Low-Cost Portable Laser Communication Device

California Polytechnic State University - San Luis Obispo
Electrical Engineering Department
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Senior Project Report

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<td>EE 462 Timeline</td>
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Acknowledgements

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Abstract

The portable laser communication device (PLCD), is a low cost system used to set up networks in data isolated regions via an optical line-of-sight communications protocol. In this manner the PLCD transmits at 9600 baud using UART protocol over the visible light band at 635nm. The device is intended to operate in indoor conditions and be semi-permanent until redeployed. The PLCD is built as a transmitter, receiver pair and when installed, utilizes tracking to find each other and automatically set up communication within a window of 30° laterally and 10° vertically. Each side of the system is less than 15 lb and portable with a volume of 1 cubic foot to allow for minimum bulk when transporting the device and installing it. The PLCD pair will communicate over lengths around 50 meters. The system latency does not exceed 30 ms and the system can interface with external USB devices. The PLCD does not exceed 6W in power consumption.
Introduction and Background

As the demand for larger data transfers rises, new emerging technologies must be able to compensate; to that extent, the ability to set up high speed local networks in data isolated regions is vital. To confront this issue a system needs to offer high portability, high reliability, low power, and low cost. The portable laser communication device (PLCD) serves as a low cost solution.

The PLCD allows for typical ‘free space optics’ (FSO) communication but also covers a specific niche with its high portability not readily seen by competitor designs. The market roles that the PLCD best fulfills exist in high mobility, non-permanent settings. PLCD consumers are expected to be groups like: mobile news crews (CNN, FOX News), large event settings (Olympics, NFL, Coachella), emergency services (Fire, Police, Natural Disaster), military (Army, Navy), and construction. The PLCD fulfills these roles due to its ability to set up secure temporary data lines with no interference from alternative electronic communication systems and their resulting signals.

Other companies that have developed similar FSO systems include CableFree, fSONA, vision engineering, and NASA. CableFree is a wireless communication company that has developed a system capable of transmitting data 2km away at a data rate of 1.5Gbps using near IR wavelengths. Their devices are bolted to poles on top of buildings and have been used in events such as the Olympics and in densely populated cities [1][2]. Similarly, fSONA’s devices use FSO to transmit data 1km away at 10GBps. Their devices are more portable and have been used in military applications[3]. Additionally, both NASA and vision engineering have used FSO systems to communicate from earth to satellites while using tracking systems to keep the connection[4][5].

The PLCD system is a light-weight tx/rx pair intended to operate in indoor conditions. The system offers a low cost portable alternative that once installed can automatically align two transceivers. A PLCD pair is intended to operate at at least 50 meters. Similar devices have obtained ranges of 800 meters and greater[6] indicating that the 50m is within previous accomplishments in the field. The PLCD will operate as a semi-permanent data channel with a packet loss of less than 10%. Previous implementations have achieved an almost zero BER (Bit Error Rate)[7] hence device stipulations are within real practice. The system latency is less than 30ms, typical of most communication systems, and will communicate via the UART protocol at 9600 baud. This transmit speed
should be possible as some laser communication iterations can reach speeds up to 10Gb/s [7]. The high mobility of the PLCD allows for swift installation of the device. This means the PLCD can easily set up dynamic networks or extend already existing ones with more functionality via its ability to interface via USB. The device portability also allows for high-speed data transfers in network isolated regions where use of cables can interfere or obstruct ongoing work. The implemented tracking feature also allows automated alignment once the system is physically installed. The PLCD system will be able to start aligning within a window of 30 degrees horizontally and 10 degrees vertically. Previous tracking systems have managed to accomplish alignment via a 30 degree horizontal window and an 18 degree vertical window[8]. The PLCD will then be able to align within 0.1 degrees of the target location. This is achievable as previous designs have reached down to 1 mm in similar conditions [9]. The system will operate within the visible band of light at 635 nm due to its shorter range, low power, and low cost objectives [10].

The use of laser communication outside of fiber optic medium constitutes as a ‘Free Space Optical’ device or FSO device where the medium of transfer constitutes as air or vacuum. The PLCD system falls under the FSO category due to its use of lasers to communicate through the atmosphere. The use of laser communication also grants the PLCD system a few significant benefits: the system does not need to allocate bandwidth due to its line-of-sight nature and hence also does not suffer interference from other devices, data transfer has a high security as the line-of-sight would need direct interception, the system does not require lengthy cables between them that require protection, reducing cost of installation. An issue with the PLCD system is the safety hazard lasers pose when exposed to the human eye. The PLCD system uses class 3A lasers. 3A lasers are hazardous to the eye and can cause blindness through significant exposure [11]. To avert this issue proper warnings must be placed on the device to indicate the “live end” and avoid misuse of the device.
Customer Requirements and Engineering Specifications

This chapter covers the development of the system requirements and specifications based on customer needs and problem definition. The primary stakeholders contributing to this project's defining requirements are the project development team, Cal Poly, FSO industries, and target end users in fields such as emergency services, military, construction, and large event services. The definition of the device is a portable, lightweight, FSO communication system. This definition will be broken down to specific requirements and then further analyzed to provide the system specifications.

<table>
<thead>
<tr>
<th>Customer Reqs</th>
<th>Engineer Spec</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>A D</td>
<td>Initial horizontal angle displacement, 30° minimum</td>
<td>Tracking contributes to user experience when installing. This spec relates to tracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A D</td>
<td>Initial vertical angle displacement 10°[8]</td>
<td>Tracking contributes to user experience when installing. This spec relates to tracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A D</td>
<td>Final alignment error, 0.1°. maximum[9]</td>
<td>Tracking contributes to user experience when installing. This spec relates to tracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Packet loss, 10% maximum[7]</td>
<td>Low packet loss is related to how well the data is transmitted.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Type of protocol, UART</td>
<td>The type of protocol used is data rate relevant as it impacts data speed.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>C</td>
<td>Power consumption, 6W per side max</td>
<td>Power consumption measurement impacts power consumption</td>
</tr>
<tr>
<td>D</td>
<td>Weight, 15 lbs per side maximum</td>
<td>Weight and size, or bulk directly impacts how portable the device is and hence how easy to install and use.</td>
</tr>
<tr>
<td>D</td>
<td>Size, each side 1 cubic foot max</td>
<td>Weight and size, or bulk directly impacts how portable the device is and hence how easy to install and use.</td>
</tr>
<tr>
<td>E H</td>
<td>Minimum transmitting distance, 50m[6]</td>
<td>The minimum transmitting distance relates to how long the device can communicate across. This spec also relates to free space optics as it is contained to line of sight laser communication.</td>
</tr>
<tr>
<td>D</td>
<td>Interface with common device, USB</td>
<td>Users will have an easier time using the device if it can connect to common ports and devices.</td>
</tr>
<tr>
<td>H G F</td>
<td>Type of laser, class 3A maximum [11]</td>
<td>The type of laser directly impacts how safe the system is and how expensive it will be to buy the laser. This spec also relates to the Free space optics req because FSO requires a laser to be used</td>
</tr>
<tr>
<td>H G F</td>
<td>Wavelength of light used, 635nm[10]</td>
<td>The wavelength of the laser directly impacts how safe the system is and how expensive it will be to buy the laser. This spec also relates to the Free space optics req because FSO requires a laser to be used</td>
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<tr>
<td>G</td>
<td>Cost of development, $600 max</td>
<td>Total money spent is related to a low cost project</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>G</td>
<td>Time spent developing, 30 weeks, maximum</td>
<td>Total time spent is part of the cost</td>
</tr>
<tr>
<td>B</td>
<td>Latency of signal, 30ms maximum</td>
<td>This spec is related to data rate and low latency</td>
</tr>
</tbody>
</table>

Requirements:
A - Good Tracking
B - Data Rate
C - Low Power Consumption
D - Good User Experience
E - Capable of Communicating Over Long Distances
F - Very Safe
G - Low Cost
H - Must Be Free Space Optics Device
<table>
<thead>
<tr>
<th>Spec #</th>
<th>Parameter</th>
<th>Target Units</th>
<th>Tolerances</th>
<th>Risk</th>
<th>Compliance</th>
<th>Test Equipment Needed?</th>
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<tbody>
<tr>
<td>1</td>
<td>Initial horizontal angle displacement</td>
<td>30° [*15 from center]</td>
<td>Min</td>
<td>H</td>
<td>D,T</td>
<td>-</td>
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<tr>
<td>2</td>
<td>Initial vertical angle displacement</td>
<td>10° [5° from center]</td>
<td>Min</td>
<td>H</td>
<td>D,T</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Final alignment error</td>
<td>0.1°</td>
<td>Max</td>
<td>H</td>
<td>D,T</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Packet loss</td>
<td>10%</td>
<td>Max</td>
<td>M</td>
<td>T</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Type of protocol</td>
<td>UART</td>
<td>-</td>
<td>L</td>
<td>I</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Data rate</td>
<td>9600 Baud</td>
<td>(UART tolerances)</td>
<td>L</td>
<td>T</td>
<td>-</td>
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<tr>
<td>7</td>
<td>Power consumption</td>
<td>6W(Per side) max</td>
<td>L</td>
<td>T,A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Weight</td>
<td>15 lb (per side)</td>
<td>Max</td>
<td>L</td>
<td>I,T</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Size</td>
<td>1 cubic foot</td>
<td>Max</td>
<td>M</td>
<td>I,T</td>
<td>-</td>
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<td>Transmitting distance</td>
<td>50m min</td>
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<td>D,T</td>
<td>-</td>
<td>-</td>
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<td>L</td>
<td>D,S</td>
<td>-</td>
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<td>12</td>
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<td>3A</td>
<td>Max</td>
<td>H</td>
<td>I</td>
<td>-</td>
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<td>13</td>
<td>Wavelength of light</td>
<td>635nm ±5nm</td>
<td>H</td>
<td>I</td>
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<td>-</td>
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<td>14</td>
<td>Total money spent</td>
<td>$600</td>
<td>-</td>
<td>M</td>
<td>I</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Total time spent</td>
<td>30 weeks max</td>
<td>M</td>
<td>I</td>
<td>-</td>
<td>-</td>
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<tr>
<td>16</td>
<td>latency</td>
<td>30ms max</td>
<td>M</td>
<td>T</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Design

The PLCD is designed to be a transmitter receiver paired system that can be easily reinstalled as appropriate. In order to achieve this design each device side (transmitter/receiver) needs to be appropriately constructed.

![Receiver Design](image)

*Figure 1: Receiver Design; shows the block diagram for the final design for the PLCD receiver as implemented.*

The PLCD receiver has the purpose of transducing digital signals from light signals and transmitting such data to an external system. The PLCD also must activate a designation light to allow for transmitter tracking. In order to accomplish these actions the PLCD receiver is composed of three modules: the receive module, the tracking light, and the microcontroller.

The receive module is where light is transduced into electrical signals and then into digital signals. Transduction is achieved through a photodiode; the signal from the photodiode is then amplified and converted into a digital signal through an operational amplifier and comparator chain. The tracking light module is an LED which is powered to produce the indication light. The microcontroller module is responsible for processing the data transduced by the receive module and sending it to the external system.
Figure 2: Transmitter Design; shows the block diagram for the final design for the PLCD transmitter as implemented.

The PLCD transmitter has the purpose of taking data from an external system and transducing the electrical signal into a light signal. The PLCD transmitter must also be able to align to the PLCD transmitter by using a camera to detect the designation light and servos to create motion for alignment.

The external data entering the PLCD transmitter is first processed by the microcontroller for distribution to the transmit module. The transmit module transduces light from electrical signals via the laser diode. The laser diode is driven via a gate driver which toggles based on the data input from the microcontroller. The microcontroller also aligns the PLCD transmitter to the receiver designation light through the use of a camera to detect the light. The microcontroller then processes the camera input through software to determine the correct motion to apply via the Pointing modules servos.
Implementation:

Electrical Design:

The overall electrical design of the PLCD can be broken down into two primary sections. The receiver electronics, which convert signals in the form of light to digital signals, and the transmitter electronics, which convert digital signals into light through driving a laser diode. Figure 3 demonstrates the full electronic design of the system.

Figure 3: Complete Schematic; shows the full electrical block diagram for the PLCD system with transmitter on the left and receiver on the right.
Receiver:
The receiving circuit uses a photodiode array to collect light emitted from the transmission laser. The photodiode array produces a reverse current in relation to the quantity of light absorbed by the diodes. This current is then translated into voltage using an op amp and then converted into a digital signal by a comparator. The threshold for the comparator to trigger is determined by a resistive divider circuit that is varied using a potentiometer. The receiver circuit also utilizes a generic green LED for target designation with the transmission side’s tracking algorithm and a red gel filter overlayed onto the photodiode array for light filtering. Initial designs used a singular photodiode, however current designs improved by using an array to collect more light. Figure 4 shows the spice design of the receive circuit. The data is received and processed by an Arduino microcontroller.

Figure 4: Receive Schematic; shows the electrical spice schematic for the PLCD receiver.
Transmitter:
The transmitter circuit utilizes a TC4428A gate driver to provide the current that the laser module needs. This IC takes a digital input and outputs that same polarity while sourcing the necessary current. The chip is rated for a maximum output current of 1.5A, which is much larger than the actual current drawn by the laser. By toggling the gate driver following serial communication patterns the laser can then be used to transmit data through light. Figure 5 shows the transmit path of the design.

![Figure 5: Transmit Schematic; shows the electrical schematic for the PLCD transmitter, specifically the transmit module.](image)

The remainder of the transmit circuit uses two servos and a camera for alignment. The servos provide pitch and yaw rotation for alignment while the camera detects the designation LED on the receive circuit for effective alignment using image processing techniques. The transmit circuit is driven by a RaspberryPi microcontroller.
Tx Mechanical Design:
All mechanical parts were designed using the free CAD software OnShape and 3D printed at the Innovation Sandbox at Cal Poly. These parts house all transmitting electronics, camera module, and servos, as well as enable the system to align itself automatically to the receiver. The figure below shows the assembly of the final CAD design.

![Figure 6: Complete CAD; shows the full assembly of the transmit portion of the PLCD system.](image)

Description of each part:
1. The base has 12 small holes where a servo horn is mounted. The servo attaches to the horn and turns the top part of the assembly when activated. The 4 larger holes allow the base to be mounted on a wider piece of wood. This adds stability and prevents the assembly from tipping over when the servos move.
2. The bottom servo is securely attached to the servo holder using a bar that is screwed into the holder and encloses the servo. There are also 4 studs at the bottom of the holder that locate the servo and prevent it from rocking during operation. This part was designed so that the weight of the project rests on the servo, which further prevents it from rocking. The top servo is inserted in the enclosure and secured in place with screws. The back of the top servo enclosure is left open for easier cable management.
3. The camera and laser holder has 12 small screws when a servo horn is mounted. This allows the holder to be attached to the top servo and gives it the ability to aim up or down. The laser and camera are mounted at the front of the piece and are always aiming in the same direction, which allows the alignment algorithm to use feedback in the control loop. There is a small slit at the back of the piece where a perforated board with the transmitting electronics is mounted. There is a hole at the bottom of the piece which connects to the laser hole for easy cable management.

Figure 9: PLCD Pointer; shows the CAD model of the pointing component of the transmit portion of the PLCD system.

4. The lens holder screws into the camera and laser holder with the 4 holes. The two lenses can slide into the front of the lens holder and be secured with tape on the two open sides. The lenses allow the laser beam width to be adjusted and makes alignment at longer distances much easier.

Figure 10: PLCD Lens Holder; shows the CAD model of the lens holder component of the transmit portion of the PLCD system.
**Rx Mechanical Design:**
The purpose of the receiver mechanical design is to house the receiver circuit and provide a stable mounting point for the photodiode sensor. The following box is designed to hold the circuit breadboard. The small hole in the front is designed for the photodiode to fit in. The most recent iteration of the receiver circuit uses an array of multiple photodiodes in parallel, which do not fit in the small hole. We did not redesign this box to accommodate the new iteration because it was unnecessary given that the new sensor array could be easily mounted using adhesives.

*Figure 11: Receiver Box; shows the CAD model of the container for the receive portion of the PLCD system.*
Photodiode Array:
The final design uses a photodiode array to increase absorbed light energy. The shape of the array was chosen to be an oblong hexagon made up of 10 photodiodes. Figure 12 shows the physical implementation of the array.

Figure 12: Photodiode Array; shows the physical implementation of the photodiode array.

Lens Design:
The beam-widening system was implemented through a dual lens system involving a biconcave and plano-convex lens pair. The biconcave lens disperses the light from the laser diode which is then collimated by the plano-convex lens. Varying the distance between the two lenses varies the final width of the beam. Figure 13 shows how the light travels through the lens set.
**Figure 13: Lensing Diagram;** shows a representation of the dual lens system using a biconcave into a plano-convex to alter beam width.

**Receive Software:**

The purpose of the following code is to receive data from the rx circuit and calculate bit error rate (BER), which tells us how well the data is being transmitted. This works by comparing the data received with the data sent and dividing the number of wrong bits with the number of total bits. The code first starts in a loop that checks only one byte, looking for the start character that the tx code is sending: “!”. Once the receiver gets this character, it stores 126 bytes of data from the serial pin to an array. Lastly, it goes through every bit of the array, comparing each one to the corresponding bit in the expected data array. Every time there is a difference between a received bit and its corresponding expected bit, the code increments the bitError variable. Once this comparison is done, it prints the number of errors detected. This code is very useful to quickly test the BER of the system at different distances and beam widths.

**Figure 14: Receive Flowchart;** shows the flowchart for the top level receive software.
Transmit Software:

The purpose of the transmit software is both to align the transmitter to the receiver and to transmit data. The alignment code is split up into two flowcharts: Locate Target - which analyzes a picture from the camera and finds the green LED - and Servo Align - which uses Locate Target in a control loop to place the green LED in the center of its field of view. When this whole sequence is done, the code begins data transmission using the UART serial protocol.

Locate Target:

This function uses the openCV library to take a picture with the USB camera and analyze it to find the green designator LED. First, the code takes the picture and uses a gaussian blur to reduce glares and make the contour that we are looking for smoother. Then it isolates the green channel by removing all non-green pixels and thresholds the image by removing all pixels with a green value below a threshold. This results in an image that is completely black except where there are very intense green pixels. After this, the code finds all the contours, which correspond to any green shape in the image, and adds them to an array. The code iterates through this array of contours and only keeps the ones that have an area greater than the minimum area and smaller than the maximum area. This ensures that any noise or large glares are not detected as the green LED and do not interfere with our alignment. Lastly, the code finds and returns the coordinates of the center of the first eligible contour. Ideally, there would only be one of these contours, however in the event that there are multiple, this function also returns the number of contours found. This helps during debugging to determine when there are more than one contour and helps fine tune the threshold and area variables.
Figure 15: Locate Target Flowchart; shows the flowchart for the locate target function in the transmit software.

Servo Align:
The purpose of this function is to align the transmitter to the receiver using Locate Target and a PID control loop. First, the function uses Locate Target to take a picture and locate the green LED. It calculates the initial error by subtracting the desired coordinates with the actual coordinates of the LED. If this error is larger than the threshold (a window of a few pixels), the code takes a new picture, calculates new P,I,D errors, and calculates the motion variable using the constants. If the motion variable is greater than the maximum servo value, it is set to the maximum value to avoid an error. Once the servos have moved, the error is checked again to see if it is now smaller than the threshold: if it is, the loop is terminated and the data is transmitted.
Tests and Results:

Early Electronics Tests:
The electronics of the device were verified with short range tests confirming signal quality by studying receiver end outputs. Once the hardware had successfully passed a squarewave from transmitter to receiver, serial data was sent to confirm functionality of the tx/rx system at variable distances. These tests were achieved with a single photodiode sensor.
Figure 17: Short Range Squarewave; shows the receiver output from a 50% duty cycle squarewave at the input of the laser diode at 1kHz at a 1ft distance. The waveform quality permits digital communication.

Figure 17 above shows the output of the receiving circuit when the laser is transmitting a 3.3Vpp, 1kHZ, 50% square wave. This test shows that the receiving circuit performs very well at short distances; there is no overshoot or ringing and the amplitude of the received wave is the full 3.3V. This confirms that this design is viable at short distances.
Figure 18: Pre-Serial Test; shows the receiver output from a 50% duty cycle squarewave at the input of the laser diode at 9.6kHz at a 1 meter distance. The waveform quality permits digital communication.

Figure 18 above shows the same test as Figure 17 but at a longer range of 1 meter. Once again, the test shows that the received wave is exactly the same as the transmitted wave. This confirms that this design will also work at this longer range.
Figure 19: Full UART Test; shows the receiver output from receiving a laser signal from the transmitter that encodes 0xC3695B12 in a repeating manner at 9600 baud, no parity, and 1 stop bit at point blank range. This shows successful serial data communication over light.

Figure 19 above shows the results of the first UART serial communication test of the tx/rx pair. The laser transmitter was sending the following four hexadecimal numbers: C3, 69, 5B, 12 using an arduino microcontroller. This test was done with no distance between the transmitter and receiver for ease of alignment, however this was later corrected when the alignment software and mechanical designs were implemented. The test results show that there is successful serial communication through the optical link and confirms that this design is viable.

Lens Testing:
The tx/rx system proves to be versatile beyond 20 feet when transmitting serial data with 0 BER given manual alignment. Following the qualification of the electronics, they were installed with the dual lens modification to allow for beam widening. The system during these tests implemented a single photodiode sensor. Initial tests found a 0 BER at short ranges with beam widening properties.
The final version of the design implements a photodiode array in an hexagonal shape to capture more light from the transmitter module. The following tests verified the functionality of the alignment system working alongside the transmission system as modified by beam widening.

**Range BER Testing:**
The system was tested at varying distances with the beam widening technique. BER was measured by dividing the number of wrong bits to the number of total bits transmitted. The following table was made by averaging the BER of 5 trials for each distance. The sample size was 1000 bits. The results of this test show that BER increases with distance, but it stays at a reasonable level even at very long ranges. These results also show that BER is much lower when beam widening is not used.

<table>
<thead>
<tr>
<th>Distance between tx and rx (feet)</th>
<th>Average BER</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>0.00%</td>
<td>Taken with beam widening</td>
</tr>
<tr>
<td>5.1</td>
<td>0.00%</td>
<td>Taken with beam widening</td>
</tr>
<tr>
<td>5.75</td>
<td>0.04%</td>
<td>Taken with beam widening</td>
</tr>
<tr>
<td>14</td>
<td>0.98%</td>
<td>Taken with beam widening</td>
</tr>
<tr>
<td>70</td>
<td>0.00%</td>
<td>Taken without beam widening</td>
</tr>
<tr>
<td>180.55</td>
<td>0.00%</td>
<td>Taken without beam widening</td>
</tr>
</tbody>
</table>
Alignment Testing:

Figure 21: Alignment Grouping; shows the results for a precision grouping test for the alignment system when tracking. The red dot represents the average location where 0,0 represents the designator LED.

Figure 21 above shows the grouping of repeated runs of alignment protocol at 30 inches of tx/rx distance. The test showed a standard deviation of 2.99mm for the y axis and 12.43mm for the x axis. This means that 97.9% of tests are expected to fall within a 24.86 mm by 5.98mm rectangle in the worst case scenario. Translating into degrees for the vertical and horizontal limit this results in a tolerance of 1.93° horizontally and 0.466° vertically.
Figure 22: Receiver Implementation; shows the final implementation for the receiver side.

Figure 23: Transmitter Implementation; shows the final implementation for the transmitter side.

Figure 22 and 23 show the complete and final design for the receiver and transmitter respectively.
Conclusion

The increasing commonality of FSO systems in contemporary data networks and the features which are brought forth by such systems continue to increase the value of FSO systems in digital communication. Hence, implementation of short range systems capable of mobility offer value that is not typically found in contemporary systems. The PLCD design acts as a preliminary proof of concept for portable lightweight FSO systems.

The PLCD design was capable of meeting the majority of physical specifications assigned to its design, however it struggled in the precision and capability of its alignment/tracking subsystem. The PLCD failed to meet its alignment tolerance of 0.1° for both vertical and horizontal with angle tolerance being 0.466° vertically and 1.93° horizontally in the final design. As a result of these tolerances the PLCD is capable of alignment at ranges below 3 feet and would require manual alignment at distances exceeding 3 feet for accurate data transmission. The PLCD device however, was capable of starting its alignment operation within a 60° degree by 60°.

The PLCD system was able to meet its physical requirements such as weight and size with volume of either receiver or transmitter less than 1 cubic foot and each side weighing far less than the specified 15lb. The PLCD wattage while in use also remains below the specified 6W for each side.

A key requirement for the PLCD was the 50m communication minimum. Testing of the system shows that it is capable of operating at 269ft (or 82m), which outperforms the 50m requirement by 64%. The system successfully used a photodiode to absorb light from the class 3A 635nm laser. The PLCD is also capable of having a latency from transmission end to receiver end of less than 30 ms and is able to successfully communicate at 9600 baud using UART protocol with less than 10% BER when manually aligned.

Future Improvements:

The design for the PLCD met its intended purposes and specifications with still room for improvement. There is space for improvement particularly in the software and mechanical design of the device.

A prominent mechanical change that can be made to further improve its functionality would be the upgrade of the alignment system. In particular the use of stepper motors over servos would’ve allowed for high accuracy, or alternatively use of DC motors with PID control of velocity instead of position might’ve yielded greater results. Additionally use of metal servo horns would’ve reduced play between the mounting surface and the servo. Further improvements to the design would be load bearings to reduce the strain on the motors which is seen especially in the x axis from its comparatively large standard deviation for alignment precision. Another significant improvement to the design would be to better center the second armature allowing for improved balance.
For software improvements further tuning of the PID control loop for the alignment would reduce overshoot, increase accuracy, and increase alignment speed. This would help the system meet the alignment tolerance of 0.1°. Additionally, using a more reliable tracking technique than computer vision (CV) might improve overall alignment performance because of the inherent limitations of using CV. The major limitations of CV is that it is easily influenced by ambient light such as glares and bright light and that the contour detection software has inconsistencies when finding the center of the green LED. A potential alternative to this alignment technique is using a hybrid RF and FSO system that first uses a radio tx/rx pair to align and establish the optical link and then use the laser to send data.

One way that the electrical systems could be improved is using a better laser module. One major limitation of the laser module used in this system is that it does not work with higher frequency signals. For example, increasing the baud rate of the serial communication leads to slew rate issues and the system stops working. This could be remedied by using a higher bandwidth laser module. Additionally, much faster data rates could be achieved by using a higher bandwidth modulation technique than UART such as phase shift keying or frequency shift keying. These techniques are more modern and capable of much faster data rates than UART.
References

[1] CableFree, "Free Space Optics (FSO) CableFree Gigabit range Overview", CableFree Gigabit datasheet, 2018


## Appendix A - Bill of Materials

**TABLE IV**

**BILL OF MATERIALS**

<table>
<thead>
<tr>
<th>Parts</th>
<th>Total Cost [$]</th>
<th>Justification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Diode</td>
<td>15.60</td>
<td>1 laser for the transmitter module. Price around 15 on amazon</td>
<td>Outputs a light beam when driven by current.</td>
</tr>
<tr>
<td>Phototransistor</td>
<td>1.64</td>
<td>2 phototransistors are needed for two transceivers in module 3.2 and typically less than $1.00 as indicated by Mouser and Digikey</td>
<td>Light activated switch.</td>
</tr>
<tr>
<td>Servo Motors</td>
<td>20.99</td>
<td>2 servo motors needed for the alignment (vertical and horizontal motion). Pack of four on Amazon</td>
<td>High accuracy limited range actuator.</td>
</tr>
<tr>
<td>Cameras</td>
<td>29.99</td>
<td>1 camera is used for alignment on the transmitter side. Price is from amazon</td>
<td>Device to provide visual data.</td>
</tr>
<tr>
<td>Enclosure</td>
<td>10</td>
<td>2 enclosures needed to house both sides. based on typical price of PLA filament for 3D printing</td>
<td>Physical structure to protect and hold devices.</td>
</tr>
<tr>
<td>Optical Filter</td>
<td>16.67</td>
<td>1 pack of filters needed for filtering light at the receiver. between 10 and 20. Based on Amazon, and optical filter retailers.</td>
<td>Thin film that acts as a bandpass for light.</td>
</tr>
<tr>
<td>Optical Lenses</td>
<td>92.16</td>
<td>2 lenses needed to control the width of the laser beam. Price from Newport website</td>
<td>Glass lenses to control the width of the laser beam.</td>
</tr>
<tr>
<td>Electrical Components</td>
<td>10.83</td>
<td>ICs, resistors, etc... needed for the whole project.</td>
<td>Variety of ICs, chips, resistors, capacitors, diodes. and other components.</td>
</tr>
<tr>
<td>Micro Controllers</td>
<td>50.00</td>
<td>Transmission and Receiving data processing.</td>
<td>A RaspberryPi and an Arduino used for data handling</td>
</tr>
<tr>
<td>Misc</td>
<td>10.83</td>
<td>Miscellaneous items for the project.</td>
<td>Additional small items that contribute to device manufacture such as fasteners, adhesives, and labels.</td>
</tr>
<tr>
<td>Total</td>
<td>258.71</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Based on online job review services, and online recruiting services such as Ziprecruiter and Glassdoor, the estimated salary for a newly graduated Electrical Engineer in California is around $80,000 annually. This breaks down to approximately $38.46 an hour. A single individual in this project will work ~185 hours based on Gantt projections. To hire a single individual for the allotted time the cost would be $7,137 per person for $14,274 for the full team of two engineers.

Appendix B - Gantt Charts

EE 460

Figure 24: EE 460 Timeline; shows the Gantt chart for EE 460.
EE 461

Figure 25: EE 461 Timeline; shows the Gantt chart for EE 461.

EE 462

Figure 26: EE 462 Timeline; shows the Gantt chart for EE 462.
Appendix C - Software

Receive Code:

```c
#define SAMPLE_SIZE 126

const char setData[] = "ImniJKrdUl8MGvEfjHNAV4pZTe9ijEUA1Pmn3qgwTMU8rQkAGSmZv5uR6ne2Nkn6H0Ea01c1; //Random 126 characters to test BER. The transmitter is sending these exact bits
byte binSetData[1008];
int start = 0;
int byteErrors = 0;
int bitErrors = 0;
int counter = 0;

void setup() {
  Serial.begin(9600, SERIAL_SN2);

  //These for loops turn the hex ASCII values of setData into Binary values stored in BinSetData
  for (int i = 0; i < SAMPLE_SIZE; i++) { //Goes through setData
    for (int j = 0; j < 8; j++) { //goes through each byte

      binSetData[counter] = bitRead(setData[i], j);
      counter++;//used to add data to binSetData
    }
  }
}
```
```java
void loop() {
  char receivedData[SAMPLE_SIZE];
  char incomingByte[1];

  Serial.readBytes(incomingByte, 1); // read 1 byte received at a time

  // check if the byte received is '!', which is the start character sent by the tx
  if(incomingByte[0] == '!') {
    start = 1; // set start to 1 if '!' was detected
    counter = 0;
    Serial.readBytes(receivedData, SAMPLE_SIZE); // read 126 bytes from register, store it in receivedData

    // turn the bytes received into binary data and compare it to binSetData to get bitErrors
    for(int i = 0; i < SAMPLE_SIZE; i++){
      Serial.println("Expected: " + (String)setData[i] + " Actual: " + (String)receivedData[i]); // print expected and actual
      for(int j = 0; j < 8; j++){
        if(bitRead(receivedData[i], j) != binSetData[counter]) // add to bitErrors if the actual bit differs from expected.
          bitErrors++;
        counter++;
      }
      if(receivedData[i] != setData[i]) // count byte errors: if the actual byte differs from expected
        byteErrors++;
    }
  }
}

// Once the comparisons are done, print the bitErrors and byteErrors forever.
while(start == 1) {
  Serial.println("Byte Errors: " + (String)byteErrors + " Bit Errors: " + (String)bitErrors);
}
```

Transmit and Alignment Code:
import numpy as np
import cv2
from gpiozero.pins.pigpio import PiGPIOFactory
from gpiozero import Device, Servo, DigitalOutputDevice
from time import sleep, monotonic
import serial

my_factory = PiGPIOFactory()

#initialize camera
Cam = cv2.VideoCapture(0)
Cam.set(cv2.CAP_PROP_FRAME_WIDTH, 1280)
Cam.set(cv2.CAP_PROP_FRAME_HEIGHT, 720)

#initialize servos
servoX = Servo(12, pin_factory = my_factory) # This is physical pin # 32
servoY = Servo(18, pin_factory = my_factory) # This is physical pin # 12

def capturePicture(cam): #Takes picture; uses camera object; returns image
    print("capturePicture")
    ret, image = cam.read()
    return image
```python
def locateTarget(src):
    
    Finds green target designator in image; uses
    image; returns center of designator; returns
green designator number;
    
    print("locateTarget")
greenThresh = 230
min_area = 1
max_area = 3500
cx = 0
cy = 0

blur = cv2.GaussianBlur(src,(5,5),1) #Apply gaussian blur to reduce noise

green_chan = blur[:, :, 1] #isolate green channel

#threshold image to remove pixels with green value below greenThresh
ret, gray_green_chan = cv2.threshold(green_chan, greenThresh, 255, cv2.THRESH_BINARY)

cnts = cv2.findContours(gray_green_chan, cv2.RETR_EXTERNAL, cv2.CHAIN_APPROX_SIMPLE) #find contours
cnts = cts[0] if len(cnts) == 2 else cts[1]

white_dots = []
for c in cts: #iterate through all contours
    area = cv2.contourArea(c)
    if area > min_area and area < max_area: #only add contours between the min/max areas
        white_dots.append(c)

for i in white_dots:
    M = cv2.moments(i)
    if M['m00'] != 0: #find centroid of contours
        cx = int(M['m10']/M['m00'])
        cy = int(M['m01']/M['m00'])

return cx, cy, len(white_dots)
```
def servoAlign(x, y, cam):
    
    #
    # aligns servos to designator; uses x and y
    # values of designator in image; uses cam object; returns nothing
    #
    print("servoAlign")
    img_wid = 1280 #width, height of image
    img hei = 720
    servoRange = 60
    Kpx = 0.00009 #Gains for PID controller
    Kix = 0.0007
    Kpy = 0.0001
    Kly = 0.0005
    Kdx = 0.00000
    Kdy = 0.00000
    
    #PID errors
    errornx = (img_wid/2) - x
    errory = (img_hei/2) - y
    Ierrorx = 0
    Derrorx = 0
    Ierrory = 0
    Derrory = 0
    prev_errorx = 0
    prev_errory = 0

    prev_time = monotonic()
    #loop until error is low enough
    while (abs(errorx) > 7) or (abs(errory) > 5):
        #calculate motion variables
        motornx = errorx*Kpx + Ierrorx * Kix + Derrorx * Kdx
        motiony = errory*Kpy + Ierrory * Kiy + Derrory * Kdy

        current_time = monotonic()
        del_T = current_time - prev_time

        #calculate integral error
        Ierrorx += del_T*errorx
        Ierrory += del_T*errory

        #calculate derivative error
        Derrorx = (errorx - prev_errorx)/ del_T
        Derrory = (errory - prev_errory)/ del_T

        prev_time = monotonic()

        if abs(motionx) >1:
            motionx = motionx/abs(motionx)
        if abs(motiony) > 1:
            motiony = motiony/abs(motiony)

        #move servos
        servoX.value = motionx
        servoY.value = -1 * motiony

        #take new picture to check error
        x, y, length = locateTarget(capturePicture(cam))
prev_errorx = errorx
prev_errory = errory

calculate new error
errorx = ((img_w+ 80)/2) - x
errory = ((img_hei + 110)/2) - y

print(f"x: {x} y: {y}")
print(f"errorx: {errorx} errory: {errory}")
print(f"motionx: {motionx} motiony: {motiony}")
print(f"Error: {errorx} Errory: {errory}"

def Alignment(cam):
    ""
    Runs alignment super function; uses a cam object;
    returns nothing
    ""
    print("Alignment")
    # Takes an initial picture and find designator
    x, y, count = locateTarget(capturePicture(cam))
    servoAlign(x, y, cam) #runs servo align function

Alignment(cam)#run the alignment

#begin serial comms
ser = serial.Serial("/dev/ttyAMA0", 9600, serial.EIGHTBITS, serial.PARITY_ODD, serial.STOPBITS_2)

#once alignment is done, send message continuously
while (True):
    ser.write(b'2023 Cal Poly Senior Project Testing\n')
    sleep(1)
Appendix D - Analysis of Senior Project Design

Project Title: Portable Laser Communication device

Student’s Names: Basile Scoffie, Tom Elkayam

Advisor’s Name: Dr. Jin

1. Summary of Functional Requirements
The product is a portable laser communication system with automatic alignment that is designed to be easily installed for semi-permanent communication. It uses Free space optics to transfer data between a transmitter and receiver and uses its alignment system to eliminate the need for fine manual alignment. The user is able to install the system and allow them to align themselves automatically. This device is intended to bring fast data transfer to remote areas with little to no cell service.

2. Primary Constraints
The biggest challenge for this project was the tracking system. This is because any play in the mechanical design, inaccuracy in the servos, or inconsistencies in the CV software translated to errors in the alignment. Another issue we ran into is budget constraints and parts shortages. High quality lasers, lenses, and optical filters can get very expensive and hard to find, which made it hard to find the parts we needed without going over our 600 dollar budget.

3. Economic
The development of this product will require human and financial capitals. The human capital will come from the two Cal Poly electrical engineering students working on this project. They will put in all the time necessary to design and build this product. Most of the financial capital will come from the Cal Poly EE department as they are providing a budget of 400 dollars for the development of this device. An additional 200 dollars will be provided by the students if necessary. During the lifecycle of this product, the costs will come from manufacturing each component, shipping the components to a central location, and assembling the devices. However, both the consumer and the seller will see benefits. The consumer will have the benefit of being able to transmit data without having to build expensive infrastructure such as cell towers or fiber optics. The seller will be able to profit from each unit sold; therefore, the investment to manufacture will become worth it.

4. If manufactured on a commercial basis:
   a. Estimated number of devices sold per year: 1000
b. Estimated manufacturing cost for each device: $300

c. Estimated purchase price for each device: $500

d. Estimated profit per year: $200,000

e. Estimated cost for the user to operate the device, per unit time (specify time interval): If operated non stop at average US national price for kWh, costs are expected to be 2.44 cents a day or 73.2 cents a month.

5. Environmental
The production of these devices consumes metals, plastics and synthetic materials. Inherently this device uses difficult to recycle materials such as PCBs, plastics, and fiberglass creating a negative impact on the environment. This device however intends to replace cables that would need to be laid in place of it while also being reusable and relocatable. This system hence provides a benefit over cables, reducing the need and waste produced by cables.

6. Manufacturability
An issue that may arise when manufacturing this product is obtaining components and shipping them to the assembly location. Manufacturing could be slowed or even halted if there are supply chain issues preventing even a single component from reaching the assembly location. Such supply chain issues have been common lately and can be caused by global conflict, pandemics, strikes, and much more. The main way to prevent these issues is to plan for alternate providers for each part, and make sure that they are reliable.

7. Sustainability
The device will require common electrical components for the manufacturer. This will result in the waste byproducts typical for ICs, microcontrollers, passive components, and silicon devices for the production of the device. Further manufacturing of the device from these base components will require soldering, adhesives, plastic casings, and metals in the form of servos and minor framework. The listed resources for the manufacture of the device will stay on the device with replacement likely only occurring for batteries and servos. The device’s end of life will most likely be disassembly and disposal with only the plastic casing and motors having some direct recyclability as other components are composite in nature.

Improvement design sustainability would involve increasing system modularity to allow for easier replacement of damaged or worn systems with fresh replacements or upgraded modules containing superior systems. Reduction of adhesives to only intermodal connections followed by use of latches and standardized screws would also further device repairability and hence lifetime before disposal. Use of more sustainable materials such as bio-composite PCBs would reduce environmental harm and introduce renewable materials to enhance device sustainability.
8. **Ethical**
One ethical concern that may arise due to the misuse of this device is secret communication of illegal information. Since free space optics communication is inherently more secure than RF systems, it would be easier for users to use this device to transmit illegal or unethical information such as trade secrets, human trafficking, or drug dealing. Additionally, users could misuse this device to intentionally point the laser in other people’s eyes and injure them. This could result in permanent eye damage and large medical bills for the victims. The large-scale production of the device can also lead to ethical concerns if lower class workers are abused by factories that provide components, and pollute local regions.

9. **Health and Safety**
The biggest health and safety concern with our project is the risk of eye damage to users and bystanders due to laser exposure. In order to mitigate this risk and prevent injury, we must make sure that there are several safety features that prevent the tracking system from pointing the laser in unpredictable directions. Additionally, using a low power laser is essential to keep the system safe to use because the beam is less likely to injure anyone and labeling the live end of the device is also essential.

10. **Social and Political**
The main social issue with manufacturing this product is the potential use of cheap labor overseas. This labor benefits the company financially but can have a negative impact on the local community around the factories. In order to make sure that the manufacturing of this product does not harm people overseas, it is necessary to either make this product in the US or to choose a country where workers are respected, not abused. Some of this product’s stakeholders include communication companies (AT&T, Verizon,...), researchers in remote areas, and the shareholders of the company. The success of this product could potentially harm the communication companies because our device competes with their mainstream RF systems. However, stakeholders such as researchers in remote areas will benefit from this device because they will be able to communicate the data they need without having to use expensive RF systems or laying cable between locations.

11. **Development**
Developing this project allowed for introduction to photonics and the use of lasers in practical applications. This introduced many uncommon components such as laser diodes, photodiodes, and phototransistors. The use of lasers also emphasized optical theory and the use of lenses to manipulate lasers and optical filters to selectively isolate particular wavelengths of light and
focus them onto precise points. There was also emphasis on creating efficient software in the form of computer vision using Python libraries such as OpenCV and relating it to an alignment algorithm matched by servos. This software and hardware system embodied a full-scale mechatronics project.