$305) and it meets our known specifications. We left the other options open if the project runs into complications and different modules are required.



### 3.3.4 Exploring Telemetry Module Solutions

Once the research was finalized on the GPS module, we began research on how to communicate between the two MCUs. The first thing each micro controller needs to do is find its own location, altitude, and acceleration. Once it has done that, it needs to be able to communicate said information to the other microcontroller. This project requires this to be done long distance and wirelessly. Some of the options we researched are listed below:

MCU Communications Consideration		
Type	Distance	Average Cost
Wi-Fi	Typically up to 100 meters indoors, longer outdoors depending on environmental conditions and antennas.	\$5 - \$20
Bluetooth	Around 10 meters for Class 2 devices (standard), up to 100 meters for Class 1 devices (extended range).	\$5 - \$10 (depending on version)
RF (Radio Frequency) Modules	Around a couple 100 meters, can be extended with external antennas.	\$5 - \$10
Cellular Modules	Coverage area depends on cellular network provider, can range from local to global coverage.	\$20 - \$60
LoRa (Long Range)	Can reach several kilometers in rural areas on average. This depends on how much noise is in the area.	\$20 - \$60
Satellite Communication	Global coverage, can communicate from anywhere on Earth.	\$400 - \$2000
Visible Light Communication (VLC)	Typically up to 10 meters, depending on the intensity of the light source and ambient light conditions.	\$20 - \$200
Infrared (IR) Communication	Generally up to a few meters (line-of-sight).	Less than \$5

Table 3.3.4-1: Comparison of Telemetry Modules.

The first requirement listed in this project requires that the system to work around 1 kilometer. This already excludes Wi-Fi, Bluetooth, most RF modules, visible light communication, and infrared communication. None of these options could reach over a couple hundred meters, especially with extensive setup and or, in the case of Wi-Fi, a physical connection of ethernet to the board itself. The group did see some modules done using Wi-Fi to connect to the microcontroller remotely and then said micro controller communicates with the other microcontroller with Wi-Fi as well. This, however, would require the system to be in range of a base station. This system should be autonomous. This left the group with three options: LoRa, satellite communication, and Cellular modules. This was easily changed to two options as satellite communication was too expensive.

One important thing the group had to consider is that the system should be super reliable in any location as it is a real-time system. For one, the system should be able to work in most locations on the planet, including rural areas. Of the two options left that the group was considering, using a cellular module would require cell towers. LoRa is also one of the lowest power consuming of the researched modules. It is also not necessary that the system can communicate worldwide as the limit is how far the QPD can reliably read the laser diode array. LoRa modulation is designed to be robust against interference and noise, which can be beneficial in environments where there might be other sources of electromagnetic interference (EMI). This includes near-infrared light sources or other telemetry signals. Cellular modules can easily be affected by interference, such as buildings and other signals, especially when using LTE and above. Choosing modules that are compatible with multiple wavelengths adds to cost. The added complications with cellular. They tend to be lacking incompatible or easy to use communication protocols such as UART. For this reason, the group chose LoRa as our telemetry module.

There are many different LoRa modules in terms of performance. The ones the group looked at had to have a certain frequency band and were at least FCC compliant. Among the topmost used brands in this category, the group had to choose ones that had a balance in data rate, range and power consumption. Among these, some were knocked out that had no compatible communication protocol. The following were the following: Digi XBee-PRO 900HP, Digi XTend 900MHz RF Modem, XStream-PKG RF Modem, Yost V2-900M, CUAV P9 Radio Telemetry Module, Holybro Telemetry Radio V3, and RFD900x-US. A graph comparing their specs is listed below:

Telemetry Module Consideration Part 1					
Brand/Type	Input Power	Frequency Range	Operating Temp	Range	Cost
Digi XBee-PRO 900HP	+5 V nominal, (+3.5 V min, +5.5 V max)	900 MHz	-40 - 85°C	Up to 14 kilometers with high-gain antenna	\$50 - \$70
Digi XTend 900MHz RF Modem	2.1 to 3.6 VDC	900 MHz	-40° - 85°C	Up to 64 kilometers with high-gain antenna	About \$200
XStream-PKG RF Modem	2.8 to 5.5 VDC	900 MHz	-40° - 85°C	Up to 32 kilometers with high-gain antenna	\$150 - \$200
Yost V2-900M	6 to 30 VDC	902-928 MHz	-40° - 85°C	40 miles with high-gain antenna	\$120 - \$150
CUAV P9 Radio Telemetry Module	5-12V	902-928 MHz	-40°C - 85°C	Up to 60 kilometers with high-gain antenna	\$69.00
Holybro Telemetry Radio V3	3.7-6V	915 MHz	-40°C - 85°C	1 to 2 kilometers	\$39.00
RFD900x-US	4.75-5.5V	902-928 MHz	-40°C - 85°C	40 kilometers depending on antennas and setup (80 kilometers demonstrated)	\$96

*Table 3.3.4-2: Comparison of LoRa Modules part 1.*

Concerning the range, just being able to transmit up to 1 or 2 kilometers does not mean it is good enough for our application. It needs to reliably communicate up to that distance without using a low power. This meant that the Holybro Telemetry Radio V3 and potentially the Digi XBee-PRO 900HP would not suffice for this project.

Another issue is the cost. Digi XTend 900MHz RF Modem, XStream-PKG RF Modem, and Yost V2-900M are too expensive. This graph denotes their cost per module. The system needs two modules in order to communicate.

Operating temp and frequency range were all within the expectations for this system. All of the modules were able to operate at 85 degrees celsius and the frequency range was around the 900 to 930 MHz range. ALL modules were also compatible with UART, the group's communication protocol of choice. All modules come with antennas but only the RFD900x-US, Yost V2-900M, XStream-PKG RF Modem, and Digi XTend 900MHz RF Modem come with their own high-gain antenna.

Below are additional specs that the group weighed on when considering the right module for this project:

<b>Telemetry Module Consideration Part 2</b>					
<b>Brand/Type</b>	<b>Current Consumption</b>	<b>Air Data Rate</b>	<b>Communication Protocol</b>	<b>Weight</b>	<b>Receive Sensitivity</b>
Digi XBee-PRO 900HP	215 mA at 3.3V (transmit), 29 mA at 3.3V (receive)	Up to 200 Kbps	UART, RS-232, RS-485, USB	3.9g	-101 dBm
Digi XTend 900MHz RF Modem	900 mA at 5.5V (transmit), 80 mA at 5.5V (receive)	10 Kbps to 115.2 Kbps	UART, RS-232, RS-485, USB, Ethernet	84g	-110 dBm
XStream-PKG RF Modem	150 mA at 9V (transmit), 50 mA at 9V (receive)	10 Kbps	UART, RS-232, RS-485	84g	-110 dBm
Yost V2-900M	350 mA at 12V (transmit), 40 mA at 12V (receive)	Up to 500 Kbps	UART, USB	28g	-108 dBm
CUAV P9 Radio Telemetry Module	100-180mA (transmit) at 12v, 20-30mA at 12v(receive)	902-928 MHz	UART	55g	-110 dBm
Holybro Telemetry Radio V3	500mA at 6v (transmit), 80mA at 6v(receive)	915 MHz	UART, USB	22.7g	-117 dBm
RFD900x-US	1A at 5.5v(transmit), 80mA at 5.5v(receive)	902-928 MHz	UART	18g	-117 dBm

*Table 3.3.4-3: Comparison of LoRa Modules part 2*

### 3.3.4 Optical Components

When choosing optical components, especially lenses, there are much less comparisons to make. For lenses, the only real factor to consider is the material, since other factors like focal length, diameter, and anti-reflection coating are design choices. The most common lens materials are N-BK7 and UV Fused Silica. Both materials can transmit the wavelengths we require, so choosing between them will be based on cost and damage threshold. The general pros and cons of both materials can be summarized in the table below.

Pros/Cons	N-BK7	UV Fused Silica
Pro	Lower Cost	Higher Chemical Resistance
Pro	Higher Transmission Band	Lower Scattering Loss
Pro	High Mechanical Damage Threshold	Higher Thermal Damage Threshold
Con	Lower Thermal Damage Threshold	Lower Mechanical Damage Threshold
Con	Higher Scattering Loss	Higher Cost
Con	High Density	Smaller Transmission Band

*Table 3.3.4-1: Comparison of common lens materials.*

Since UV Fused Silica has a higher damage threshold but costs more, we'll likely use that material for most of the transmitter system since the beacon will emit a high power. However, we can use the cheaper N-BK7 for the receiver side since the incident power will be much lower.

The other optical components that require comparison are the dichroic mirrors and diffuser plate. Dichroic mirrors will transmit a certain wavelength band while reflecting another, which makes them essential components to the optical design. They are often sold by Thorlabs and Edmund Optics for reasonable prices, so we'll compare the dichroic mirrors from both companies that are 1 inch in diameter and capable of transmitting and reflecting our required wavelengths. The comparison can be summarized in the table below.

Company	Product ID	Transmission Band (nm)	Reflection Band (nm)	Cost
Thorlabs	DMLP1180	1260 - 1700	750 - 1100	\$230.46
Thorlabs	DMLP1000	1020 - 1550	520 - 985	\$310.06
Edmund Optics	87-039	985 - 1600	715 - 900	\$171.00
Edmund Optics	87-040	1035 - 1600	750 - 950	\$176.00

*Table 3.3.4-2: Comparison of dichroic mirrors*

While the Edmund Optics mirrors may appear to be much cheaper whilst transmitting and reflecting the required wavelengths, their listed diameters are 25mm rather than 1 inch (25.4mm). It's not a huge difference, however it can affect their compatibility with different optomechanical components. If compatibility is a non-issue, then we'll likely use the Edmund Optics 87-039. If there is a problem with compatibility, then we'll use the Thorlabs DMLP1180. Both mirrors are the cheaper option from their respective companies that will meet the requirements of this project.

The last optical component that requires comparison is the diffuser plate. Diffuser plates will help blend the laser diode array so that it appears as a single light source, however they can also absorb a lot of optical power whilst adding extra divergence to the beam. We'll have to select a diffuser plate that transmits the maximum amount of power whilst also applying the least amount of divergence. The plate will also require a higher damage threshold since it will be placed directly in front of the laser array. There are engineered diffuser plates that can accomplish this, however they are much more expensive than simple sanded glass. We'll once again be turning to Thorlabs and Edmund Optics and comparing the best options for engineered diffusers.

Company	Product ID	Transmission Efficiency (%)	Dispersion Angle (Deg)	Cost
Thorlabs	ED1-C20	90	20	\$142.56
Thorlabs	ED1-C50	90	50	\$142.56
Thorlabs	EDG5C20	90	20	\$280
Edmund Optics	47-680	85	0.5	\$457.50
Edmund Optics	55-849	85	5	\$457.50
Edmund Optics	48-507	85	15	\$457.50

*Table 3.3.4-3: Comparison of engineered diffuser plates.*

The Edmund Optics diffusers have a slightly lower transmission efficiency, but the dispersion angles are much better than their Thorlabs counterparts. The dispersion angles

being so much lower would be worth the lower transmission efficiency, but unfortunately the Edmund Optics diffusers are nearly double the cost of the most expensive Thorlabs diffusers. Because of the cost difference, it's most likely we'll use either Thorlabs ED1-C20, or Thorlabs EDG5C20.

### 3.3.5 Optoelectronics

There are a few critical pieces of optoelectronics for this project, and in this section we'll be comparing quadrant photodiodes sensitive to 850nm and standard photodiodes sensitive to 1550nm. Photodiodes, quadrant or standard, that are sensitive to 850nm are typically made of Si. While Si photodiodes aren't necessarily rare, their responsivities at 850nm are relatively low compared to other wavelengths. The key parameters we'll be looking for are responsivity, dark current, active region size, and cost. High responsivity and low dark current will make it easier to detect the incoming light, a large active region will be easier to focus light into, and lower cost would be ideal for the budget. A collection of Si quadrant photodetectors we've investigated are tabulated below:

Company	Product ID	Responsivity (A/W)	Dark Current (nA)	Active Area (mm <sup>2</sup> )	Cost
Advanced Photonix	197-23-21-041	0.58	1.4	5.84	\$99.03
OSI Optoelectronics	RD15	0.58	1	14.9	\$134.22
Edmund Optics	SPOT-9D	0.58	0.5	19.6	\$230
Edmund Optics	SPOT-4D	0.58	0.1	1.61	\$68
Marktech	MT03-004	0.55	0.5	5.8	\$24.67

*Fig 3.3.5-1: Comparison of Si quadrant photodetectors.*

Based on our research, the Edmund Optics SPOT-9D would be the most effective option. It's the most expensive by far, however the low dark current and relatively massive spot size make the cost worth it. The responsivity was the same for all the photodiodes so it was not much of a factor

The next critical item for comparison is the 1550nm detector. Most photodiodes that are sensitive to 1550nm are made of InGaAs and have high responsivities at that wavelength. Luckily, 1550nm is one of the most common wavelengths for telecommunications. This makes it easy to find components with high responsivities and low dark currents for reasonable prices. Much like the Si quadrant photodiode, the key parameters we're comparing are responsivity at the specified wavelength, dark current, active region size, and cost. However, most InGaAs photodiodes list their active region as a diameter,

instead of the squared area. A collection of InGaAs photodetectors we've investigated are tabulated below:

Company	Product ID	Responsivity (A/W)	Dark Current (nA)	Active Area Diameter (mm)	Cost
Thorlabs	FGA015	0.95	0.5	0.15	\$65
Thorlabs	FGA10	1.05	1.1	1	\$182.07
Edmund Optics	#55-754	0.95	0.05	0.12	\$95
Edmund Optics	#62-271	0.95	0.5	0.5	\$100
Marktech	MTPD2601 T-100	0.75	300000	1	\$25.20
Marktech	MTPD260T 8-300	0.75	80	3	\$51.19

*Fig 3.3.5-2: Comparison of InGaAs photodiodes sensitive to 1550nm*

Based on our research, the Thorlabs FGA015 will be our best option for InGaAs photodiodes. The Marktech brand photodiodes are the cheapest option, however the dark current and responsivity levels are far too low compared to the Thorlabs and Edmund Optics photodiodes to warrant selecting them. The Edmund Optics photodiodes have similar specs to the Thorlabs models, and the Thorlabs FGA10 has the best specs, however the Thorlabs FGA015 has the best specs-to-cost ratio of them all. The only downside is the active region size, however it shouldn't be an issue with the optical design.

## 4 Standards and Constraints

Standards and constraints can range from useful tools, to inconvenient obstacles. Standard hardware and software such as USB and . Constraints, such as time and environment, are less useful and more inconvenient for the team. In this chapter we'll be discussing the standards and constraints for the project as well as how they'll affect our design and progress.

### 4.1 Standards

#### 4.1.1 Laser Safety Standards



There are a number of standards we'll have to follow throughout the project, chief among them being laser safety. We'll be working with two different laser wavelengths, 850nm and 1550nm, and while 1550nm is generally considered to be "eye safe" during normal operation even at high powers, 850nm lasers are not. Because 850nm lasers are not eye safe, it's even more important for us to follow laser safety guidelines, especially during any indoor live demos. Laser safety standards will normally include items such as laser classification, safety protocols, and control measures.

Laser classification is determined by how dangerous a laser can be towards living things, whether to the skin or retina, when under normal operation. The classes for lasers range from Class 1 to Class 4, and can be summarized as follows:

- Class 1: Completely safe under normal operation.
- Class 2: Can cause damage to the retina, however damage is minimized by the human blink response (0.25ms).
- Class 2B: Can cause damage to the retina, however damage is minimized by the human blink response, unless the beam is amplified by optical components.
- Class 3: Can cause damage if handled inappropriately. Generally safe, however the human blink response is not fast enough to prevent damage to the retina if the beam is directly incident upon the eye. Beams reflected off of non-mirror surfaces are usually safe for viewing.
- Class 3B: Hazardous to the eye. Any exposure without eye protection will cause damage, and prolonged exposure on the skin or flammable materials may cause burning.
- Class 4: Extremely hazardous. Even reflected beams will damage the eye without protection, and exposure to the skin or flammable materials will cause burning. Class 4 lasers should only be used by trained operators.

With the output power we will require in order for the beacon to be detectable 10km away (10 Watts or more), the beacon would technically be considered a Class 4 laser. However, with the high divergence from the optical design, the actual incident power will be very low. Even still, all team members will take the required training courses on safe laser operation, and we will only test the long range functionality in a controlled environment.

For indoor demonstrations, we will have to ensure the beacon only emits enough power to be considered Class 1. 850nm lasers can be especially dangerous to the eye, since it's a non-visible wavelength but still capable of damaging the retina. However, 850nm lasers can still be considered Class 1 as long as they output less than 1mW. By limiting the input current as well as applying neutral density (ND) filters, we can limit the amount of optical output power. The limited power, as well as the divergence from the optical design, will ensure that the laser can be safely used for indoor demonstrations.

The other laser safety standards, control measures and safety protocols, are the standards that must be in place in order for the use of hazardous lasers to be considered "normal

operation”. We’ll be putting an extensive amount of time into ensuring that the laser can be considered Class 1 for indoor operations, however for outdoor testing we’ll have no choice but to use the Class 4 laser. For our outdoor tests, we’ll have to make sure we use safety protocols and control measures so that no team members or bystanders are harmed. Since we’ll only be using the Class 4 power for private field tests, the control measures will mostly be for our own protection. The control measures we can employ for safe laser operation are:

- Personal Protective Equipment (PPE). These include optical safety goggles rated for the wavelength and optical power we’ll be working with.
- Engineering blocks, such as protective housings, beam blockers, and shutters over the output beam.
- Safety training. All team members will take a training course on laser safety so that everyone knows what steps to take for operating a hazardous laser safely.

Outside of control measures, there are also the safety protocols we’ll follow. The safety protocols will apply to our private field tests, as well as indoor demos. Even though the indoor demos will only use Class 1 laser power, the safety protocols will still be important to ensure a safe demonstration for everyone in the room. The safety protocols we’ll follow are:

- Environmental controls. Making sure the area around the operating laser is clear of bystanders, or that all bystanders are aware of the laser being operated.
- Written policies. All safety requirements will be written on paper so that everyone within the vicinity has a clear understanding of the laser being operated.
- Visible alerts. Items such as bright signs or blinking lights so that anyone in the vicinity that is not aware a laser is being operated, is made aware.

#### **4.1.2 Software and Communication Standards**

The following is a list of software and communication protocol standards that will be used in the project:

##### **Standard: FCC Part 15 (Radio Frequency Devices)**

Impact on Design:

- Ensures the telemetry modules (RFD900x) comply with RF emissions regulations.
- Requires testing for interference and certification, impacting design timelines and costs.

##### **Standard: GNSS (Global Navigation Satellite System)**

- **Standard:** IS-GPS-200, IS-GPS-705, IS-GPS-800
- **Description:** These standards define the interfaces and performance for GPS

signals, ensuring interoperability and reliability of GNSS devices.

- **Impact:** Ensures the Here+ GPS module accurately receives and processes satellite signals for precise positioning and timing, critical for both transmitter and receiver alignment.

#### **Standard: GPS (Global Positioning System)**

- **Standard:** ICD-GPS-870 (Interface Control Document for GPS)
- **Description:** Defines the protocols and data formats used in GPS receivers.
- **Impact:** Ensures the Cube Orange+ and Here+ GPS modules can effectively communicate and process location data, crucial for maintaining accurate positioning of the gimbal and laser alignment.

#### **Arduino and C Code**

- **Standard:** ISO/IEC 9899:2018 (C18)
- **Description:** Specifies the requirements for the C programming language, including syntax, libraries, and compiler behavior.
- **Impact:** Ensures code portability and reliability across different microcontroller platforms, including the Cube Orange+ and ESP32.

#### **Bluetooth**

- **Standard:** IEEE 802.15.1
- **Description:** Specifies the protocol and architecture for short-range wireless communication using Bluetooth technology.
- **Impact:** Ensures any Bluetooth-enabled devices used in the project (e.g., for diagnostics or additional telemetry) are compatible and can communicate effectively.

#### **CAN (Controller Area Network)**

- **Standard:** ISO 11898
- **Description:** Defines the standards for CAN bus communication, including physical layer, data link layer, and protocol.
- **Impact:** Ensures reliable communication between different microcontrollers and sensors, particularly if CAN bus is used for data transfer between the Cube Orange+ and other components.

#### **USB (Universal Serial Bus)**

- **Standard:** USB 2.0 (High-Speed), USB 3.0 (SuperSpeed)
- **Description:** Defines the specifications for USB interfaces, including data transfer rates, power supply, and physical connections.

- **Impact:** Ensures reliable data transfer and power supply for USB-connected devices, such as the ESP32 or other peripheral devices used in the project.

## 4.2 Constraints

We'll be constrained by more than just technology and chosen specifications during this project. Factors such as economics, environment, and time will be obstacles that we need to overcome in order for our project to be a success. In economics, we're limited to the budget given to us by the Knight Vision Lab. The budget of our project is discussed in more detail in section 8.1.

For time, we're limited by the deadlines set for Senior Design 1 and Senior Design 2. In total, we would have had twelve weeks for researching the project and writing this initial report, as well as preliminary experiments to help us grasp the concepts we'll need to finish the project. If we continue to work over summer break, we'll have fourteen to fifteen weeks to actually build the project and have it functional in time for our final showcase at the end of Senior Design 2. More information about our deadlines among Senior Design 1 and Senior Design 2 can be found in section 8.2.

For environmental constraints, we'll be limited in locations to test or showcase the functionality of the project. For indoor showcases, we'll be constrained by the bystanders present for the demonstration. In section 4.1.1 we discussed laser safety standards and the precautions we'll have to take in order to ensure safe operation of the project for both ourselves and any bystanders during live demonstrations. For outdoor tests, we'll have to find locations with open space up to a kilometer, and without any bystanders present. Locations such as these do exist, but they're hard to find and often charge fees to use their space.

## 5 Comparison of LLM Platforms

In this section we hope to provide insight and comparison of OpenAI's ChatGPT and other platforms such as BARD or Gemini developed by google. To begin, both services can be useful and offer a similar product but one of the first things that will stand out to any user is that Gemini offers a bit more accuracy or rather fact checking. To elaborate, when you get a response from Gemini it will highlight certain statements and flag them for credibility whether it can or cannot find relevant content via a simple google search. This helps handle the accuracy issues and concerns we are all aware of while using a LLM. However, the use case for either platform has revolved around brainstorming at this point in our design. The reason being is that even with credibility checking there is no assurance that the suggested solutions generated by either ChatGPT or Gemini are even possible. Furthermore, compatibility in part selections can be questionable at best. To exemplify these concerns and others there will be three different conversations compared below. The first is going to cover a generic question applicable to the concept of the project, the next topic/question will be more specific and in depth and so on. The

responses generated by ChatGPT and Gemini will be marked with [GPT] and [GEM] respectively and be recorded in the appendix at the end of this paper.

Comparison 1: Both of the responses resulted in beneficial information on how to approach the problem without overextending into part selection and direct implementation. The inclusion of this conversation was to illuminate the value of LLM in brainstorming and conceptual approach in the design process. While the results between the two are similar there are some key differences to note.

The first notable difference being a pro for Gemini is that it recommended a better optical design, calling for collimator lenses to combat divergence as well as mentioning a photodiode able to receive the NIR spectrum. Another favorable component in Gemini's response was the overall brevity itself. While the prompt was admittedly vague, Gemini seemed to give a conceptual prompt a short conceptual answer. Comparatively ChatGPT seemed a bit on the redundant side using twice as many words with little additional substance to show for it. For example in the "Set Up the Tracker" section if the GPT response has two bullet points telling the user to first mount the photodiode to the gimbal and then the gimbal to the drone, simply a blatant waste of space.

However, there are some notable drawbacks for Gemini too, the failure to recommend an ADC, even at the conceptual level, can be considered a significant oversight considering the clear use of a quadrant photodiode in optical tracking. Another con found when comparing the gemini response to ChatGPT's is the resources for further information suggested simply google searching for various retailers to find part specifications. Although an important step in the design process is part selection and comparison, a more conceptual resource would be arguably more useful and important at the brainstorming stage of a project.

The next notable difference is a pro for ChatGPT in its recommendation for a communication fail safe using redundancy in critical components, similar to the spin protocol we plan to implement. This in addition to the recommendation of RF technology, which again is similar to our design in implementing a telemetry module, described in our hardware section.

In sum, both of the platforms identified a course of action that could be useful in starting the design process. While ChatGPT generated more redundant and superfluous information Gemini and also attempted to give overly specific step-by-step instructions it did make up for it in recommending a communication fail safe, an RF based telemetry module, and some useful ideas for possible implementation. Contrastingly, Gemini provided a more concise response while addressing the need for collimator lenses and the need for a photodiode that can handle the appropriate wavelengths. It also wasn't short of flaws, considering the absence of an ADC to control the gimbal with analog signals received from the quadrant photodiode. While both LLM platforms shared strengths and weaknesses I would say that the more beneficial response to the prompt came from ChatGPT. This is due not only to the pros listed above but because one of its major flaws was over description. Additionally, during this description there was a separation between

beacon and receiver components and function which made it easier to decipher which end was being referenced during the response.

Comparison 2: In this second prompt we are a bit more specific in a desired task and can begin to see a larger divergence between the two responses. Unlike the last prompt we are now asking how to implement specific types of technologies to transmit location and orientation data of the beacon. Because this is an implementation prompt certain aspects that were viewed as a con in the previous section actually work as a pro in this one. For example, in this response ChatGPT again went into much greater detail than Gemini, where in the last example this was a major con here it is more applicable and can be seen as a possible pro. While the lists of various parts and model numbers for GPS modules, IMUs, MCUs, quadrant photodiodes and more are provided, this shouldn't be viewed as an exact shopping list because there aren't any guarantees that the combination of hardware recommended will work. The information is useful in guiding research in potential parts and components along with their capabilities. While building the hardware diagram ChatGPT proved useful in explaining various components and technologies that could be used and how they could interconnect.

Furthermore, another pro outside of part suggestions is the provided pseudo code for both the beacon and the receiver to communicate position between one another. Despite only being pseudo code it is a visual aid and linear reference to how implementation of the recommended components could be possible. For example, the beacon code is simple, a loop transmitting the GPS and IMU data with a delay to ensure a proper update rate. The pseudo provided for the tracker is a bit more complicated, it essentially loops a continuous read of the GPS and IMU data from its own modules while also receiving the data from the beacon modules. This loop also includes instructions to calculate the necessary gimbal angles and to set them. The only way that this loop gets broken is if the quadrant photodiode detects the laser diodes of the beacon. Obviously this code is bare bones and doesn't account for the adjusting of the laser diode array but it provides valuable insight into the programming and implementation of the diodes and gimbal.

Now considering Gemini, some of the pros in its response are that it mentions the possibility of atmospheric interference and the need for sensor accuracy in pre-aligning the gimbal. To elaborate on the need for accuracy Gemini states that factors like satellite visibility along with atmospheric conditions can greatly hinder performance. Additionally, Gemini states that proper calibration of components like the IMU is needed to ensure proper operation. These considerations are important in moving forward with the design process and can be viewed as valuable pointers.

However, despite the valuable insight in implementation, Gemini still gave a short and conceptual answer despite the prompt calling for specific technologies and devices. The previous prompt did suggest part research via retailers websites but made no mention of it here, which is odd to say the least. Furthermore, Gemini also included a recommendation for a telemetry module but left the type of technology open ended. A preferable response would have done a brief comparison between radio, cellular and satellite technologies mentioned in its recommendation for telemetry models. To conclude, the better response

once again came from ChatGPT. This conclusion can be made from the additional information provided about parts along with the pseudo code. It is important to note that the response from ChatGPT was once again flawed in its redundancy and excessive length, while more information tends to be beneficial in this instance the listing of implementation steps could have been halved while still relaying the same amount of information.

Comparison 3: This third and final case exemplifies a complete contrast in responses due to comprehension. The third prompt inquired whether it was best to route power through the MCU to route the power directly from the battery and use the MCU to switch the power supply to the batteries. This prompt was chosen to show the suggestions made by each LLM given a question asking for insight of approach.

However, there appeared to be an issue in comprehension, ChatGPT understood that the drivers would be modulated through the MCU regardless and that I was asking if the drivers should be powered directly from the power supply or have it routed through the MCUs PCB for direct digital modulation. On the other hand Gemini perceived that I wanted to directly supply the laser diodes from the power supply and modulate that directly. However, despite the misinterpretation Gemini recommended a solution similar to that of ChatGPTs in that it called for routing the power through the MCU circuit board with a separate regulated power supply. Unfortunately due to the misinterpretation it also generated a warning about the inability to modulate if powered directly from the battery, which was never considered to be an option.

Another notable difference proving to be a pro for ChatGPT and a con for Gemini is the mention of current control and power regulation. These are key components of powering our laser diodes and Gemini made mention of neither. Overall, it seems that no matter the subject, whether it be vague or specific, ChatGPT generates more useful responses than Gemini and was better for the overall brainstorming for design. While Gemini provided fact-checking and warnings of credibility this project or rather the prompts provided seemed to be too niche for it to flag any of the information it provided. Furthermore, GPT was able to make good on its oversized responses by including crucial information that was all but overlooked by its counterpart. In sum, for the first three prompts on design and implementation ChatGPT was the clear winner.

## **8 Administrative Content**

### **8.1 Budget Estimates and Funding**

Our team is sponsored by the Knight Vision Lab (KVL), a research group at CREOL, and they will be providing the budget for this project. Our limit for the project is \$5000. Luckily the KVL will provide certain components, such as the receiver gimbal, so they won't come out of our budget. The table below consists of very rough cost estimates of the most critical components we'll need for the project.

Item	Quantity	Unit cost	Total cost
850 nm LD	25	\$10	\$250
1550 nm LD	4	\$200	\$800
SI Quadrant Photodiode	1	\$100	\$100
InGaAs Photodiode	1	\$65	\$65
Optical Bandpass Filters	2	\$165	\$330
Engineered Optical Diffuser	1	\$280	\$280
Lenses	6	\$35	\$210
Dichroic Mirror	2	\$160	\$320
Arduino Nano	2	\$20	\$40
Receiver Gimbal	1	\$1800	*Acquired
Beacon Gimbal	1	\$100	\$100
GPS modules	2	\$30	\$60
IMU modules	2	\$30	\$60
LoRa Modules	2	\$20	\$40
Li-Ion Power Supplies	2	\$300	\$600
Rough total cost estimate			\$3,255

*Table 8.1 Rough estimate of project cost*

## 8.2 Project Milestones

There are several milestones and deadlines we'll have to meet in order to finish the project. Each milestone has been addressed and its planned work time has been roughly established. The tables below roughly encompass these milestones.



<b>Task</b>	<b>Start Date</b>	<b>Anticipated End Date</b>	<b>Duration</b>
Project Brainstorming	Spring Semester	Spring Semester	10 weeks
Project details worked out (some optimizations)	05/13/2024	05/23/2024	1.5 week
Individual Research Delegations and Assessments	08/16/24	09/23/24	1 weeks
Initial Design Document (Based upon the D&C documents)	05/21/24	05/31/24	1.5 weeks
20-Page D&C (improvements made, more research done, and any recommended changes through consultation)	5/31/24	06/7/24	1 week
Meet and Discuss with Sponsor/mentor (seek guidance)	06/7/24	06/21/24	2 weeks
60-Page Milestone (improvements made, more research done, and any recommended changes through consultation)	06/21/24	07/5/24	2 weeks
Group Review: Final Draft (90 pages)	07/5/24	07/23/24	2.5 weeks

*Table 8.2.1: Senior Design I deadlines*

Task	Start Date	Anticipated End Date	Duration
Final Selection of components and Ordering the Parts	05/24/24	06/7/24	2 weeks
System Design (designing schematics for PCB, filters, etc.)	05/27/24	06/17/24	3 weeks
PCB Design	06/07/24	06/17/24	2.5 weeks
Testing components, arrays, and filters	06/17/24	07/5/24	2.5 weeks
PCB and MCU Testing	06/17/24	07/5/24	2.5 weeks
Develop prototypes for Mini Demo Video	07/5/24	07/23/24	2.5 weeks

*Table 8.2.2 Senior Design I Project Design Milestones*

Task	Start Date	Anticipated End Date	Duration
PCB and Other Design Testing (improving on prototype)	08/21/24	09/11/24	3 weeks
Assembling Parts/System Integration for final prototype	09/11/24	09/23/24	3 weeks
Prototype testing for final product	09/23/24	11/15/24	7 weeks
Finalize the Documentation	11/1/24	11/15/24	2 weeks
Practice Final Presentation	11/15/24	11/22/24	1 weeks
Final Presentation	TBA	TBA	TBA

*Table 8.2.3 Senior Design II Project Design & Documentation Milestones*

## 8.3 Work Distributions

There are three members of our team, each from a different discipline. The PSE, Seth, will handle the design and assembly of all optical components in the system. As the team

leader, Seth will also be responsible for the administrative content and relaying information between the team and the sponsor. His epThe EE, Raymond, will be in charge of designing the necessary power supply and integrating the GPS, IMU and LoRa modules into usable PCBs for both the receiver and beacon. Other responsibilities will be to support Blake with software implementation and Seth in properly driving the laser diodes. The CPE, Blake, will be responsible for most of the software work required for the project. This includes demodulating the signals from the QDP, as well as using those signals to give directions to the gimbal.

## Appendix A: Citations

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## Appendix B: LLM Prompts and Responses

Prompt 1: I would like to construct an optical beacon tracker using two drones. One will operate as a beacon with an array of laser diodes and the other a tracker outfitted with a quadrant photodiode to follow the beacon using a 2-axis gimbal.

[GPT] Constructing an optical beacon tracker using two drones involves several key components and steps. Here's an overview of the process:

### Components Needed

1. **Beacon Drone:**
  - Laser Diodes: An array of laser diodes to serve as the optical beacon.
  - Power Supply: Adequate power source to run the laser diodes.
2. **Tracker Drone:**
  - Quadrant Photodiode: To detect the position of the laser beam.
  - 2-Axis Gimbal: To adjust the orientation of the photodiode to follow the beacon.
  - Microcontroller or Processor: To process the photodiode signals and control the gimbal.
  - Power Supply: To run the electronics and gimbal.
3. **Communication Modules:**
  - Wireless communication modules (e.g., RF modules) to transmit data between the two drones if necessary.
4. **Software:**
  - Control algorithms for tracking and gimbal control.
  - Signal processing algorithms to interpret the photodiode data.

## **Steps to Construct the System**

1. **Setup the Beacon Drone:**
  - Arrange the laser diodes in a pattern that ensures visibility from various angles.
  - Connect the diodes to a power source and a control circuit if you need to modulate the light (e.g., for encoding information).
2. **Setup the Tracker Drone:**
  - Mount the quadrant photodiode on the 2-axis gimbal.
  - Connect the photodiode to a signal processing circuit that can convert the analog signals into digital signals for the microcontroller.
  - Mount the gimbal on the drone and ensure it has a stable power source.
3. **Programming the Tracker:**
  - Write a control algorithm for the microcontroller to interpret the signals from the quadrant photodiode. The algorithm should calculate the position of the laser beam on the photodiode and adjust the gimbal to center the beam.
  - Implement PID (Proportional-Integral-Derivative) control or another suitable control method to ensure smooth and accurate tracking.
  - If needed, program the drones to communicate wirelessly for additional coordination.
4. **Integration and Testing:**
  - Assemble the hardware and ensure all connections are secure.
  - Test the beacon and tracker systems separately to ensure they function correctly.
  - Conduct field tests with both drones to fine-tune the tracking algorithm and ensure reliable performance.
5. **Calibration and Optimization:**
  - Calibrate the photodiode to ensure accurate position detection.

- Adjust the sensitivity and response time of the gimbal control to optimize tracking performance.
- Conduct tests in various lighting conditions to ensure the system performs well in different environments.

## Considerations

- **Safety:** Ensure the laser diodes are eye-safe or implement safety measures to avoid direct eye exposure.
- **Environmental Factors:** Consider how environmental conditions (e.g., sunlight, obstacles) may affect the tracking performance and plan accordingly.
- **Redundancy:** Implement fail-safes and redundancy in critical components to enhance reliability.

## Example Implementation

1. **Beacon Drone:**
  - Use multiple laser diodes in a circular arrangement.
  - Control the diodes with a microcontroller to turn them on/off as needed.
2. **Tracker Drone:**
  - Mount the quadrant photodiode on a gimbal.
  - Connect the photodiode to an ADC (Analog-to-Digital Converter) and then to a microcontroller.
  - Implement a control loop in the microcontroller to adjust the gimbal based on the photodiode readings.
3. **Communication:**
  - Use an RF module to transmit the beacon's status to the tracker if needed.

By following these steps, you can construct an optical beacon tracker using two drones. Ensure to test and iterate on your design to achieve the best performance.

[GEM] Your concept for an optical beacon tracker using two drones is a very interesting approach! Here's a breakdown of the components and some considerations for building it:

### Drone 1: Beacon

- **Laser Diode Array:** Choose a laser diode array with a specific wavelength suitable for your photodiode and with enough power to be detectable at the desired range. Visible or near-infrared (NIR) lasers are common choices.
- **Collimator:** A collimator lens will be needed to focus the diverging laser beams from the array into a more collimated beam for better detection range.
- **Control System:** A microcontroller can be used to control the laser array, potentially pulsing or modulating the laser light for easier tracking by the receiver drone.

### Drone 2: Tracker

- **Quadrant Photodiode:** This photodiode has four sections that allow you to determine the direction of the incoming light based on the intensity difference between the sections.
- **2-Axis Gimbal:** A gimbal will be crucial for precisely pointing the photodiode towards the beacon. The control system will adjust the gimbal based on the photodiode's output.
- **Control System:** This system will process the signal from the quadrant photodiode and determine the direction error. It will then send control signals to the gimbal motors to keep the beacon centered within the photodiode's field of view.

#### **Additional Considerations:**

- **Calibration:** Carefully calibrate the photodiode and its alignment with the gimbal's axes.
- **Software:** Develop software algorithms for the control systems on both drones. The beacon drone's software might simply control the laser pulsing. The tracker drone's software will need to interpret the quadrant photodiode signal, calculate direction error, and translate it into gimbal control commands.
- **Safety:** Eye safety is crucial when dealing with lasers. Choose a laser wavelength and power level that complies with safety regulations. Never point the laser beam towards people or aircraft.
- **Communication:** While not essential, consider a communication link between the drones. This could allow for data exchange or provide a backup for tracking in case the photodiode signal is lost momentarily.

#### **Resources:**

There's limited information readily available for building a specific optical beacon tracker with drones. However, you can find resources related to the individual components:

- Laser Diodes and Drivers: [Online retailers specializing in electronic components]
- Collimators: [Online retailers specializing in optics]
- Quadrant Photodiodes: Same as Laser Diodes
- Gimbal Control Systems: Several companies offer ready-made gimbal control systems designed for drone applications.

Building this project will require knowledge of electronics, optics, control systems, and potentially some software development. If you're new to these areas, consider breaking it down into smaller, more manageable projects to gain the necessary skills before tackling the entire system.

Prompt 2: I would like to implement a GPS module and IMU to transmit location and orientation of the beacon to the tracker to preemptively align the gimbal with the beacon before the quadrant diode has read a signal from the laser diodes. How can I do this?



[GPT] Integrating a GPS module and an IMU (Inertial Measurement Unit) into your beacon and tracker drones can significantly enhance the tracking system by providing location and orientation data. This allows the tracker to preemptively align its gimbal towards the beacon, improving responsiveness and accuracy. Here's how you can implement this:

## **Components Needed**

### **1. Beacon Drone:**

- GPS Module: To provide the beacon's location.
- IMU: To provide orientation data (pitch, roll, yaw).
- Communication Module: To transmit GPS and IMU data to the tracker drone.

### **2. Tracker Drone:**

- GPS Module: To provide the tracker's location.
- IMU: To provide the tracker's orientation.
- Communication Module: To receive GPS and IMU data from the beacon drone.
- Quadrant Photodiode: To fine-tune the tracking once the beacon is within range.
- 2-Axis Gimbal: To orient the photodiode.
- Microcontroller or Processor: To process the GPS, IMU, and photodiode data.

## **Steps to Implement the System**

### **1. Setup GPS and IMU on Beacon Drone:**

- Connect the GPS and IMU to the microcontroller.
- Ensure the GPS module has a clear view of the sky for accurate positioning.
- Calibrate the IMU for accurate orientation data.

### **2. Setup GPS and IMU on Tracker Drone:**

- Connect the GPS and IMU to the microcontroller.
- Calibrate the IMU on the tracker drone as well.

### **3. Establish Communication:**

- Use RF modules (e.g., XBee, LoRa) or any other suitable wireless communication module to transmit the beacon's GPS and IMU data to the tracker.
- Ensure reliable and low-latency communication between the two drones.

### **4. Processing GPS and IMU Data:**

- On the tracker drone, use the received GPS data to calculate the relative position of the beacon drone.
- Use the IMU data from both drones to determine the relative orientation.
- Implement an algorithm in the microcontroller to convert the relative position and orientation data into gimbal angles.

### **5. Preemptive Gimbal Alignment:**

- Before the quadrant photodiode detects the laser signal, use the calculated gimbal angles to orient the gimbal towards the predicted position of the beacon.
  - Once the quadrant photodiode detects the laser signal, switch to fine-tuning mode to accurately track the beacon.
- 6. Integration and Testing:**
- Integrate all components and ensure secure connections.
  - Test the system in a controlled environment to ensure that the GPS and IMU data correctly pre-align the gimbal.
  - Conduct field tests to fine-tune the algorithm and ensure reliable performance.

## Example Implementation

### 1. Beacon Drone:

- GPS Module: e.g., u-blox NEO-M8N.
- IMU: e.g., MPU-9250.
- Microcontroller: e.g., Arduino, STM32.
- Communication Module: e.g., XBee.

```
// Pseudocode for beacon drone
void setup() {
  initGPS();
  initIMU();
  initCommunicationModule();
}
void loop() {
  GPSTData gpsData = readGPS();
  IMUData imuData = readIMU();
  sendDataToTracker(gpsData, imuData);
  delay(100); // Adjust based on required update rate
}
```

### 2.Tracker Drone:

- GPS Module: e.g., u-blox NEO-M8N.
- IMU: e.g., MPU-9250.
- Microcontroller: e.g., Arduino, STM32.
- Communication Module: e.g., XBee.
- Quadrant Photodiode: e.g., Hamamatsu S5981.
- 2-Axis Gimbal: Servo motors or brushless gimbal.

**\*\* Pseudocode for tracker drone also provided.**

## Considerations

- **Latency:** Ensure that the communication between the drones is fast enough to make real-time adjustments.
- **Synchronization:** Synchronize the clocks of both drones to ensure accurate time-stamping of GPS and IMU data.
- **Error Handling:** Implement error handling for scenarios where GPS or IMU data is unavailable or unreliable.

By following these steps, you can enhance your optical beacon tracker with preemptive alignment using GPS and IMU data, ensuring more responsive and accurate tracking.

[GEM] That's a great improvement to the system! Integrating a GPS module and IMU (Inertial Measurement Unit) on the beacon drone can significantly enhance the overall tracking performance. Here's how it can work:

#### **Beacon Drone with GPS/IMU:**

- In addition to the previously mentioned laser diode array and collimator, you'll equip the beacon drone with a GPS module and an IMU.
- The GPS module will provide the beacon drone's location (latitude, longitude, altitude).
- The IMU, typically consisting of an accelerometer, gyroscope, and magnetometer, will provide the beacon drone's orientation data (pitch, roll, yaw).

#### **Data Transmission:**

- Choose a telemetry system to transmit the GPS location and IMU data from the beacon drone to the tracker drone. Options include radio modules (e.g., UHF/WiFi) or cellular depending on your range and data rate requirements.

#### **Tracker Drone with Gimbal Control System:**

- The tracker drone will receive the GPS location and orientation data of the beacon drone through the telemetry link.
- The tracker drone's control system will use this information to pre-emptively aim the gimbal in the general direction of the beacon. This can significantly reduce the time it takes for the quadrant photodiode to acquire the beacon's signal and improve tracking accuracy.

#### **Control System Improvements:**

- The tracker drone's software will need to be modified to incorporate the received GPS and IMU data. It will calculate the relative position and orientation between the two drones based on this data.
- Based on the calculated relative position, the software will determine the necessary adjustments for the gimbal to point towards the beacon's location.

#### **Benefits:**

- **Faster Acquisition:** Pre-positioning the gimbal based on GPS/IMU data significantly reduces the time it takes for the quadrant photodiode to acquire the beacon's signal, especially during initial lock or after temporary signal loss.
- **Improved Accuracy:** The initial pre-alignment by the gimbal improves the overall tracking accuracy, particularly when dealing with smaller beacon signals or longer tracking distances.

#### **Additional Considerations:**

- **Data Latency:** Factor in the latency introduced by the telemetry link between the transmission from the beacon and reception by the tracker. Account for this delay when calculating the gimbal pre-positioning.
- **Sensor Accuracy:** The accuracy of the pre-alignment will depend on the accuracy of the GPS and IMU data. GPS accuracy can be affected by factors like satellite visibility and atmospheric conditions. IMU readings might experience drift over time, requiring calibration procedures.

Overall, incorporating a GPS/IMU system on the beacon drone is a valuable addition to your optical beacon tracker project. It improves tracking performance by allowing the tracker to anticipate the beacon's location and pre-position the gimbal for faster and more accurate acquisition.

Prompt 3: When driving the laser diode array should power be routed through the MCU circuit board to allow modulation or is it possible to modulate the laser diodes being fed from a 22.8V, 23 Ah battery?

[GPT] When driving a laser diode array, there are a few considerations to ensure proper modulation and power management. Here's an outline of how you can approach this:

#### **Direct Modulation of Laser Diodes**

1. **Microcontroller (MCU) Control:**
  - The MCU can directly modulate the laser diodes by switching them on and off or varying their intensity.
  - This requires routing the power through the MCU circuit board, which allows precise control over the diodes.
2. **Power Considerations:**
  - Laser diodes typically require a constant current source to operate reliably. They are sensitive to current variations and can be damaged if overdriven.
  - The MCU will likely need to control a driver circuit (such as a constant current driver) rather than powering the diodes directly, especially if the power requirements exceed the capabilities of the MCU's GPIO pins.
3. **Switching Components:**
  - Use switching components like MOSFETs or transistors controlled by the MCU to handle higher power levels. The MCU will send a control signal to the gate/base of the MOSFET/transistor, which in turn will modulate the laser diode current.

- Ensure the switching components can handle the voltage and current requirements of the laser diodes.

## Using a High-Voltage Battery

### 1. Voltage Regulation:

- The 22.8V, 23 Ah battery is a high voltage source. Laser diodes typically require lower voltages (e.g., 3V to 5V). You'll need a voltage regulator or DC-DC converter to step down the voltage to the appropriate level for the laser diodes.
- A buck converter can be used to efficiently step down the voltage from 22.8V to the required voltage for the laser diodes.

### 2. Current Control:

- Implement a constant current driver to ensure the laser diodes receive a stable current. This is crucial for the longevity and performance of the diodes.
- The current driver can be modulated by the MCU using PWM (Pulse Width Modulation) or a digital control signal.

## Example Circuit Design

### 1. Power Supply and Regulation:

- Use a buck converter to step down 22.8V to the required voltage (e.g., 5V).
- Ensure the buck converter can handle the power requirements of the entire laser diode array.

### 2. Laser Diode Driver:

- Use a constant current driver circuit to supply a stable current to the laser diodes.
- Control the current driver with a MOSFET or transistor, which is modulated by the MCU.

### 3. MCU Modulation:

- The MCU outputs a PWM signal or a digital on/off signal.
- This signal drives the gate of a MOSFET, which in turn controls the current driver supplying the laser diodes.

## Example Schematic

### 1. Buck Converter:

- Input: 22.8V from the battery.
- Output: 5V (or suitable voltage for laser diodes).

### 2. Constant Current Driver:

- Input: 5V from the buck converter.
- Output: Constant current to the laser diodes.

### 3. MCU Control:

- PWM output from the MCU to the gate of an N-channel MOSFET.

- Source of the MOSFET connected to the ground.
- Drain of the MOSFET connected to the current driver.

[GEM] Modulating the laser diode array directly with the battery voltage (22.8V) is not recommended. Here's why:

- **Laser Diode Damage:** Laser diodes are very sensitive to current fluctuations. Directly connecting them to a battery could lead to uncontrolled current surges that can damage the diodes.
- **Limited Modulation Capability:** Batteries typically provide a constant voltage level. You wouldn't be able to modulate the laser light (e.g., turning it on and off or varying its intensity) for potential ranging or communication purposes.

#### **Power Routing with MCU for Modulation:**

- **Driver Circuit:** A dedicated laser diode driver circuit is necessary. This circuit will take a control signal from the MCU and convert it into the appropriate current profile required by the laser diode array. The MCU can modulate this control signal to achieve the desired laser output.
- **Power Supply:** The driver circuit will likely require its own separate power supply with a lower voltage than the battery (e.g., 5V or 12V) for proper operation. This power supply can be regulated from the main battery voltage.
- **MCU Control:** The MCU can generate a control signal based on a pre-programmed pattern or in response to external commands. This allows for functionalities like turning the laser on and off, pulsing it at specific frequencies, or even transmitting data by modulating the laser intensity.

#### **Benefits of MCU Control:**

- **Precise Modulation:** The MCU enables precise control over the laser diode array's output, allowing for features like pulsed operation or data transmission.
- **Safety Features:** The driver circuit can incorporate safety features like current limiting and temperature monitoring to protect the laser diodes.

In conclusion, routing the power through the MCU circuit board with a dedicated driver circuit is the recommended approach for driving your laser diode array. This method offers precise control, modulation capabilities, and safety features for your laser beacon project.