Remotely Controlled Diffused Surface Laser Beam Imaging System

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The object of this project is to design a device that can find and tracking a laser beam off a diffused target board. The lens design is an afocal three group. A bandpass filter removes ambient light, allowing only 532 nm laser light through the system. Luminous flux is collected through the optical lens system to a light sensor for measurement. The reflected light from the diffused surface propagates through the lens system into a bandpass filter which removes undesired frequencies and measured by an optical sensor placed above the camera. The camera input itself is processed through a machine learning algorithm which detects the position of the laser beam and tracks the movement between frames.

Index Terms **— Laser beams, optical filters, radio control, optical design, machine learning.**

I. Introduction

Current equipment for high power outdoor laser experiments must be aligned by hand and monitored from both the laser output as well as the target. The testing range distance can be a kilometer more. With an automated system that can locate the beam and record its characteristics, the amount of personnel on the ground can be reduced. Equipment traditionally is not designed to deal with the outdoor elements. Our design will be weatherproof to eliminate that issue. Most optical equipment on the market right now uses a direct power source to power the instruments, which is inefficient for outdoor use. A solution to this is to incorporate a power source which is both chargeable and solar powered. With such a large distance a remotely controlled device will not only cut out the need for additional personnel, saving time and potential costs, but will be able to withstand any weather without the need to be physically covered or removed from its optimal testing location.

Some objectives of designing the device is to build a zoom system with lenses that can be controlled remotely to locate a laser beam on an outdoor diffused surface. A filter system will be included to control the ambient light introduced to the device. The vital information about beam location and characteristics will be transmitted and displayed on the receiver. This device will be controlled remotely from the laser's location.

II. Lens Design

The starting point for the lens design is the afocal system, which are commonly used in zoom systems, such as telescopes and binoculars. Afocal systems involve two or more lenses where the input light and the front focal point are located at infinity. In this type of configuration incoming and outgoing rays are parallel to the optical axis. The transverse and longitudinal magnification do not change, and the system does not focus the light, rather, changes the size of the incoming beam.

Several configurations of zoom lens systems offer varying levels of magnification at the cost of complexity. Two arrangements, Negative-Positive-Negative and Positive-Negative-Positive (PNP) Donders telescopes, can provide clear images. A Donders telescope is an afocal three-group system where there is one fixed prime lens in addition two moving groups, the variator and compensator groups. The prime lens holds the location of the image plane stable and is usually located in the rear of the system. The variator typically moves linearly, while the compensator generally moves nonlinearly. The nonlinear path that the compensator move in is called the cam curve. The variator controls the zoom magnification of the system, while the compensator keeps the image plane stationary.

To take advantage of the design flexibility while mitigating complexity, a three group zoom design with a positive-negative-positive power configuration is chosen. Each group is a singlet to reduce cost, though splitting the center variator group was considered. By splitting a group, more control over aberrations can be achieved. Because the refraction of the rays are split between several elements, the total aberrations are reduced compared to one element of the same power. Spherical aberrations were the only aberration of concern in this design, which are balanced throughout the design without the need of splitting any groups shown in **Figure 1**.

To keep stay within the prescribed budget, all lenses used in the Zemax simulations are prefabricated and readily available off the shelf. This posed an interesting challenge because it limited the choices available to optimize the lens design. Simulation revealed that field of view and length of the system were important factors that inversely related to the magnification. While one design would produce a maximum magnification of 5x, the length of the system as the lenses would move through a zoom would exceed 20 cm. The large length makes these positions unusable and limits the system to just one zoomed-in position, which does not meet the objective of the project. On the other hand, one design produced a field of view of over 1/3 the image, however the maximum magnification is only 1.8x, which is not large enough for image processing. It is in balancing these parameters that the final lens design **Figure 3** was chosen. Three optimized positions were chosen **Figure 2** based on the magnification.

The only aberration of concern is spherical aberrations. Spherical aberrations will occur if the lenses are improperly positioned. The S1 seidel coefficient is nearly zero when the lenses are correctly positioned, so any spherical aberrations are a result of motor inaccuracy.

To maintain the optical axis, an optical cage system is utilized. Four guiding rods fix the optical axis in the y- and z-directions, while allowing the two front lenses to freely move forward and backwards in the x-direction. The third lens is fixed to the back of the system but is maintained to the optical axis by the guiding rods.

III. Design Flaws and Rectification

The main design flaw in the lens design is that field of view was not considered. After the initial lenses were purchased and testing began, it was clear that the zoom aspect of the design worked, but the field of view was still too small on the image. To rectify this, the front compensator singlet was doubled in size, to collect more light and the maximum length of the lens systems movement was reduced. Wide angle positions (semi-angle coverage >20°) need large front group diameter to maintain a usable field of view. The rectified design doubled the field of view from about 1/8 of the image to about ¼ and increased the magnification from 2x to 3x.

An improvement that can be made to the overall structure of the lens system would be to fix the front lens and move the back two lenses, along with the camera. This would improve the view of the image to be a full circle rather than a cross shape. Because the movement

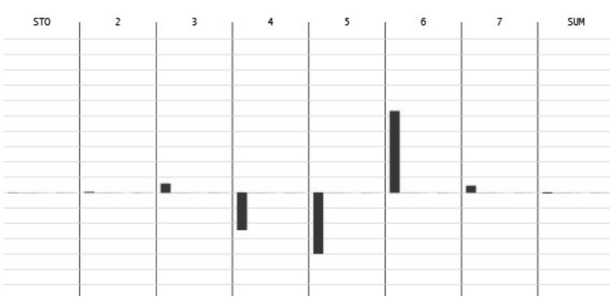


Fig. 1 Seidel diagram: spherical aberrations are balanced by the lenses through the system. All other aberrations are absent from this design

would introduce issues with the electronic components, as well as the motor inability to overcome the weight of the camera, this improvement was compromised.

Position	Distance between lens A and lens B (mm)	Distance between lens B and lens C (mm)	FOV (% of image)	Magnification
1	26	83	24.12	1.4 (zoomed out)
2	10	100	23.92	2.2
3	2	115	22.66	3.0 (zoomed in)

Fig. 2 Three lens positions with their FOV and Magnification

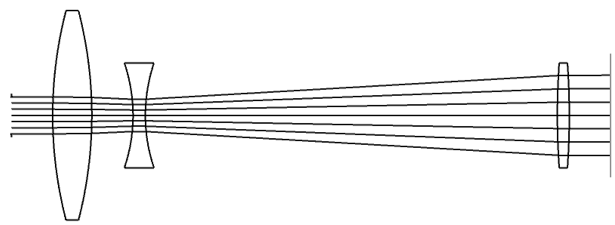


Fig 3. PNP three group lens design, where the camera is positioned on the orange image plane. Position 2, magnification is 2.2x.

IV. Laser Source

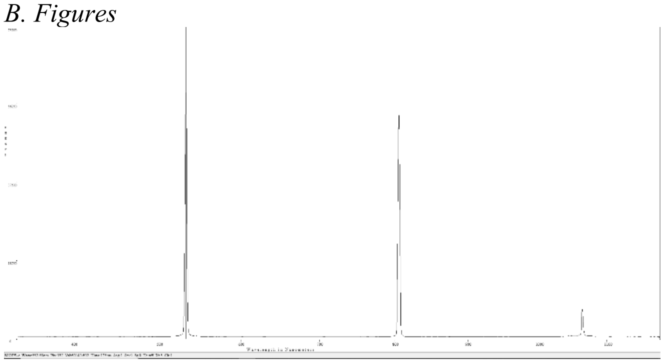
The requirement for this design is a laser source with a narrow peak bandwidth as close to 532 nm as possible. The particular laser source chosen is a handheld laser with a power of 100 mW. In lab testing with a power meter and a neutral density filter of optical density 2 confirmed the power to be 100 mW. The spectrum of the laser was measured with a spectrometer and included some infrared leakage which is common with less expensive light sources due to the materials used to reach the 532 nm lasing. The spectrum of the laser and its leakage is shown in **Fig. 4**. This infrared leakage will not be a problem because the bandpass filter used in the design will filter out the undesired frequencies. The laser measured with the spectrometer aligned with the bandpass filter filtering out the infrared frequencies is shown in **Fig. 5.** A close up of the spectrum in the green region with a marker indicating the 532 nm is shown in **Fig. 6.** This confirms that the laser lases in the desired bandwidth region roughly + or – 2 from the center which is acceptable for this application. The beam aperture is 3mm and using **Equation 1** the intensity of the laser with a coherent beam is measured to be 1.4147 W/mm^2.

A. Equations

1.

$$I = \frac{P}{\pi * d^2}$$

B. Figures



Fig, 4. Spectrum of Handheld 100 mW laser with peaks in 532 nm wavelength region and infrared leakage.

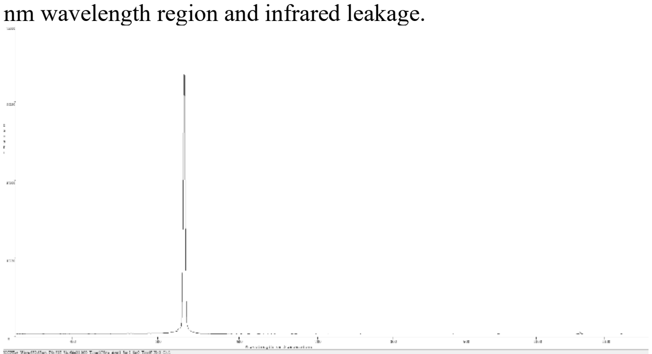
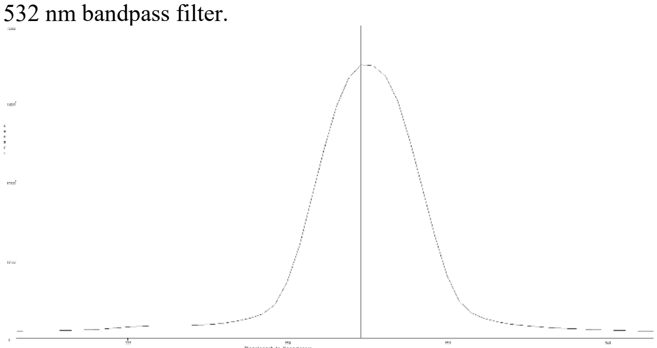


Fig. 5. Spectrum of Handheld 100 mW laser measured through 532 nm bandpass filter.



Fig, 6. Spectrum of Handheld 100 mW laser measured through bandpass filter zoomed in on 525 – 545 mm wavelength with line indicating 532.25 mm wavelength.

V. Laser Source

A filter is necessary for the design of this project for the sole reason of blocking out the highest percentage of undesired ambient light frequencies that would propagate through the system to the camera and the optical sensor. One main objective of this design is to gauge how much light intensity measured in lux is being collected by the systems camera and is penetrating the surface of the light sensor. The filter is placed on axis behind the stationary converging lens in front of the camera and optical sensor. The ideal bandpass filter for this design will have seven desirable traits. These traits are as follows; a central wavelength of 532 nm, a narrow bandpass bandwidth of a maximum + or – 10 nm, a high optical density greater than two, a wide wavelength blocking range, a minimum transmission percentage at desired frequency no less than 40%, a filter size not smaller than the smallest lens in the system (25 mm), and in a price range window less than $150.00.

A. Filter chosen for design

The chosen filter for the project is the Edmunds #65-700 optical filter. The specs of this filter are as follows. The central wavelength of the filter is 532 nm. The bandpass bandwidth is 10 nm. The optical density is 3 blocking out undesired frequencies at a degree of 10^3. The blocking wavelength range is from 200 – 1200 nm which will block out a large portion of ambient light as well as the undesired leakage infrared frequencies from the laser. The minimum transmission percentage is ≥ 45%. The diameter of the filter is 25 mm. The price of the filter is $143.00. This filter meets the criteria for this design on all aspects. **Figure 7** shows the bandpass properties of the filter provided by the Edmund Optics website.

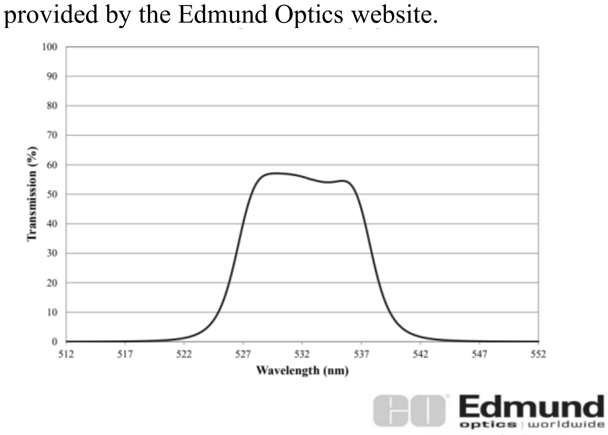


Fig 7. Bandpass region of 532 nm Bandpass filter provided by the Edmund Optics website. https://www.edmundoptics.com/p/532nm-cwl-10nm-fwhm-25mm-mounted-diameter/20218/

VI. Hardware Components

There are various hardware components in the system that interface with each other in the final overall product.

These components themselves are either designed or purchased to fulfill certain applications. The following is a brief technical overview of each component used.

A. Microcontroller

At the heart of the motor control system lies two ATMega 4809 microcontrollers, one used to operate the motors themselves and the other used for the wireless controller, communicating with each other utilizing components discussed later. There is also a third controller that is used for the light detector to analyze the light that is being shown into the camera. This controller was selected based on broad library support, higher memory capacity, and better temperature tolerances among other features. The chip can run at 20MHz which allows for better speeds given the amount of component interfacing required for this application. The chip is programmed and debugged utilizing the Arduino IDE for the purposes of software development.

B. Wireless Communications

The Nordic Semiconductors nRF24L01+ radio transceiver module is an all-in-one transceiver-receiver that utilizes the 2.4 GHz ISM band. The transceiver is capable of transmitting at 250kbps, 1Mbps, and 2Mbps with a communication range that can exceed 1km (line of sight). The module only requires a regulated 3.3VDC input, making this a simple hardware implementation.

C. Motor Control

To simplify the controlling of the stepper motors the Allegro A4988 Stepper Motor Driver board is utilized. This driver allows for a much simpler interface between the microcontroller and the stepper motors, requiring only two pins to control the step and the direction of the motor, allowing for more motors to be controlled by a single microcontroller while still leaving enough connections for the nRF24L01 module.

D. Single Board Computer

The Raspberry Pi 4B is the mind for the object detection and tracking system, taking the images extracted from the camera and processing them to track the laser beam profile. Utilizing the OpenCV machine learning library, the Raspberry Pi will be able to extract frames from the camera and analyze them to detect the profile of the laser beam and track it. The tracking will be saved as a video file for analyzation.

VII. Object Tracking

The object tracking program running on the SBC operates on a process can be better understood by following the visual aid below highlighting its main functions.

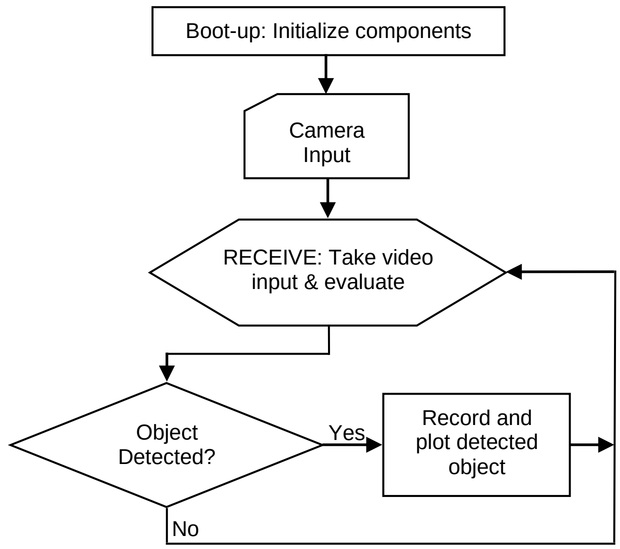


Fig 8. Flowchart of the system functions of the object tracking.

The object tracking system runs cyclically, as illustrated, with no internal stopping point. Rather it relies on user to start and stop the object tracking software. When the process is ended the video of the tracking will be saved onto the SBC for further analysis.

The program analyzes the incoming frames and breaks them down to the HSV (hue, saturation, luminescence /value) color properties of each of the pixels in the frame. The pixels are then filtered through to see which of the pixels fall within a defined threshold of values. The filtered frames are then analyzed to determine if there is a significant amount of pixels in a particular area that would warrant detection and tracking. If a group of pixels meet the criteria the program notes where the center point of the group is, marks the center position, and moves onto the next frame for analysis.

VIII. Transceiver

The following diagram highlights the components used in the Transceiver used to remotely communicate user inputs for the adjustment system.

The user inputs come in the form of button and analog stick inputs, buttons for zooming in and out and the analog stick inputs for the ability to implement adjustments on the X and Y axes. These commands are processed through the microcontroller to be sent out through the nRF24L01 communication module and received by the receiver on the adjustment system end. The transceiver is powered independently through a battery pack with a voltage of 6V that can operate the microcontroller and is dropped down for the nRF24L01.

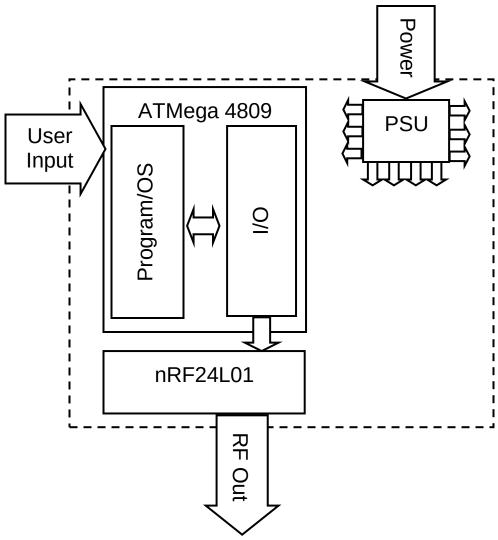


Fig. 9. Block Diagram of the Transceiver and its major components.

IX. Receiver

The following diagram highlights the components used in the receiver used to remotely communicate user inputs for the adjustment system.

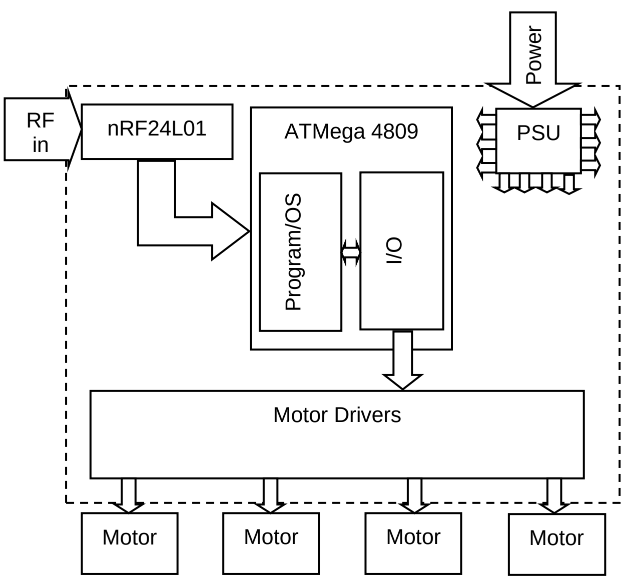


Fig. 10 Block Diagram of the Receiver and its major components.

The commands from the transceiver are received via the nRF24L01 module and are processed through the microcontroller which, based off those commands, determines which motors operate at which speed and in which direction. These processed commands are then communicated to each motor's allotted driver which takes the direction and step instructions from the microcontroller and processes the instructions through the 4-pin stepper motor interface. The receiver is powered through a 12V battery, with the motors requiring the 12V, which for the remaining components is filtered through an LDO voltage regulator rated for 5V and 3A, suitable for the microcontroller and the motor drivers, and is then further processed to a 3.3V power signal for the nRF24L01 module.

X. Light Detector

A light sensor is used to measure vital information including the intensity of the light which is reaching the camera. This intensity being measured is the lux which is the luminous flux per unit area. The 5506-cadmium sulfide (CdS) light dependent resistor (LDR) is ideal for this application. The CdS LDR has a spectral sensitivity to 532 nm light of about 95%. This high sensitivity is necessary due to the dark environment of the enclosed box of this design. The LDR is set up in a voltage divider circuit with a 10k ohm resistor and a voltage bias of 5V applied to the LDR node. The voltage divider branch is measured and using **Equation 2** the luminous intensity across the LDR surface is approximated. The 5506 LDR characteristics were measured in the lab under dark light conditions with only a fiber light source (Fiber Light High Intensity Series 180 Dolan-Jenner Industries) passing through the bandpass filter shining upon the LDR with an accompanying lux meter (Dr. Meter Model LX1330). With this information a lux meter was designed using the voltage divider circuits voltage output connected to an ATMega 4809 microcontroller board and displaying the measured lux on an LCD. The lab results are shown below and were used to calibrate the lux meter design.

A. Equations

2. $Log_{10}(lux) = -1.3282 * Log_{10}(Resistance) + 6.0136$

B. Lab Results

Intensity	Resistance (K-Ohms)	Lux (Lx)
0	1M	0
1	9.97	7.4
2	8.65	9.5
3	7.55	11.9
4	6.56	15.1
5	5.81	18.6
6	5.11	23.2
7	4.43	29.8
8	3.85	38.1
9	3.37	48
10	2.93	60.9

Table 1 LDR 5506 Resistance Vs Lux of Fiber Light with Bandpass Filter, No Bias

Intensity	Resistance (K-Ohms)	Voltage Output (V)	Lux (Lx)
0	0.968	0.18	0
1	5.16	2.50	7.3
2	4.83	2.66	9.0
3	4.50	2.83	11.3
4	4.15	3.01	14.4
5	3.83	3.12	18.1
6	3.53	3.29	22.6
7	3.19	3.46	29.3
8	2.90	3.61	37.3
9	2.62	3.75	47.5
10	2.37	3.85	60.0

Table 2. LDR 5506 Resistance, Voltage, and Lux Measurements with Fiber Light through bandpass filter, 10k ohm resistor, and 5V Bias.

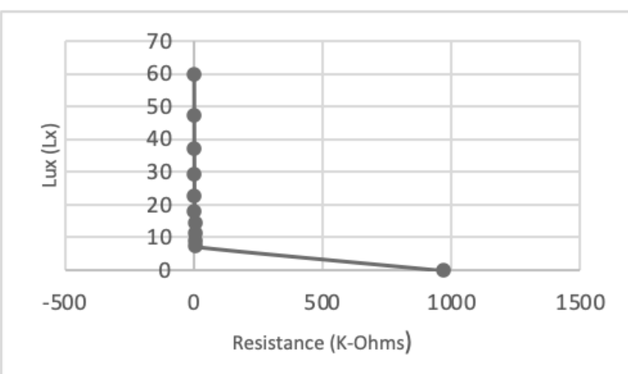


Figure 11. Lux vs Resistance of 5506 LDR with Fiber light of varying intensities, Bandpass filter, 10k ohm resistor and 5 V bias

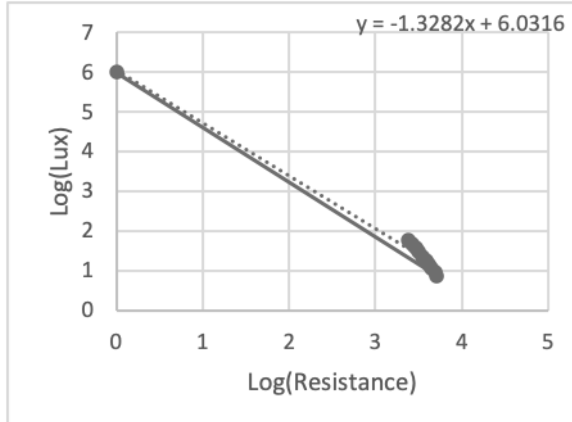


Figure 12. Log(Lux) Vs Log(Resistance) of 5506 LDR. The slope equation is used for calibration of the Lux Meter.

XI. System Alignment

Precise alignment is key for the system, to avoid the image sent to the camera being distorted. In case of misalignment, the laser beam would hit each lens at a different angle where if not aligned correctly, will create disturbances to the beam's response to the line of lenses. A 2040 V-slot rail is used in this project, to allow linear moment to each of the lenses that make up the filter. The rails' height is 40 mm, with a width of 20 mm. The lenses farthest distance between each other is 10 mm. To aid the alignment and reduce the most movement for each of the lenses, 6 mm of diameter and 8 mm of length rods are mounted to guide the lens cage. Taking into consideration the space taken by the rails, motors, and the proper alignment for the lenses. The box will have a length of 30 cm, width of 27 cm and a height of 12 cm. This gives enough spacing, as well as keeping the load weight to a minimum.

A. Top View

Distance between components that compose the filter system are very precise, where the least space is utilized to decrease weight of the overall system. Figure 14 gives a view from the top of the box, A Nema 17 motor with a horizontal length of 5.5 cm, and vertical length of 5.0 cm is attached at the bottom left corner. Aligned with the motor, the V-slot rail takes a horizontal space of 2.0 cm, and a vertical space of 16.0 cm. Attached to the rail, is a platform with dimensions of 5 cm both horizontal and vertical. An extension to the platform was designed and 3D printed. The extension is replicated the same size as the horizontal and vertical dimensions of the platform, but it extends 4 cm of the z axis or width. The platform extension has an extrusion on its side facing the lens. This extrusion extends as a square of 2 cm on each side. The extension printed directed away from the rail connects to the lens cage creating a distance of 7.03 cm from the midpoint of the cage holding the lens, and the edge of the rail closest to the lens. At the other end of the v-slot rail, the driven gear is mounted on a designed 3D printed mount, with dimensions of 2x4x6 mm. Figure 16 illustrates the lens mounts. The lens mount has an extension of 1 cm and the right mount has an extension of 2 cm as both lenses have different geometries and occupy different space in the system. Both mount's extension was also designed to allow an M4 screw which matches with the screw holes in the lens cage.

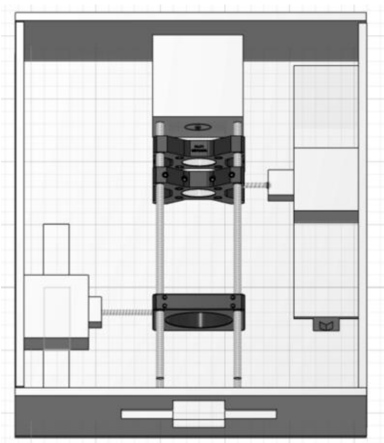
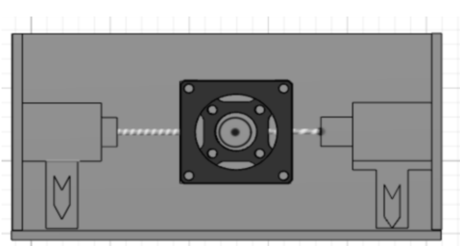


Figure 13. Top View of lens and camera alignment.

B. Front

The alignment seeing it from the front of the system is very important, for the camera's lens to align with the midpoint of the three lenses extending away from it. The goal for the system is to be precise enough where the laser beam coming into the camera is as close to perpendicular to the plane of the camera's lens. Figure. 15 shows the alignment sketch from the front of the system. The circle in between the lenses represents the camera. The bottom of figure 15, illustrates the opening where the laser beam goes into the system. The opening length was chosen carefully to avoid unwanted light pollution and was designed to be 8 cm wide and 8 cm high. Each distance connecting the lenses to its corresponding mount is taking highly into consideration and was accomplished by using a CAD software tool.



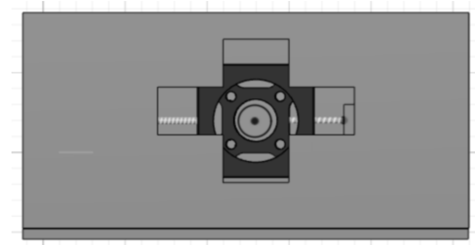


Figure 14. (Top) Front alignment of the three lenses and the camera. (Bottom) Front alignment through the opening in the front wall.

XII. Power Distribution

The power provided to the project is produced by two 12-volt Lithium Iron Phosphate batteries, made by ECO-WORTHY. Each battery is rated at 10 Amp-hours and has an overall power of 120 watt-hours.

A. Voltage regulator

As the 12-volt battery is powering the project, a regulator is utilized to step down from 12 to 5 volts, to provide the correct voltage to some of the components. This project implements the LD1085V50, providing the correct voltage to the motor, drivers, processors, SBC, and Lux meter.

B. Motors

One battery provides power for the two Nema 17 motors. Two of the motors are attached to the lenses allowing the filter system to adjust distances between lenses. The current limit for the motors is of a max current of 1.5 Amps, and minimum current of 0.4 Amps required.

XIII. Mechanics

The project implements a zoom mechanism designed by our Optics and Photonics group members. The lenses move individually while adjusting their position. This allows the image received by the camera to be able to zoom in and out from the target reflecting the laser beam.

A. Pulley System

The system transfers rotational motion, coming from the two separate motors to linear motion allowing the lenses to move along the same axis directed by the rail. Along the 13 cm rail, at the end a driven gear is mounted. Using a CAD software tool, Figure 17 illustrates the mount designed and 3D printed for the driven gear. A 5 cm x 5 cm platform is then attached to a belt with a 5 mm width belt, with the proper tension since slack in the belt could cause inaccurate position for each lens. As shown in Figure 14, inside of the project, the two rails are separated by a distance of 8 cm. The two lenses' midpoint meet in the middle measured from the rails. Figure 18 illustrates he driven gear mount designed to fit a 5 mm bearing to allow rotation once the driven gear is mounted. A 5 mm timing belt is attached to each of the lens platforms and measured with enough tension to go around the motor rotor and the driven pulley. This setup allowed each lens with motion to be precise as each lens get as closed as 1 millimeter from each other.

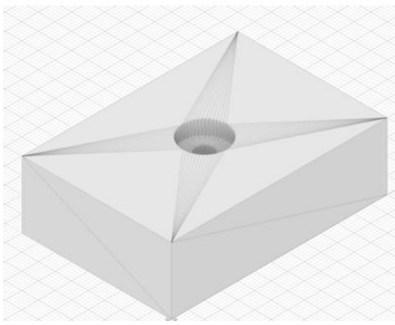


Figure 15. Driven gear for pulley system, designed in Fusion 360.

XIV. About The Authors

Miguel Ortiz is a graduating Electrical Engineering student at the University of Central Florida, graduating in May of 2022. Miguel hopes to pursue a career in power engineering to work for a company such as Duke Energy, Siemens, or GE.

Devin Benjamin is a graduating Photonic and Optical Engineering student at C.R.E.O.L in the University of Central Florida. He plans to continue his education and later seek employment after receiving his Bachelors in May of 2022.

Daniel Oquendo is a graduating Computer Engineering student at the University of Central Florida. After graduating in May 2022 Daniel hopes to pursue a career in hardware engineering for a large company such as Texas Instruments, Medtronic, or NXP.

Madelaine Smith is graduating in May 2022 with her Bachelor of Science in Photonics and Optical engineering. Madelaine will join ASML as an Opto-Mechanical Production Engineer post-graduation.

XV. Acknowledgements

The authors wish to acknowledge the support of Drs. Wei, Kar, LiKamWa, Pang, and Li; as well as the University of Central Florida.

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