Auto-Focusing and Color Identifying Utility Lenses for Mild Visual Impairments

(P.A.U.L.)

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1 Executive Summary

Across the world, 1 in every 200 women and 1 in every 12 men have some form of colorblindness. [1] Even more shocking, 2.2 billion people globally have some form of near or distant visual impairment. [2] While many of these impairments can be assisted through the help of lens systems and medical corrections, both of these methods have inherent drawbacks. For example, as presbyopia - farsightedness - continues to progress throughout adulthood, individuals can sometimes need to continuously purchase new glasses to correct their vision. To alleviate these issues, P.A.U.L has been developed by engineering students at the University of Central Florida. The project is a combination of subsystems that are meant to work in tandem to primarily assist individuals who suffer focusing issues and colorblindness, doing so by responding to inputs from the user to help interpret their environment.

The autofocusing system incorporates a button on the side of the glasses to initiate a CMOS sensor to photograph the environment directly in front of the user. Using the camera's feed, a series of lenses in front of the CMOS is moved until the image becomes clearly in focus. The exact power of the resulting lens system is then calculated, and then a series of lenses in front of the user's eyes are adjusted to match the optical power interpreted by the CMOS.

The color detection system incorporates the same CMOS along with a colorimeter to detect the color of any object in front of the user by activating a secondary button. The two systems interpret the color of the object, and if they come to a consensus the user is told through a Bluetooth audio device (not included) the color of the object in front of them.

This system was designed to be fitted onto a hat and be as comfortable as possible. Maximizing the efficiency of the assistive systems was our primary focus, as we felt that existing products typically fell short of possessing a full scope of technological suites that supported such an endeavor. The subsystems working together and being fitted onto one integrated package ensured a product that was capable of catering to the needs of as many users as possible and demonstrated a leap forward in universally applicable assistive technology.

This document records P.A.U.L.'s design process, including the motivation to pursue it, the theories needed to understand its underlying principles, necessary technology, part selection, the implementation process, and limitations. The case for the need for such technology was established first, followed by a brief look into existing technology that attempts to solve some of these stated issues. Then, discussion and selection of key technologies covers a large section of the report. This is then followed up by a discussion of the standards and constraints that were considered when producing P.A.U.L., which then leads to the section discussing the implementation of the chosen technologies along with schematics for both the

hardware and software design portions of the project. Fabrication, prototyping, and administrative content comprise the next set of chapters, and is ended with our conclusion. Appendixes containing AI-generated responses, code snippets, and references are found in the back portion of the report.

2 Project Description

The P.A.U.L headset was designed to assist individuals with mild visual impairments such as myopia, hyperopia, presbyopia, and color vision deficiency; these are also known as near-sightedness, far-sightedness, age-related far-sightedness, and colorblindness, respectively. These mild visual impairments can result in obstacles that can be circumvented through the use of the system's two primary features, auto-focusing and color-identification.

The adjustable focus provided by the auto-focusing system is capable of correcting vision for myopia and hyperopia. This allows the user to adjust the system to the same optical prescription that they would normally use for their prescription lenses. The auto-focusing feature can then compensate for the optical power that is lost to individuals with presbyopia. This would then return the ability to focus on objects at various distances to those individuals. The headset would then essentially function as reading glasses with automated variable optical powers.

The color-identification system was designed to assist individuals who struggle with differentiating between colors. Whether it be a color vision deficiency or another form of vision loss; the inability to identify unique colors can be a massive obstacle. For individuals with color vision deficiencies, the greater the deficiency, the more an individual struggles with proper identification of colors and in turn, the more beneficial our system becomes. The implementation of photodiodes provides a starting point for the color identification. Then the CMOS sensor confirms the color or colors present, improving the accuracy of the color identification. Ideally, the color identification feature should be used after the auto-focusing system to ensure the most accurate color identification possible.

As seen in Figure 2.0.1, the headset was designed around existing forms of headwear. By utilizing an existing form of headwear such as the common ball cap or visor, the headset is designed to comfortably sit on the user's head. In addition to this, the inclusion of adjustable straps enables the headset to fit a variety of head sizes. Headwear with some form of brim was prioritized as it provided stability and maintained the alignment of the optical axes.

Figure 2.0.1 Digital Rendering of Assembled System

2.1 Motivation and background

The development of assistive lenses stemmed from a motivation to enhance the quality of life for visually impaired individuals. There exists a phone application called Be My Eyes in which sighted individuals volunteer to aid visually impaired individuals with everyday tasks such as picking out clothing or navigating public spaces. [3] The visually impaired individuals simply point their phone cameras towards the subject they need assistance with and the volunteer acts as their eyes on the other end of the video call. Be My Eyes is certainly a beneficial and useful application. Yet, it relies on volunteers assisting visually impaired individuals. By developing assistive lenses with various features, visually impaired individuals can gain more independence in their everyday lives and facilitate many tasks that would normally require the assistance of another person.

The process of adjusting the focus in the human eye is called accommodation. The ciliary muscles in the eye control the roundness of the eye's lens and thus are responsible for focusing power, also known as accommodation. When focused on an object in the distance, the ciliary muscles relax, flattening the eye's lens and decreasing the focusing power. Alternatively, when focusing on an object nearby, the ciliary muscles contract, increasing the roundness of the eye's lens and increasing the focusing power. As humans age, they begin to develop a condition called Presbyopia. [4] This occurs when the ciliary muscles in the eye weaken and are no longer capable of accommodating. Without accommodation, an individual loses their near vision. A pair of reading glasses typically becomes necessary to focus on anything nearby at this point. Technology capable of adjusting an individual's focusing power is beneficial for individuals with Presbyopia.

The human eye contains multiple photosensitive receptors, of these, the cones are responsible for color. There are three kinds of cones in the human eye that work together, allowing humans to experience the full spectrum of light. The three types of cones are the L-cones, M-cones, and S-cones. [5] The L-cones are most sensitive to red light. The M-cones are most sensitive to green light. The S-cones are most sensitive to blue light. Color vision deficiencies occur when any of these cones have a reduced sensitivity. The M-cones and L-cones have a large overlap in the wavelengths that they are capable of sensing. Due to this, when there is a reduced sensitivity in either the L-cone or the M-cone, it becomes difficult to differentiate the values located in the overlapping wavelengths. This results in the most common color vision deficiency referred to as red-green colorblindness. While this is the most common color vision deficiency, many others exist that impede an individual's ability to distinguish between colors. A technology capable of identifying unique colors and relaying the information to an individual with a color vision deficiency helps said individual overcome their struggles with distinguishing between colors.

By implementing various assistive technologies into a pair of glasses, our lenses can improve the lives of visually impaired individuals. While the initial prototype is limited to assisting individuals with focusing and color-based concerns, there is potential to add additional features that can contribute to assisting individuals with other, more complex vision-based disabilities. The lenses are a tool to assist visually impaired individuals with their everyday life by simplifying tasks that are currently taken for granted by most people.

2.2 Existing Products

In our endeavor to produce a device that can support individuals with various visual disabilities, we had come across several existing products that also support visually impaired individuals through various methods. While the majority of these existing products were designed with the purpose of supporting visually impaired individuals, not all of them were. There are products that simply have features that visually impaired individuals can benefit from.

2.2.1 EnChroma Color Blind Glasses

EnChroma color blind glasses are designed to improve the ability to distinguish between colors for an individual with a color vision deficiency. The M-cones and the L-cones in the eye have a large overlap in the wavelengths that they can sense. Any deficiency in either the L-cone, the M-cone, or both can result in red-green colorblindness. Due to this, red-green colorblindness is the most common color vision deficiency. EnChroma color blind glasses do not function by broadening the wearer's ability to see the full color spectrum. Instead, they function by filtering out certain wavelengths of light where the L-cone and M-cone overlap. By filtering out these wavelengths, the overlap between the L-cone and M-cone is reduced. Reducing this overlap increases the contrast between the colors, thus improving an individual's ability to distinguish between red and green. [6] The spectrum of values they are capable of detecting is also reduced. The largest drawback of the EnChroma color blind glasses is that they are limited to only assisting individuals with red or green color vision deficiencies, protanomaly or deuteranomaly, respectively.

Our lenses do not alter the user's ability to perceive colors. Instead, they can identify colors and relay that information to the user through an auditory response. Regardless of the form of color vision deficiency, they are still helpful to the individuals. In addition to this, our lenses can help a wide variety of individuals with vision impairments.

2.2.2 Ray-Ban Meta Smart Glasses

Perhaps the product most similar to ours, these smart glasses are a collaboration between Ray-Ban and Meta. They utilize dual cameras, one 5 MP camera and one 12 MP camera. The cameras are capable of recording video as well as capturing photographs. The glasses also have built-in speakers and microphones that allow the user to listen to music or make calls. With voice assistant integration, the user can issue voice commands to interact with the distinctive features. The voice assistant feature is also compatible with certain other voice assistants allowing the user to access more information and control other smart devices. [7] These glasses currently do not have many accessibility features targeted towards assisting visually impaired individuals, but there is immense potential for implementation of more features.

The Ray-Ban Meta smart glasses are incapable of changing focus. They are locked into a single optical power. Auto focusing is a key feature that our assistive lenses are capable of. This feature is be greatly beneficial for individuals with Presbyopia.

2.2.3 Bifocal Lenses and Progressive Lenses

Although not new technologies by any means, both bifocal lenses and progressive lenses share the feature of having multiple focal powers on a single lens. These kinds of lenses are typically prescribed to individuals with presbyopia.

Bifocal lenses are eyeglasses that have two distinct optical powers. One portion of the lens, typically the upper portion, is utilized for distance vision. The second portion of the lens is utilized for near vision. This combination of two optical powers removes the necessity of reading glasses.

Progressive Lenses also allow for both distance and near vision, but unlike bifocals, there is a gradual transition between the optical powers allowing for more focusing distances instead of just two.

The auto-focus feature of our lenses benefits individuals with Presbyopia as well. A key flaw of bifocal lenses and progressive lenses is that the user must be looking through specific areas of the lenses for each optical power. This requires the individual to occasionally have to tilt their head in awkward positions to view their desired subject properly. The assistive lenses auto-focus down the center of the lenses, thus the individual only has to look in the direction of their subject to focus at the proper distance.

2.2.4 Project I.R.A.S (Intricate Real-time Assistance Spectacles)

I.R.A.S. was a UCF senior design project focused on providing different types of disability assistance using a primarily visual display with information fed through real-time data collection. [8]

I.R.A.S.'s color detection feature was focused on providing real-time assistance. They utilized a Raspberry Pi to convert their input data from an RGB color space to HSV, and then interpreted the resulting image by assigning it a binary value of 1 or 0. The matching color is then written onto a display joined to the glasses.

Additionally, the display system was also used in tandem with a speech-to-text system that was meant to translate French, German, or Spanish into English text or vice versa. The microphone for operating the system was connected directly onto the group's Raspberry Pi.

Both of these systems were meant to be used with an app that the team programmed where it was possible to select the desired language and colors to be detected.

Overall, the design philosophy of I.R.A.S. was significantly different compared to our project. Whereas theirs was meant to be centered around the use of the display feature, our system assumes that the wearer has significant visual disabilities that our system can assist with. While their real-time color detection system is useful for a display-based method, our primary concern with using a similar program is the potential for unintended irritation to the wearer.

2.3 Goals and Objectives

With this project, we developed a set of lenses that can perform various functions that revolve around the objective of improving the quality of life for individuals with mild visual impairments. The first feature, auto-focusing, can help individuals that wear corrective lenses for mild focus-based visual impairments. This includes myopia, hyperopia, and presbyopia. Myopia and hyperopia, also known as near-sightedness and far-sightedness respectively, can be easily corrected through a lens system with either a positive or negative optical power to counteract the refractive error in the eye. With a system that varies from -1.5 D to +2.5 D, our system can correct mild myopia and mild hyperopia through the manual adjustment of the lens system. Once the eye's refractive error is accounted for, the total optical power of the system is at 0 D. From there, presbyopia, the inability to accommodate the eye for near focus, is taken care of through the automated focusing of our system. The system essentially performs the task of increasing the focusing power of the user's sight in order to observe nearby objects clearly. The auto-focusing system reduces the necessity of multiple corrective eyeglasses.

While there are all kinds of color vision deficiencies, also known as color blindness, red-green color blindness is the most common due to the overlap in wavelengths that the red and green cones can perceive in the eye. We developed a color identification system that can assist individuals with all kinds of color vision deficiencies by identifying the three primary colors of additive light, red, green, and blue, then audibly informing the user which colors are present. This system can assist individuals with tasks such as color coordinating their outfits or selecting the correct apple while out grocery shopping.

2.3.1 Basic Goals

- Automated adjustment of optical power between -0.5 D and +1 D.
- Identify when focus has been acquired above the threshold value.
- Successfully identify at least three colors; red, blue, and green.
- Have a functioning auditory response system to communicate with the user.

2.3.2 Advanced Goals

- Manual focusing of the lens system to account for the users refractive errors in increments of 0.5 D.
- Improve the auto-focusing system to provide between -1.5 D and +2.5 D of optical power in under one minute.
- Improve color identification accuracy above 80%.

2.3.3 Stretch Goals

- Miniaturization of system for increased portability and comfort.
- Increase the number of accurately identifiable colors.
- A functional text-to-speech feature that allows the system to read text aloud to the user when prompted.
- A functional object identification system to assist visually impaired individuals with a variety of tasks, such as selecting the correct object when several unique options are presented.
- Implement a smart navigation system that will help guide visually impaired individuals, allowing them to move around independently.
- A walking stick that sends an audio signal when a potential obstacle is detected directly ahead of the user.
- Integrate smart phone compatibility through an app for potential customization of the auditory response system.

2.3.4 Objectives to Achieve Basic Goals

- Utilize a time-of-flight sensor to acquire an approximated desired focal length. Utilize the acquired focal length to calculate the necessary separation between lens to acquire an optical power that corresponds to the desired focal length. Adjust the distance between the lenses using motors and rails.
- Create a program for edge detection of images captured by the CMOS sensor.
- Design a color identification system in conjunction with a lens system for accurate identification of red, green, and blue.

- Integrate an audio system with an MCU and program the audio responses to give unique responses that correlate to unique scenarios, such as when a specific color is identified, or when the lens system is in focus.

2.3.5 Objectives to Achieve Advanced Goals

- Create a program that allows for the manual adjustment of the separation between the lenses such that the user can correct their mild myopia or mild hyperopia. This correction will set the optical power of the total system, including the user's eyes to approximately 0 D.
- Improved lens design for minimized aberrations, larger depth of field, and a higher range of variable optical power
- Create a program capable of color identification by isolating the colors present in the images captured by the CMOS sensor. Install a color library to improve the color identification. Correlate the identified colors from both systems to ensure color identification accuracy above 80%.

2.3.6 Objectives to Achieve Stretch Goals

- Conduct research on affordable smaller components. Adjust design as necessary to minimize the necessary size of the system without negatively impacting the effectiveness of the auto-focusing or color identification systems.
- Improve the color identification program to have a more extensive color library to accurately detect more unique colors.
- Create a program capable of detecting text from an image captured by the CMOS sensor and then map the text to a text library consisting of three common fonts. Upon successful identification, the text is read aloud to the user.
- Use computer vision to create a set of detectable objects, that upon detection, can be communicated to the user through the audio system.
- Connect the system to a map application such as Google Maps to give audible directions to the user when they are navigating their environment.
- Design a sensory system that is installable onto the end of a walking stick and is capable of communicating with the existing system. When communication or line of sight is lost between the systems an obstacle is detected.
- Develop a program in Kotlin that can connect to the existing system, enabling the user to select customized settings, such as a preferred language and a default optical power correction for people with myopia or hyperopia.

2.4 Features and Functionalities

To best support individuals with myopia, hyperopia, presbyopia, or a color vision deficiency, our system has two primary features, auto-focusing and color-identification. The auto-focusing assists in the correction of myopia, hyperopia, and presbyopia which are all due to refractive errors in the eye. In other words, the light that enters the eye does not properly focus on the retina, resulting in a blurry image. By slightly adjusting the focal length, the focal plane can be shifted forward or backward on the optical axis to focus light properly on the user's retina.

As for individuals with color vision deficiencies, the color-identification system is capable of identifying colors for the user who may not be capable of distinguishing between certain colors. The feature does not alter the user's vision in this case, it informs the user by means of an audio response instead.

2.4.1 Auto-focus

To support individuals with vision loss such as near-sightedness and far-sightedness, we included a system that provides artificial accommodation. To support this, we designed a two-lens system that can be commanded to adjust automatically by coupling it with a program utilizing a time-of-flight (ToF) sensor and a complementary metal oxide semiconductor (CMOS) sensor that determines the required distance between the lenses.

The two-lens system is necessary to correct optical aberrations that arise as the system achieves focus. Optical aberrations are errors caused by uneven spreading of light across a system. While these can be corrected with lens design, our system required a dynamic moving system to adjust and combat these aberrations, with defocus as our primary objective. Defocus occurs when the optical power of a system goes above or below the power of the eye, which is approximately sixty diopters.

To solve this issue, we implemented the two-lens system on a moving rail, allowing it to increase or decrease the optical power of the system as needed. The movement of the rail is determined through the focusing system, which begins when the wearer engages the focus button. A CMOS sensor attached to the system then captures an image, and, using its own lens system, determines whether the image is blurry. If the image is in focus according to a set parameter, an audio signal is sent to the wearer to inform them. Otherwise, the focus of the secondary lens is set using an infrared sensor that measures the distance between the system and the observed object. An image is taken of the object, and an algorithm determines the contrast on the edges of the image. If the level of contrast is too high behind the sensor, the secondary lens (the moving lens) is moved farther from the primary lens until the image is no longer blurry. If the level of contrast is too high in front of the sensor, then the secondary lens is moved closer to the primary lens. This system would enable a dynamic and user-guided method of transforming the system from a "reading mode" to a "traversal mode." Figure 2.4.1 below demonstrates a simplified diagram of the auto-focusing system.

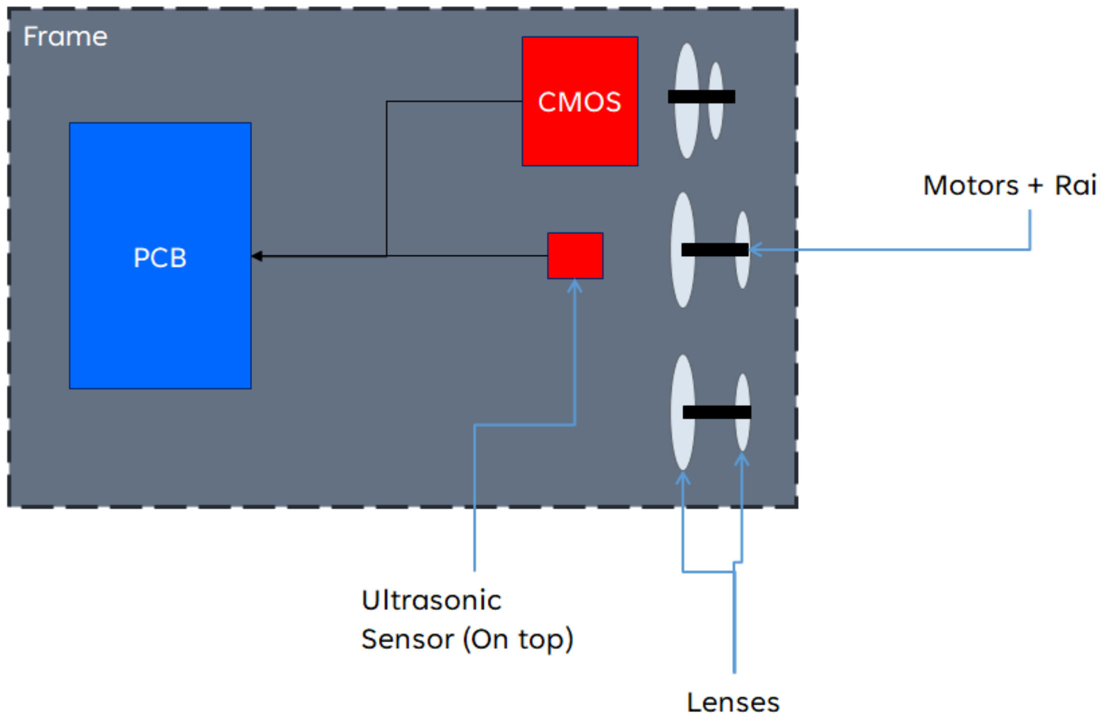

Figure 2.4.1 Auto-Focusing Feature Diagram

2.4.2 Color Identification

In addition to providing artificial optical power for the wearer, the system is intended to assist with colorblindness. Using a dual confirmation system, the system provides audio information on the dominant color of an object in central view. This system works regardless of the user's specific type of color blindness. Similarly to the auto-focus feature, it is activated manually by the user tapping a button.

To determine the color of the object being observed, three photodiodes are mounted onto the system with a respective red, green, and blue filter. Light reflecting off the object passes or reflects off the filters. If the light passes, the respective photodiode records the signal and matches it with a corresponding color or hue. This system allows for combinations different colors or hues, namely red, green, blue, cyan, magenta, and yellow. However, the main drawback of this system is its low sensitivity. To offset this, a strobe light illuminates the central area immediately in front of the user to provide more reflection and color feedback. Color accuracy could be improved by collimating the reflected light and utilizing a diffraction grating to separate the wavelengths of light, but we found this to be unnecessary for our system. This photo-diode setup is still supplementary however and would require an additional system.

This other system involves a CMOS sensor. Upon activation, the CMOS captures an image of the object in central view. Utilizing a program that involves scanning through the captured image and matching each pixel to a color library, the system considers the total percentage of a grouping of colors to determine the primary color of the image. In the event that the object captured is composed of more than one primary color, namely if it has a threshold of being composed of 40% of one color and 40% of another, two colors can be recorded.

Once both systems capture data regarding the observed object, their outputs are compared. If the output colors do not match, an audio signal is sent to the user informing them to scan the object again. Otherwise, the user is informed through audio of the primary or two primary colors of the observed object. Figure 2.4.2 below shows a simplified diagram of the color-identifying system.

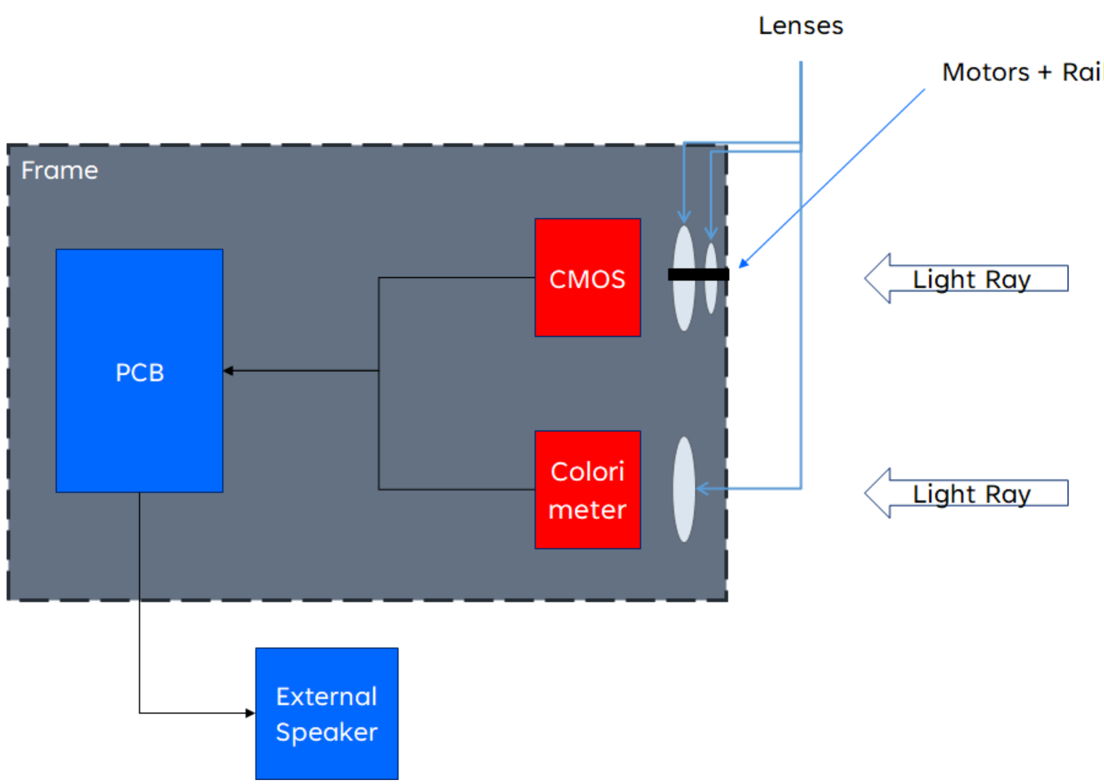

Figure 2.4.2 Color-Identifying Feature Diagram

2.5 Specifications

The specifications and requirements listed in Tables 2.5.1 and 2.5.2 below contain the demonstrable capabilities that we have achieved with our system. Table 2.5.3 lists several specifications of various components utilized in our system.

System Engineering Requirements	
Parameter	Requirements
Time to Focus	≤ 60 seconds
Audio Signal-to-Noise Ratio	≥ 65 dB
Battery Life	≥ 2 continuous hours
Manufacturability	≤ $1000

Table 2.5.1 System Engineering Requirements

Optical System Engineering Requirements	
Parameter	Requirements
Color Identification Accuracy	≥ 80%
Focusing Power	Variable from -1.5 D to +2.5 D
Color Identification	≥ 3 colors
Sensor Resolution	≥ 5 MP
Simultaneous Colors Identifiable	≥ 1 color

Table 2.5.2 Optical System Engineering Requirements

Component Specifications	
Parameter	Specification
Linear Railing Length	≤ 200 mm
Linear Railing Step Size	≤ 2 mm
Motor Maximum Power	≤ 6W
Camera Field of View	≥ 60°

Table 2.5.3 Component Specifications

2.6 House of Quality

The House of Quality is an incredibly useful tool that can be strategically utilized during product development to properly align the customer's requested requirements with the engineering specifications necessary to meet those requirements. The tool is aptly named as it resembles a simple drawing of a house. The body of the house in this case visually identifies the trade-offs between the requirements and the engineering specifications. The roof then identifies the trade-offs between the engineering specifications and how they interact with one another. Our House of Quality seen in Figure 2.6.1 displays the various requirements that we must consider and balance within our system.

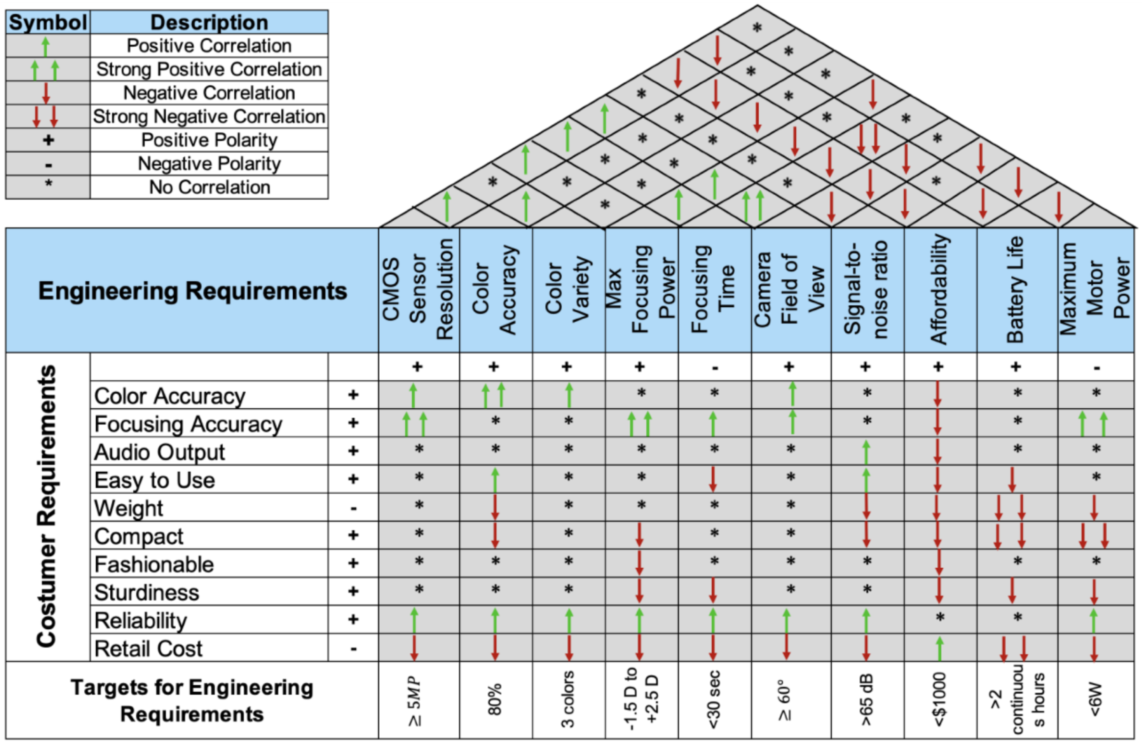

Figure 2.6.1 House of Quality

2.7 Block Diagrams and Flow Charts

Block diagrams are visual representations of different processes in a product or system. They enable complex systems to be broken down into simplified parts that can be easily understood. They are simple, quick communication tools that allow others, including customers, to understand the how a product functions. In addition to this, they are fantastic planning tools as they allow the engineer to layout the system into its individual components that can then be interconnected. The connections then demonstrate which components communicate with each other as well as how they communicate with each other. By having all the components laid out visually, it is also much easier to identify any errors in the systems. In addition to this, some components may be overlooked entirely, and the block diagram may function as a visual aid to ensure everything necessary is present. The name is rather straight-forward as each component is represented by a block. Overall, it is a clear method for conveying the functionalities of a system.

Flow charts are remarkably similar to block diagrams in the sense that they are visual representations of different processes, but they specifically represent the step-by-step workflow of the system. They are essential to show the logical progression of a system and absolutely crucial for software development.

2.7.1 Hardware Block Diagram

The hardware block diagram seen in Figure 2.7.1 demonstrates how all the physical components in our system interact with each other. For example, the sub-systems, including the diode system and the motor system may not directly interact with each other, but they do interact with other physical components thus interconnecting all the components.

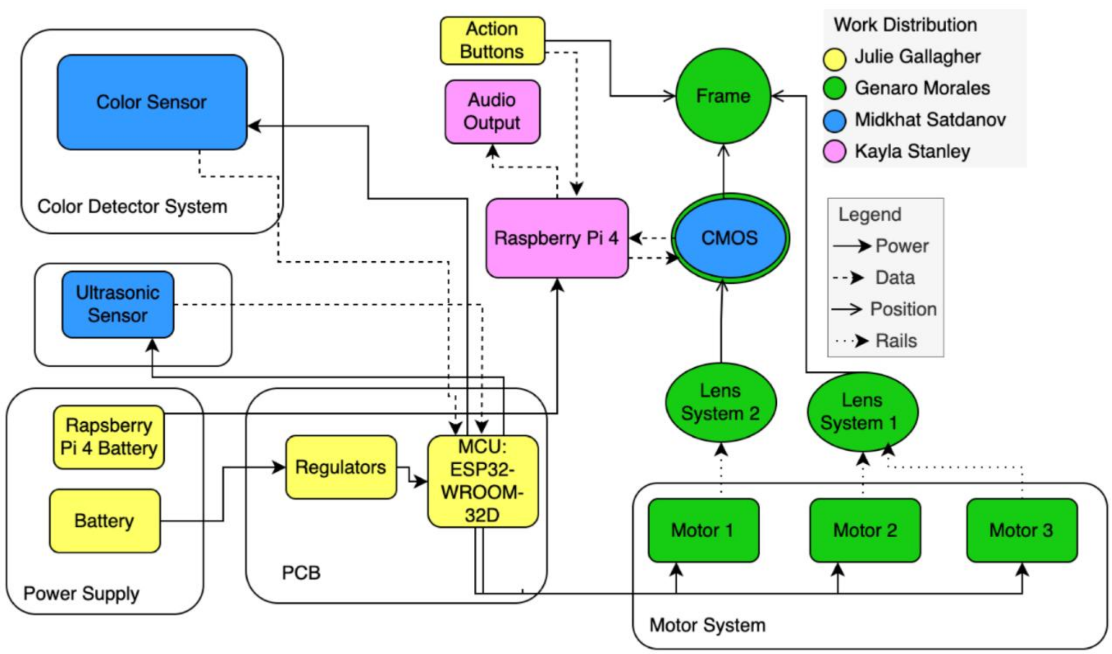

Figure 2.7.1 Hardware Block Diagram

2.7.2 Software Flow Charts

The software flow charts seen in Figures 2.7.2 and 2.7.3 demonstrate the logical progression of the auto-focusing system and the color identification system, respectively.

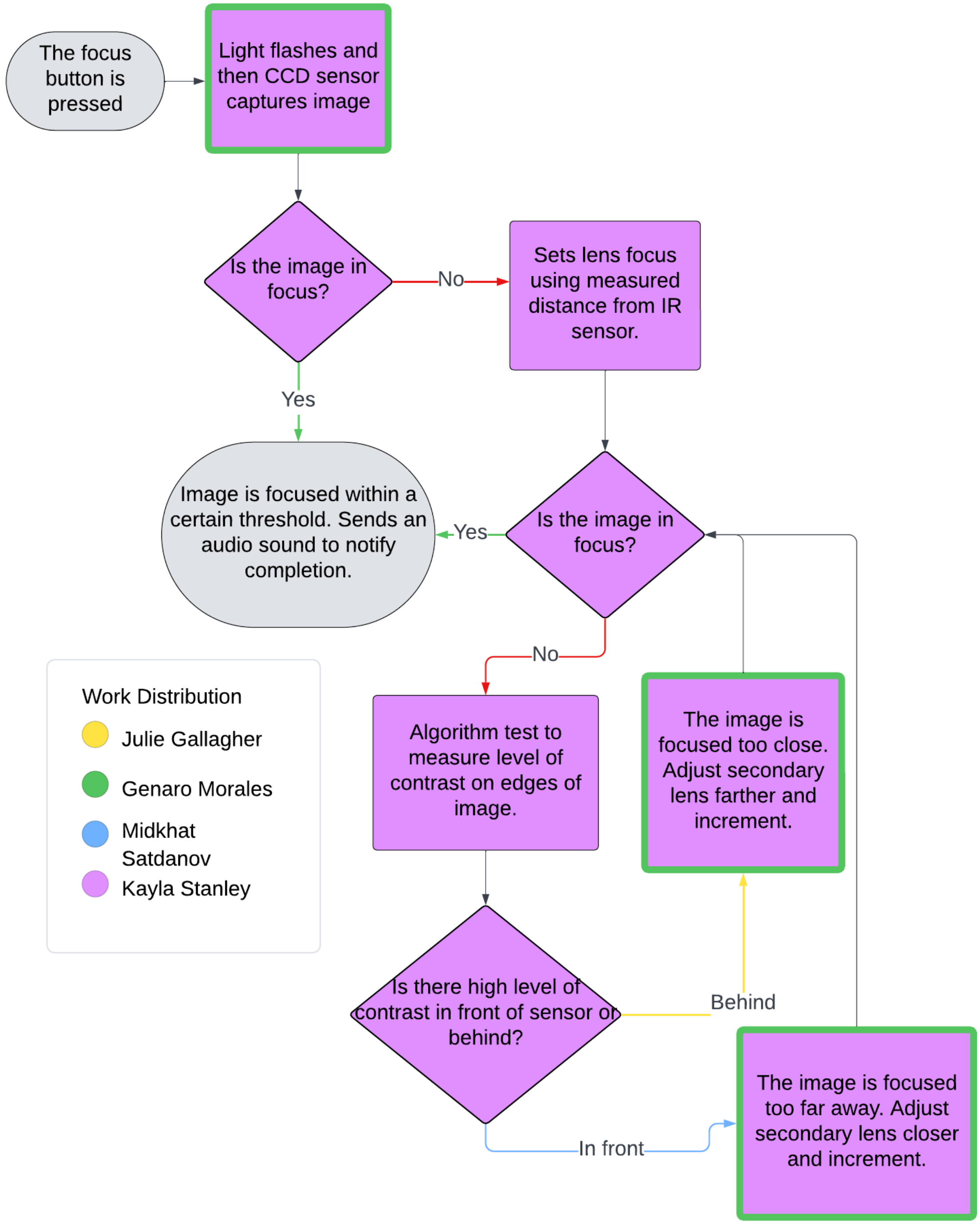

Figure 2.7.2 Auto-Focusing System Flow Chart

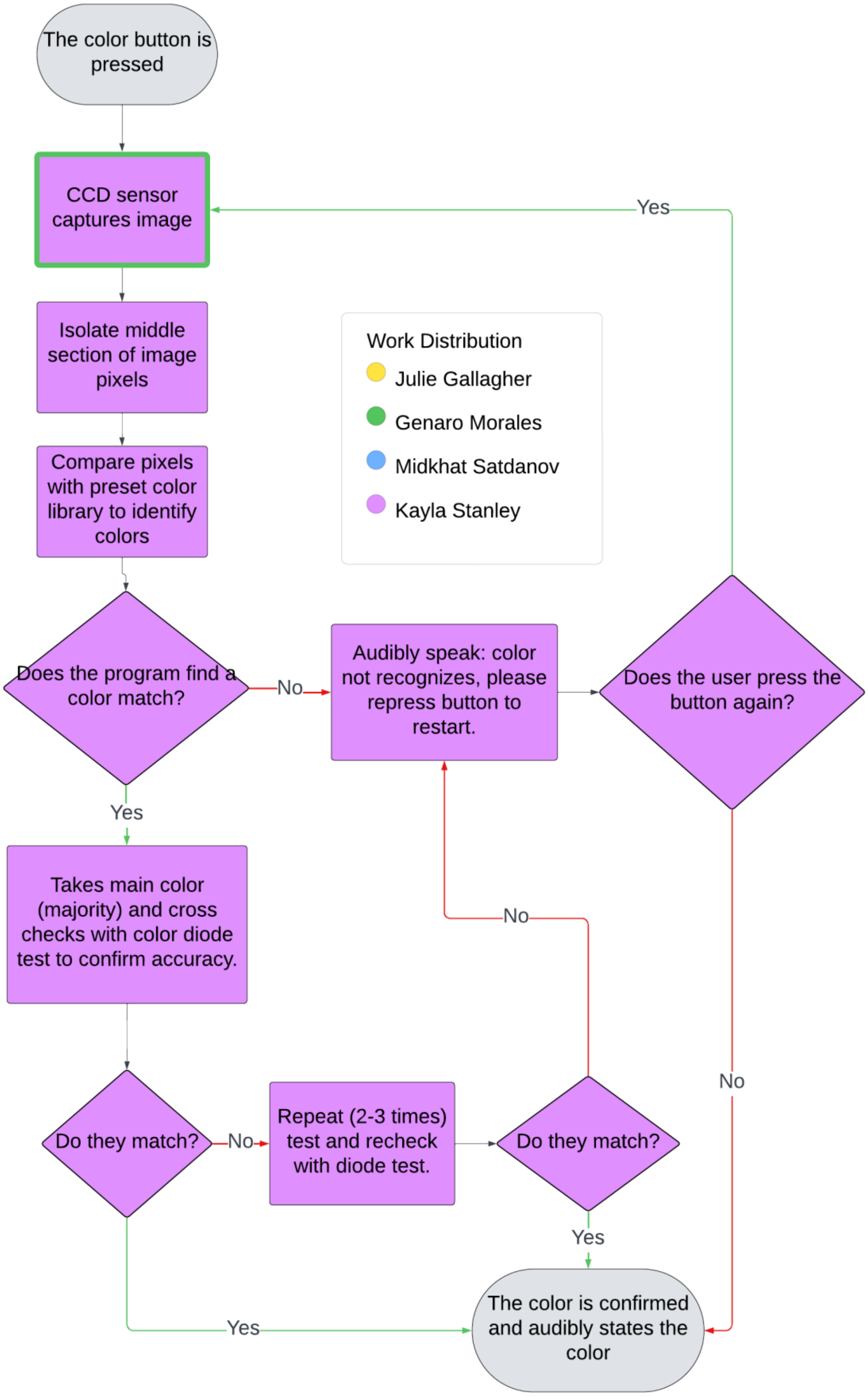
The color button is pressed
CCD sensor captures image
Yes
Isolate middle section of image pixels
Work Distribution
Julie Gallagher
Genaro Morales
Midkhat Satdanov
Kayla Stanley
Compare pixels with preset color library to identify colors
Does the program find a color match?
No
Audibly speak: color not recognizes, please repress button to restart.
Does the user press the button again?
Yes
Takes main color (majority) and cross checks with color diode test to confirm accuracy.
No
No
Do they match?
No
Repeat (2-3 times) test and recheck with diode test.
Do they match?
Yes
Yes
The color is confirmed and audibly states the color

Figure 2.7.3 Color Identification System Flow Chart

3 Research and Part Selection

During the part selection process of this project, the MCU board and the CMOS sensor were the primary concerns. This is due to certain criteria required to ensure our features would function properly. Once the MCU board and the CMOS sensor were selected, the remaining parts, such as motors, lenses, time-of-flight sensor, etc. were selected based on their compatibility with the MCU board and the CMOS sensor. In addition to this, the size and cost constraints significantly impacted our selection for the remaining parts.

3.1 Imaging Sensors

There are two primary imaging sensors that are currently. Charge Coupled Devices (CCDs) and Complementary Metal Oxide Semiconductors (CMOSs) are two imaging sensors that rely on the photoelectric effect to convert an incoming photon into an electric charge. [9]

3.1.1 CMOS vs CCD

CCD sensors directly convert this energy into an analog signal, enabling the use of nearly or all of their pixel size to the capture of light. Each pixel's charge is collected at an output node and then sent off as an analog signal to then be converted to digital if needed. This makes their output very uniform.

CMOS sensors on the other hand contain pixels that, instead of having their charges collected across the entire sensor, are instead directly amplified, and converted to digital at each pixel before being packaged at the output. While this decreases the uniformity, light collection area, and simplicity, the parallel mechanism of each pixel performing operations separately increases overall speed. [9]

For the color recognition system, we had a choice on whether we wanted to proceed with a CMOS or CCD sensor. For our system requirements, it was necessary that the sensor be capable of differentiating the colors of the image. Ideally, our goal was to achieve a color identification accuracy similar to that of a human eye with no color vision deficiency. In our attempt to match this properly, we used the Commission Internationale de l'Eclairage's definition of an ideal spectral sensitivity function (SSF). [10] We were able to see a comparison of these SSFs with the SSF of a human eye, as shown below in Figure 3.1.1.

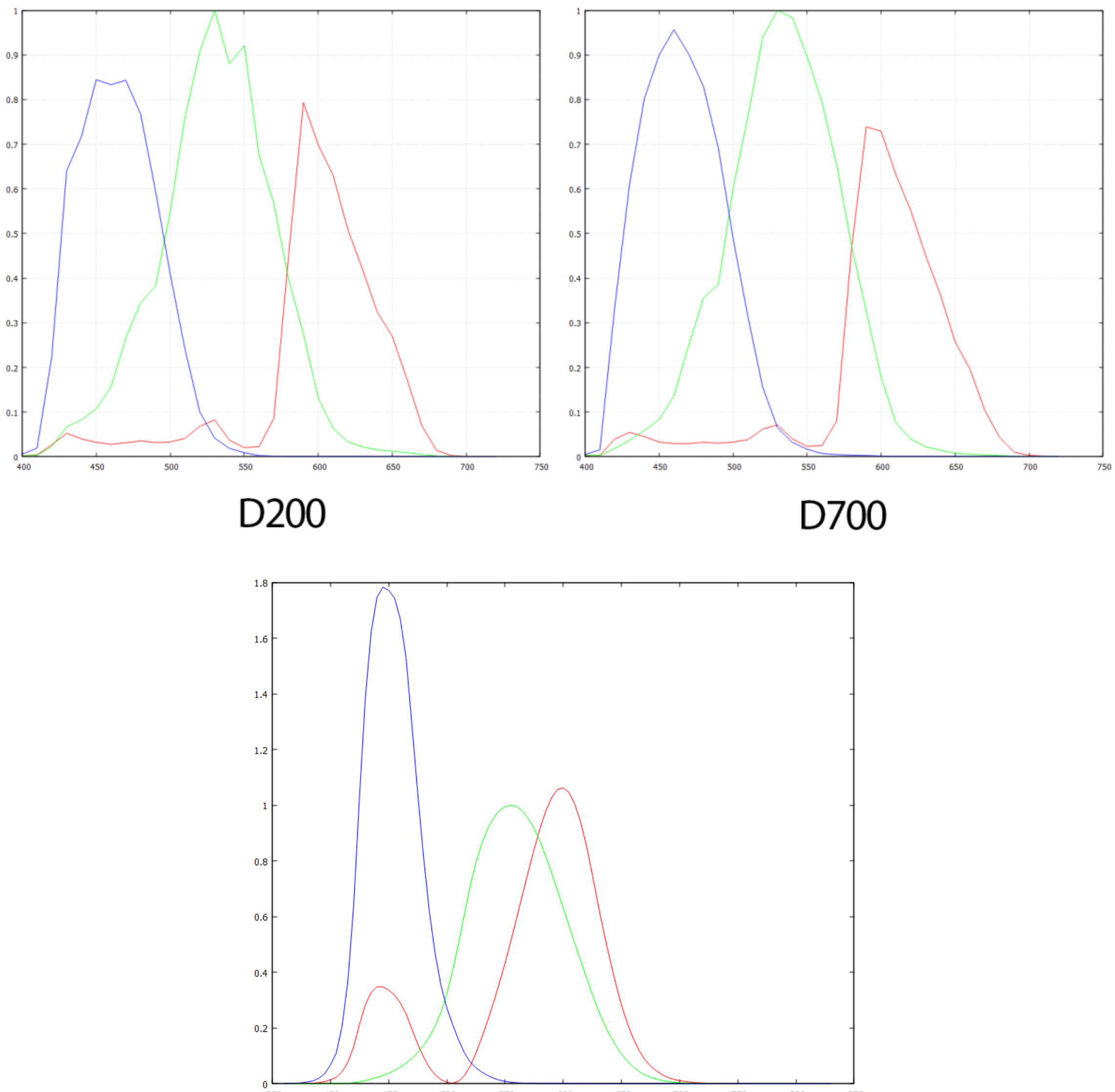

Figure 3.1.1 SSF of CMOS (left) vs CCD (right) compared with human SSF (bottom) [11]

Due to these requirements, the first concern was to identify which type of sensor would be more accurate for color detection. It became clear from our research that, when all other factors remained the same, the difference in the produced color gamut and color temperature gamut was nearly indiscernible. Our research indicated then that the more important facets in determining color were the color correction of the camera itself, the camera profile, and the characterization of the sensor.

Since the choice between the two sensors does not come down to color quality, the choice was determined by both image quality and economic concerns. In terms of image quality, the primary concern regarding CMOS sensors was their lower signal-to-noise ratio (SNR). This is caused by each individual pixel needing to pass through an amplifier first before it can be converted to a digital signal, introducing noise into the application. However, one article claimed that as recently as 2020 [9], this difference in noise ratio has been eliminated in newer CMOS models. We had considered incorporating older CMOS sensors in our design, making this a valid concern.

On average, the integrated design of CMOS sensors puts their price lower than CCDs. A major appeal of the CMOS is its camera-on-a-chip quality, enabling greater miniaturization. [9]

Additionally, the power consumption of CMOS sensors tends to be much lower depending on the product used, though this is certainly not standardized. With these factors in mind, our team had chosen to move forward by pursuing a CMOS sensor for our project.

3.1.2 Sensor Size Selection

There are many different kinds of image sensor formats that determine the physical size and shape of the sensor. Several factors flow from the determination of these physical constraints, which are discussed in this section.

Full frame cameras are the standard for photography. They follow the traditional 35mm film format and are physically the largest standard size for camera sensors. As with APS-C sensors, their standard aspect ratio, defined as an image's ratio of width to height, is 3:2. [12]

Full-frame sensors by physical necessity are therefore the largest standard type of sensor and thus posed a potential constraint on our design if we had chosen to use them. This can impose both financial and design limitations on us, although they were considered as we were looking into specific types of sensors.

The wider field of view of full frame cameras, defined as the angular extent of the image sensor's observable area, would lend itself well to applications where there is a need to observe larger landscapes, which in our case is not what our camera system is intended on doing. However, one especially important aspect of full frame cameras to consider that would have truly been beneficial for our design is their tendency to have larger light receptors, enabling greater light-gathering potential that can filter out image noise. This could have been crucial in outdoor applications, something our team had been investigating as we pursued the application of the color identification photodiode system in light-saturated conditions. If we had chosen to manipulate our sensor's ISO settings, its sensitivity to light, then we could have furthered this application. [13]

The Advanced Photo System type-C (APS-C) sensor is a popular alternative to the full-frame sensor and comes with their own unique advantages.

APS-C sensors are distinct in three main ways compared to full frame sensors. The aspect ratio of these sensors, defined as their characteristic ratio of width to height, matches the classic aspect ratio of full frame cameras (3:2) but produces images that have a smaller area and a narrower angle of view. The exact dimensions of these differences depend on the sensors themselves, but the difference is consistent. Additionally, the crop factor, defined as the size of the area in the imaging space that has its focal length multiplied by the given crop factor, is usually 1.5x to 1.6x. Finally, these factors combine to produce a much deeper depth of field (the distance between the furthest and nearest in-focus objects in the image) than in full-frame cameras, enabling better applications for imaging objects that are far away. [14]

1-inch sensors, as with full-frame, refer to the size of the image space of these particular sensors. They can be found in some high-end compact cameras, a type of camera that fills the niche between simple point-and-shoot low-end compact cameras and the more advanced interchangeable lens cameras like those of the APS-C and full frame discussed above. [13]

Unlike those point-and-shoot cameras, 1-inch sensors are typically capable of capturing more light and producing higher quality images, and they come with a wider variety of lens options. While they do not possess the same capabilities or diversity as APS-C or full frame cameras, they would be an ideal balance between cost and quality. The main consideration that prevented us from using this particular sensor is the fact that it was still a bit too cumbersome to attach to our system. [13]

As for 1/2-inch, 1/2.3-inch frames, 1/3-inch frames, ¼-inch, and other similar small sensors, these sizes are found only on the most compact and portable camera designs, including those attached to smartphones. We had decided to group these sensors in a general sense because the limitations that they come with can be applied to virtually all sensors at these size ranges. [13]

Primarily, the main concern with such small form factor lenses is the noise they introduce to our produced images. Given that half of our color identification system comes from our ability to read the images produced by the sensor, adding noise to our system is detrimental to the legibility of this system. For this reason, when considering the use of a small form factor lens, we focused on only the options larger than a half inch frame.

3.1.3 Imaging Sensor Selection

When selecting an appropriate camera, we required one that had a field of view smaller than 120 degrees as that is within the range of our lens experiment requirements. In addition, we also required a decent resolution of at least several megapixels or an equivalent measurement to ensure correct color recognition and autofocusing assistance. In addition, another necessity was the capability for the sensor to connect effortlessly with the RaspberryPi purchased.

3.1.3.1 BETAFPV C02 FPV Micro Camera 1/4”

This wide-angle CMOS sensor uses an analogue video system that produces images in TVL (Television lines) as its unit of resolution. TVL measures resolution by counting the number of distinct vertical bars can be detected and depicted across an area of the imaging space with a horizontal length equal to the height of the picture. [15] This aspect of the sensor means that, without its own digital converter attached, we would have had to convert this analogue signal to a digital one, adding constraints to our selection of MCU boards. However, a rating of 1200 TVL is fairly high for resolution, which would have made the conversion process smoother.

The aspect ratio for this sensor is 16:9, it sports a 2.1mm lens, and a field-of-view (FOV) of 160 degrees. Perhaps the most important facets of this sensor that we want to consider are its weight and signal-to-noise ratio (SNR). For the former, the sensor’s net weight is 1.4g and for the latter the stated SNR is greater than 50 dB. [13]

An issue could have arisen with the FOV, however. Our detection and autofocusing system rely more on the concept of focusing on one specific point in front of the user, and this wide angle of view would have interfered with or obscured some of the incoming data. Ideally, we desired an FOV of less than 120.

Perhaps the main advantage of this sensor was the fact that we already had it, as Genaro possessed it from a previous drone project.

3.1.3.2 Raspberry Pi Global Shutter Camera

This camera is uniquely suited, as stated by its manufacturer, for applications where accurate imaging is required in the presence of rapid motion. It has a resolution of 1.58 megapixels (without the lens), producing an image that is 7.9mm long diagonally and claims to avoid the distortions produced by rolling shutter cameras. Additionally, the sensor comes with an infrared filter already integrated, which is vital in producing images without color distortion, especially under daylight conditions. If our applications required it, we could have (irreversibly) removed this filter. The most important aspect we had to consider with this sensor is that it does not already come pre-equipped with a lens. The manufacturer recommends the use of either a 16mm telephoto lens or a 6mm wide angle lens. [16]

The use of the telephoto lens would have produced an image format of one inch, which as stated previously would have produced higher quality photos under most normal conditions. Additionally, it was unlikely that at the sensor sizes we were investigating, we could have found an image space much larger than this. The field of view of the telephoto lens would have been 22.3 degrees, well within the desired range. Adding the telephoto lens would have changed the resolution to ten megapixels (MP). The final consideration was that the back focal length produced by this lens would have been 17.53mm, although this facet would not have been critical given that our desired range for the color identification and autofocusing systems lie within 2 meters. [16]

The 6mm wide angle would have produced images in the half inch space with an FOV of 56 degrees. The resulting resolution would have been equivalent to 3 MP. Additionally, the wider angles would have distorted the image, reducing the resolution by a significant margin. As a final aside, the back focal length would have been 7.53mm. [17]

The final choice then depended on our desired field of view. While the telephoto lens would have produced higher quality images, the wide-angle lens' field of view could have been more beneficial necessary as we continue further research into the exact mechanism of the two primary systems of the system. Importantly, we must also remember that the wide-angle lens would have produced a greater depth of field, which could have been particularly important if the color of the object we are examining is spread across an uneven surface. On the other hand, a shorter depth of field would have assisted in ensuring that the autofocusing system produced sharper and clearer images for the user. We chose to err on the side of caution, so the wide angles were preferable.

Overall, given that we were likely to move forward with a Raspberry Pi, a camera that integrates seamlessly into that system was incredibly useful. Despite the lower resolution, the wide-angle lens is both cheaper and easier to work with for our applications. The edges of the image would likely have been distorted to fit into the frame, but this was not as critical given that our intent was to only consider the object(s) in the center of the image when using the camera.

3.1.3.3 Raspberry Pi High Quality Camera

The High Quality Camera (HQ) from Raspberry Pi is extremely similar to the Global Shutter (GS) model but may have been more suitable for our design. The size of this sensor is slightly shorter and lighter, with a height of 18.4mm as opposed to 19.8mm and a weight of 34g (41g with adaptor and dust cap). Given that the system would need to be as comfortable to wear as possible, even tiny differences such as this became non-negligible. [17]

As stated by the manufacturer, the resolution of the HQ and the GS should be comparable. However, an added benefit to the HQ is its ability to have M12 mounted lenses, which could have enabled us to use 8mm, 25mm, and fisheye lenses. The 8mm in particular was enticing, as it changes the image space to a 1/1.7", which would have enabled us to capture more of the object we're imaging while increasing the resolution to 12 MP. The resulting FOV of this lens would have been 62 degrees, perfect for our needs. [16]

Perhaps the only drawback of the HQ when compared to the GS is that the GS was purposefully designed to capture images in motion. However, this is a constraint we were willing to accept, as the color identification feature is intended to focus on stationary objects.

3.1.3.4 Raspberry Pi Camera Module 3 Wide

Yet another in the Raspberry Pi series, the Module 3 Wide was particularly interesting to us sue to its wider FOV. Unlike the HQ and the GS, the camera comes pre-equipped with a lens and itself was only $35, significantly cheaper than the base $50 for the HQ and GS. [16]

The Camera 3 Wide (C3W) is smaller than the previous two models by a significant margin, with dimensions of 25 mm by 24 mm by 12.4 mm, with far less weight at 4g as opposed to the roughly 30 to 40g of the other two. With a still resolution of 11.9 MP and an image space of 1/2.43", it is also still well within the high quality range of the other cameras. [16]

3.1.3.5 Raspberry Pi Camera Module v2

The final consideration for the Raspberry Pi camera modules was the v2. Its parameters are virtually worse in every way compared to the previously considered modules, with a smaller image space of a quarter inch, 8 MP resolution, and the same price as the module 3. [16]

There was only one reason we considered the Module v2 at all: its lack of an autofocusing feature. [18] All of the previous cameras had an integrated autofocusing feature within their program. Normally this would be considered a useful feature, but it is one that we personally chose to discard due to our need to calibrate the autofocusing ourselves. After scouring online forums, we found that the newer modules could be programmed to not perform this feature, but the code to do so appeared unreliable at best. Thus, we considered moving forward with the v2 for this reason alone.

3.1.3.6 Camera Comparison Table

Conveniently, the Raspberry Pi website already contained a list comparing the cameras considered above (and others), listing their general attributes. These are mentioned along with the attributes of the BETAFPV sensor as we evaluated the drawbacks and strengths of the different modules. For the HQ and GS Raspberry Pi cameras, attributes were assumed as if the 6mm wide-angle lens was attached. It is also important to note that the BETAFPV camera uses television lines in a custom-built camera and that not all information is readily available online for it. The full comparison is shown below in Table 3.1.1.

	Camera Module v2	Camera Module 3 Wide	HQ Camera	GS Camera	BETAFPV C02
Net Price	$25	$35	$75	$75	Free
Size	25 x 24 x 9 mm	25 x 24 x 12.4 mm	38 x 38 x 18.4 mm	38 x 38 x 19.8 mm	13 x 11 x 8 mm
Weight	3g	4g	30.4g	34g	1.4g
Still Resolution	8 MP	11.9 MP	12.3 MP	3 MP	1200 TVL
Video Modes	1080p47, 1640 × 1232p41 and 640 × 480p206	2304 × 1296p56, 2304 × 1296p30 HDR, 1536 × 864p120	2028 × 1080p50, 2028 × 1520p40 and 1332 × 990p120	1456 × 1088p60	N/A
Sensor	Sony IMX219	Sony IMX708	Sony IMX477	Sony IMX296	N/A
Sensor Image Area	4.6 mm diagonal	7.4 mm diagonal	7.9 mm diagonal	6.3 mm diagonal	2 mm diagonal
Pixel Size	1.12 µm × 1.12 µm	1.4 µm × 1.4 µm	1.55 µm × 1.55 µm	3.45 µm × 3.45 µm	N/A
Image Format	1/4”	1/2.43”	1/2.3”	1/2.9”	1/4”
FOV	62.2°	102°	71°	56°	160°
Focal Length	3.04 mm	2.75 mm	7.53 mm	7.53 mm	2.1 mm

Table 3.1.1 Camera Comparison Table

3.2 Photodetection System

While the CMOS sensor that scan for color was a crucial component in our system, we determined that it would not be sufficient to ensure our color detection was accurate. Rather than simply analyzing an image, the project needed to incorporate optics to measure the wavelengths of incoming light that our system attempts to detect, ensuring a sort of two-factor confirmation for the color identification system.

Photodetectors or photosensors can all be differentiated by the various effects and structures they possess that they use to convert photons to electrons. It was important to investigate the merits of each method and any variations therein to decide which component would have served our interests best.

The means by which all photodetectors activate is through the photoconductive effect. Essentially, incoming light generates electron-hole pairs across the surface of the material that then become photocurrent. This basic principle can be stretched into multiple different uses and the effect can be altered by the structure of the device where photoconductivity occurs [19]. For our purposes, we investigated photodiodes, phototransistors, and photoresistors to discover which would be most suitable for our applications.

However, this alone was unlikely to be enough. The light reaching our sensors, whether it passed through color filters or not, still needed to be aligned with the detectors themselves. While some incoming light would hit the detector properly, a lack of collimation would prevent maximum efficiency with the amplifier. Ideally, we wanted the reflected light to first be collimated and then pass into a diffraction grating to best separate the wavelengths before reaching the photoconductors. For economic reasons, our team initially attempted to build the system without using collimating lenses or a diffraction grating. As senior design 2 progressed, we quickly determined the system was adequate enough without these components.

3.2.1 Photodiodes

Photodiodes are a type of PN junction semiconductor that rely on incident light generating electron-hole pairs in the depletion region of their junctions, which produces a photocurrent. It is important to note that while such devices can be left unpowered and still produce this photocurrent, the introduction of an electric field across them encourages the separation of the electron-hole pairs to induce stronger current, with electrons moving along with the field and the holes away from it. This mode is specifically known as “photoconductive” mode. In this mode, the relationship between incident light and produced current becomes linear, which is the reason why photodiodes have a wide range of wavelengths that they can operate in [19].

Although this relationship makes these diodes relatively easy to use, their photocurrent output is relatively small. To offset this, it seemed likely that we would need to add a trans-impedance amplifier onto the circuit to ensure that the output signal was high enough to properly use [19].

Perhaps the most important disadvantage to the photodiode was its dark current. When powered in a reverse-biased fashion, dark current is noise added to the total current. The only way to overcome this is to have enough intensity from the incoming light to overcome this background noise. Given that our incoming light will be reflected and then filtered and possibly even diffracted, this is an important consideration.

3.2.2 Phototransistors

Phototransistors can be simplified to appear almost as a photodiode with a built-in amplifier. They tend to be smaller than photodiodes, which is not necessarily a good thing, as more surface area means greater area for capturing light. It also means that dark current, which also exists in phototransistors, is being amplified with no way of controlling that amplification [20].

It also seems to be a common trend that phototransistors on average are slower than photodiodes in their response time. This is less of an issue for us, as we did not require precise timing in the range of nanoseconds as that would be imperceptible to the average user.

The main advantage of using a phototransistor over a photodiode was that it would have been easier to implement the physical spacing within our design. The lack of a separate amplifier meant that we could fit more onto the detector system without worrying about additional space.

3.2.3 Photoresistors

Photoresistors are quite different compared to the other two technologies. Whereas with the other two, their current and voltage changes with light intensity, with photoresistors their resistance and conductivity are the factors at play. Photoresistors function by having their resistance reduce as light falls onto their surface [21].

The main benefit of photoresistors is that they do not require a bias to operate and are in general easy to implement within a system, as they are bi-directional. Additionally, they are cheaper than the former options listed [21].

Having said that, it was extremely unlikely that our group would move forward with photoresistors, as they possessed several drawbacks that simply were not conducive to our project. For our system, high sensitivity to light was a necessity, and this practically ruled photoresistors out automatically. To add onto the negatives though, the response time, meaning the time it takes for the cell to change its resistance in response to incoming light, can be as slow as 10 seconds, with the fastest photoresistors only functioning at a few hundred milliseconds compared to the much faster responsivities of phototransistors and photodiodes. Even worse, fluctuations in temperature tend to have severe effects on the resistivity of the components [21].

3.2.4 Photodetector Selection

It was clear based upon the above parameters that photodiodes were likely the best choice of technology for us moving forward. Photoresistors could have been discounted almost immediately as their drawbacks, namely the slow responsivity and low sensitivity, made them highly impractical. While we were considering phototransistors, many of their functions can be achieved simply by pairing a photodiode with an amplifier, and their smaller light collection areas made them less useful for our system, where maximum light collection was desired.

3.2.4.1 TEMD6200FX01

The TEMD6200FX01 is an ambient light sensor that is a silicon NPN phototransistor. Its primary advantage was that it is sensitive to wavelength similar to those of the human eye and has peak sensitivity at 550 nm. Its tiny collection area at mm can be disregarded mostly since this is a phototransistor (meaning it has built-in amplification). Although our group preferred not to use phototransistors, the TEMD6200FX01 was considered due to its spectral sensitivity graph, as shown below in Figure 3.2.1. With a peak at 550 nm and roughly 40% sensitivity at around 450 nm, it satisfies requirements for both our green and blue spectral ranges [22].

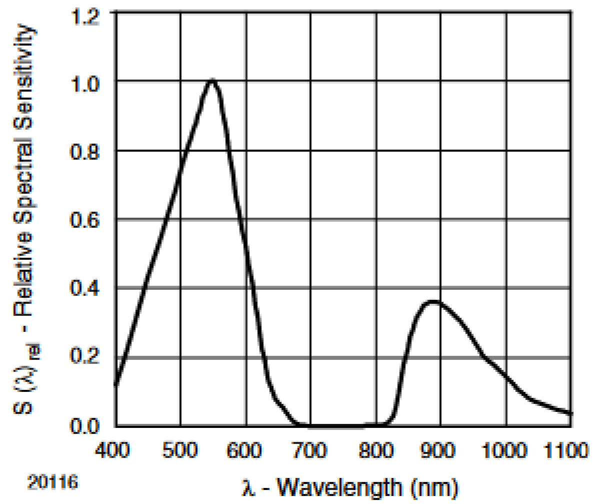

Figure 3.2.1 TEMD6200FX01 Responsivity Function [22]

Our difficulty with using the TEMD6200FX01 was integrating it into the rest of the system. While we were looking into breakout boards that would have enabled us to connect these components to the rest of the system, our inexperience with such technologies deterred us from using them.

3.2.4.2 BPW34S

The BPW34S is another photodiode, this time rated with a peak sensitivity at 900 nm. The intention behind choosing this diode was to acquire one that would cover our red portion of the color identification system. With a light collection area of 7.5 square mm, it is also larger than the TEMD6200FX01, which would have been useful for our light collection needs in ensuring that we processed an incoming signal [23].

Although the CIE defines red at 700 nm and the peak sensitivity for the BPW34S at 900, we could see from the relative spectral sensitivity graph (shown below in Figure 3.2.2) that its sensitivity at 700 is still between 60% and 80%, plenty high for our purposes (especially once we amplify the signal) [23].

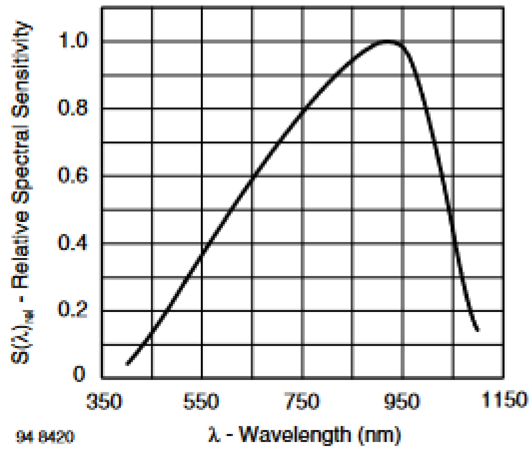

Figure 3.2.2 BPW34S Responsivity Function [23]

3.2.4.3 SFH 2430

The SFH 2430 is a photodiode that operates mostly in the blue-green range. With a sensitive area of 7.02 square mm, it is comparable to the other two components discussed thus far. Like with the TEMD6200FX01, it is a surface mount, meaning that it will require a breakout board to be attached to our system [22].

Our group had trouble finding photodiodes that would cover blue-green wavelengths, which is why we paid particular attention to this component. Its sensitivity graph is shown below in Figure 3.2.3.

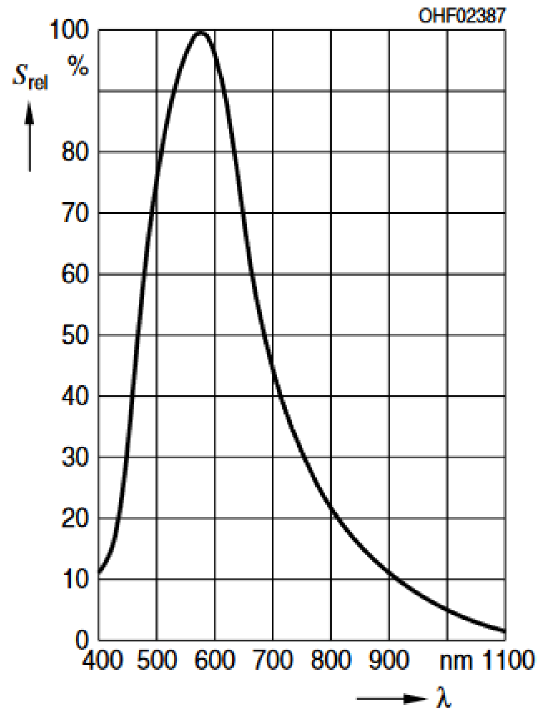

Figure 3.2.3 SFH 2430 Responsivity Function [22]

As can be seen in Figure 3.2.3, the SFH 2430 has a peak at 550 nm, just like the TEMD6200FX01, with a decent sensitivity to blues at 450 nm at about 30-40%. While this is less efficient than the TEMD6200FX01, the SFH 2430 does not have the same mounting issues that its transistor counterpart does, and the fact that it is a photodiode made it better for our needs than the TEMD6200FX01 [24].

While this normally would have meant that we have the two photodiodes we needed to move forward with, namely the SFH 2430 and the BPW34S, new considerations in the development of the project pushed our thinking on the matter of photodetection into other fields.

3.2.5 Colorimeters

Originally, our intention was to design what was essentially a colorimeter using a combination of photodiodes. As we continued researching the issue, however, we realized that it would be far more beneficial to instead simply purchase a colorimeter and then use optics to enhance its functionality, through combinations of elements such as diffraction gratings and lenses to shape incoming light and integrate the output of the colorimeter's readings into the overall design.

Colorimeters are essentially the same as the design we wanted to originally create from scratch. Namely, they function by illuminating a surface and then use photodiodes paired with a current-to-frequency converter on a single CMOS integrated circuit to detect the color frequencies of that reflected light [23].

Our team chose a color sensor that can be integrated with the ESP32 and the Raspberry Pi seamlessly. This allowed for the two-method identification that we originally intended to use with the CMOS sensor and the photodiodes. Ultimately, a custom PCB was designed using the selected color sensor as a framework to best fit our needs.

3.2.5.1 TCS3200

The TCS3200 is a programmable color light-to-frequency converter. It possesses sixty-four photodiodes in an eight-by-eight array, with the sixty-four being subdivided into four groups of sixteen photodiodes that are equipped with red, blue, green, and clear color filters. According to its spec sheet, these four selections are interdigitated to minimize any non-uniform incident irradiance that shines onto the sensor, which would have been vital for reducing any ambient light that we didn’t wish to observe while using the color system [25].

The basic operation of the system involves bright light LEDs shining onto the target area, and then the reflected waves shining back onto the device. From there, the photodiodes send the resulting electrical signals to a current-to-frequency converter, where they produce square waves that have frequencies directly proportional to the intensity of the reflected light [25].

The TCS3200 is a popular option for many small-scale hobbyist projects because of its reliability and price. Importantly, it was also capable of communicating directly with our MCU. It is also 3.1 x 3.3 x 3.1 cm., which would still fit comfortably onto the hat assembly for the system. The only unfortunate aspect of the system is that its stated ideal color sensing distance is approximately 10 cm. While this was capable of being improved with optics, it was still important to consider [25].

3.2.5.2 TCS34725FN

The TCS34725FN is another RGB color sensor that is stated as being compatible with an ESP32. With dimensions of 2 x 2.4 x 0.65 mm, it is significantly smaller than the TCS3200. While this does mean that it would have fit onto the system more comfortably, it would also have meant that the light collection area would be smaller, making the whole system less reliable for color detection [20]. The primary reason, then, that we were considering this color sensor is due to its advertised maximum range of 20 meters [26]. Unfortunately, we found it difficult to actually verify this claim as it seemed unlikely.

Therefore, other benefits were considered. Unlike the TCS3200, the TCS34725FN possesses a built-in IR filter that could have helped absorb much of the ambient light with which we were concerned. Additionally, its small size and low power absorption at just 3V necessary for operating supply meant that it was more ergonomically viable than its alternative. Ultimately, consideration between the two was determined as we had to prioritize accuracy over size. Adding and IR filter onto the TCS3200 was also a simply solution if we had found it necessary [20].

3.2.5.3 Colorimeter Selection

After careful consideration, we decided that the TCS3200 is the better choice for our system. While the TCS34725FN's smaller size could have been potentially be more convenient for our system, in the end the difference was minimal. Power supply considerations were also minimal. The most important consideration for us was color accuracy, and the larger light collection area of the TCS3200 was more conducive towards this goal. Our comparison of the two is listed below in Table 3.2.1.

Colorimeter	Supply Voltage (V)	Total Photodiodes	Price ($)	Light Collection Area (mm^2)
TCS3200	5	12	19.99	432
TCS34725FN	3	64	15.99	149.8

Table 3.2.1 Colorimeter Comparison Table

3.3 Time-of-Flight (ToF)

For our auto-focusing feature to function properly, we needed to measure distance. This could be accomplished by utilizing the principle of time-of-flight. The measured distance is utilized as the starting point for our auto-focusing system. Range-sensing systems and devices rely on known constants such as the speed of light or the speed of sound to measure distances. [27] They function by measuring the time it takes for a wave to travel through a medium from the source to its destination and back to the source. While light waves are typically used, other types of waves can also work if the velocity at which the wave travels in the medium is known.

3.3.1 Direct vs Indirect ToF

There are two methods in which a device can utilize ToF, direct and indirect. [28] Direct ToF functions by emitting a signal as a pulse of either light or sound. The velocity of light and sound are both known, thus either will work. In either case, the signal travels to an object, reflects off of it, then returns to the source as seen in Figure 3.3.1. The distance (d) can then be calculated using Equation 3.3.1 [27] since the velocity (v) and the time (t) are known. Of course, it should be taken into consideration that since the signal traveled to the object and back, it is traveling twice the distance. Direct ToF has the advantage of more accuracy for longer distances. A disadvantage of direct ToF is that it requires incredibly fast sensors capable of measuring the time difference. Another disadvantage is that they are highly susceptible to noise interference.

$$d = \frac{v \times t}{2} \tag{3.3.1}$$

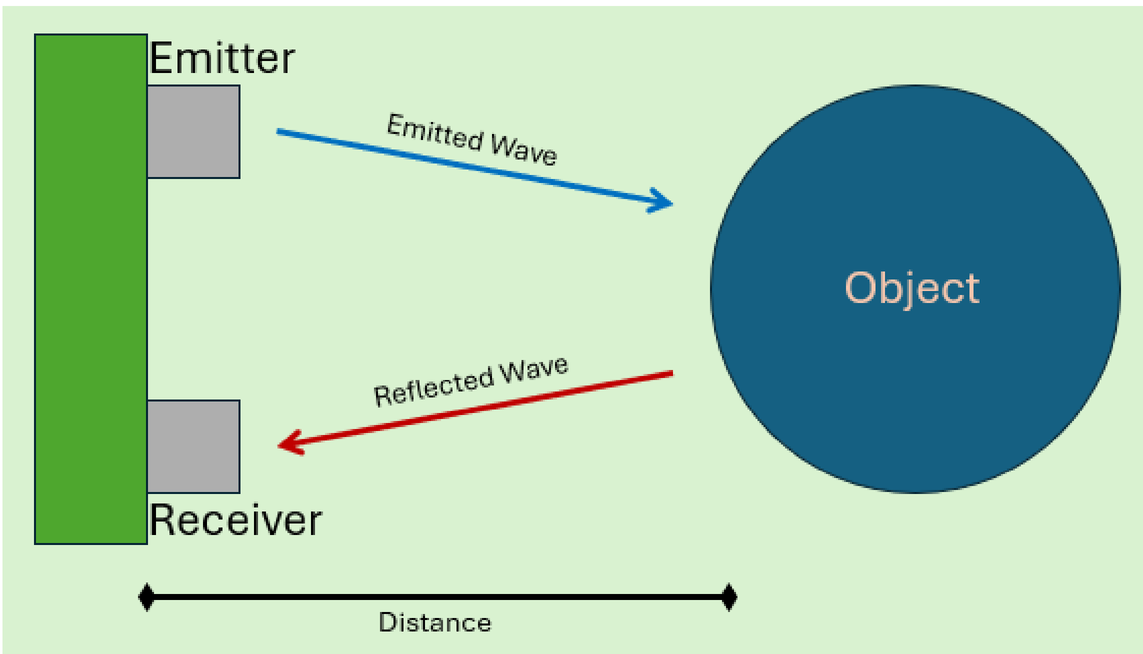

Figure 3.3.1 Direct Time-of-Flight (ToF) Visual Representation

Indirect ToF also functions by emitting a signal of either light or sound. The difference, however, is that indirect ToF does not emit a pulse. Instead, a continuous modulated wave is emitted that travels to the object, reflects, and returns to the source. In this case, the phase difference (θ) of the wave when it returns to the source is used to measure the distance instead of the travel time as seen in Figure 3.3.2. Equation 3.3.2 [29] can be utilized to calculate the distance using indirect ToF. Here the modulation frequency (f), will determine the accuracy of the measurement. A higher modulation frequency will result in shorter wavelength and subsequently more accuracy at shorter distances. That being said, to measure at longer distances, a lower modulations frequency will be necessary as it produces larger wavelengths. This results in a loss of accuracy over longer distances. Indirect time-of-flight has the advantage of being more accurate at short distance and can be utilized for 3D imaging.

$$d = \frac{v \times \theta}{2\pi f} \qquad (3.3.2)$$

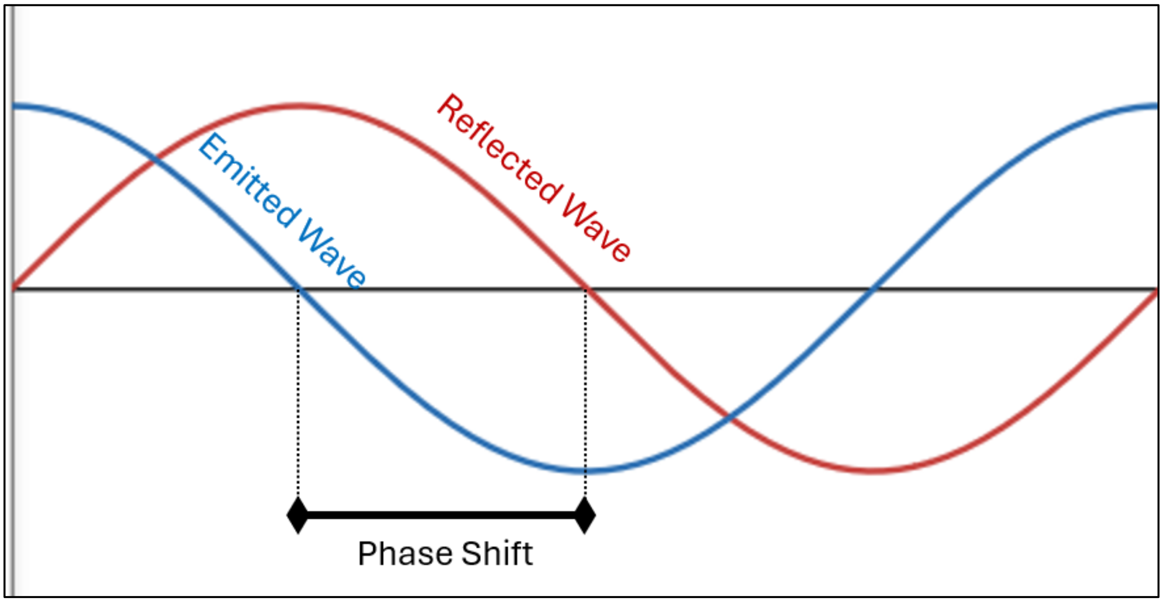

Figure 3.3.2 Indirect Time-of-Flight (ToF) Phase Difference

We are utilizing direct ToF, because this provides better accuracy at longer distances, giving us a better starting point for the auto-focusing to work from.

3.3.2 Ultrasonic Sensor

Ultrasonic sensors utilize sound waves to measure distance. Under normal conditions, sound travels at a velocity of 340.29 m/s. [30] For the source wave, an alternating current is converted into ultrasound, which is then transmitted in a wide cone-shaped beam. The ultrasound wave continues by echoing off of an object and returning to the sensor. The cone-shaped beam is typically around 30° which is much larger than you would expect from a light sensor. [30] While the large beam is still capable of detecting objects regardless of size, the drawback is that the exact location of the object is much less precise. The surface of the object being detected also greatly affects the performance of the ultrasonic sensor. Hard surfaces will produce better echoes, while soft surfaces will reflect fewer sound waves. Sound requires a medium for displacement, thus an ultrasonic sensor would not function in a vacuum. Perhaps the largest disadvantage of an ultrasonic sensor is that it is not as effective at truly short distances. They typically have a detection range between 4 cm and 255 cm. Considering sound does not travel as quickly as light, ultrasonic sensors do have a slower response rate. An ultrasonic

ToF sensor would be unsuitable for detecting objects moving quickly. A huge advantage of ultrasonic sensors is that sound works under all lighting conditions, with no noise from ambient light sources. Ultrasonic sensors are definitely the most affordable option for ToF.

3.3.3 Light-Emitting Diode/Infrared Sensor

Light-emitting diodes (LEDs) are utilized to produce a signal made of light. The speed of light is another well-known constant that does not require a medium to travel. In addition to that, air has a minimal impact on the speed of light. Light has a velocity of approximately 3×10^8 m/s. LED sensors are typically very compact and lightweight. The use of light has the huge advantage of a faster response rate since light is considerably faster than sound. The faster response would allow for much faster focus acquisition. Since light does not require a medium to travel through, these ToF devices could be utilized in space, although we will not need to for our purposes. Just as ultrasonic ToF sensors are susceptible to sound based noise, LED ToF sensors are susceptible to light-based noise. Ambient light could interfere with the accuracy. Sunlight and reflective surfaces can significantly with the distance at which the sensor is capable of operating. An LED ToF sensor also produces a cone-shaped signal, but the angle depends on the optics utilized to focus the light. This angle will greatly impact the precision of the device. While it may seem that a smaller angle would be more beneficial for its precision, in some cases, a wider angle is preferred as it will detect a wider area. For diode-based ToF devices, there are short-range, mid-range, and far-range sensors. There are several factors that impact the distance at which a sensor will function, including the power output, the wavelength of light, the optics used to focus the light, and the sensitivity of the receiver. LED sensors are typically found to be power efficient and are perfect for short-range applications.

As mentioned previously, ambient light can result in noise and interfere with the accuracy of the sensor. Different wavelengths of light can be used to circumvent this to some extent, such as ultraviolet (UV) or infrared (IR) light. Infrared LEDs are commonly used for distance measuring purposes because they have reduced interference from visible light. They are also eye-safe and much less noticeable since they operate outside of the visible spectrum. The maximum distance of LED ToF sensors is around 15 m. As the detection range of the LED ToF sensor increases, the cost also increases in cast. IR LED sensors are also typically more expensive than visible LED sensors. While faster and potentially more accurate than an ultrasonic ToF sensor, LED sensors capable of the required distances for our needs are much more expensive.

3.3.4 Laser Diode/LiDAR Sensor

Laser diode ToF sensors also produce a light-based signal. Since lasers are used in this case, the accuracy is much higher. They also have a significantly greater range than the previously mentioned ToF sensors. Laser ToF sensors can measure at ranges of 300 m and beyond. This increase in range is due to the minimal divergence that lasers experience. This allows for incredible precision and accuracy, even at large distances. LiDAR utilizes the principles of ToF with laser diodes to produce three dimensional representations of objects or spaces. While not necessary for our purposes, this technology has the potential to lead to many incredibly beneficial accessibility features. A key drawback of laser diode ToF sensors is that they can be potentially dangerous and harmful to human sight. Due to this, they typically produce light outside of the visible spectrum such as IR light. This also adds to the discrete nature of the sensor as it will not be visible to the human eye. All these benefits do come at a cost, however. A laser diode or LiDAR based ToF sensor is significantly more expensive than any other kind of ToF sensor. As the range and accuracy increases, the cost also tends to increase, so that must be considered greatly. For our purposes, we did not require the incredible range and precision that lasers provide, thus we were not planning to utilize this kind of sensor. The prohibitive cost further solidified our decision not to use a laser diode ToF sensor.

3.3.5 Time-of-Flight (ToF) Sensor Selection

While selecting which ToF sensor to utilize for this system, the largest restrictions were cost, size, and measurement range. Presbyopia is the loss of an individual's ability to accommodate their vision. This means that they are no longer capable of increase the optical power of their eyesight and focus on nearby objects. Since the auto-focusing is primarily meant to be utilized by individuals with this kind of visual impairment, we chose to prioritize accuracy within a few meters rather than further distances. In addition to this, the ToF sensor is simply providing a starting point for the auto-focusing, so amazing accuracy was not absolutely necessary, although it would certainly be beneficial. This gave us some freedom to consider some of the more cost-efficient options.

3.3.5.1 TeraRanger Evo Mini

The TeraRanger Evo Mini utilizes an infrared laser diode for its range finding. This sensor emits light at a central wavelength of 940 nm and is imperceptible to the human eye. With multiple pixel modes, this ToF sensor can detect distances in four directions at once. When in the four-pixel mode, it can function as a LIDAR sensor for object detection. When operating at the higher pixel modes, the update rate is significantly reduced. For example, the one-pixel mode has an update rate of 40 Hz at short ranges while the four-pixel mode has an update rate of only 6 Hz at short ranges. This ToF sensor also functions at ranges from 3 cm up to 330 cm, giving a large range of detection with great accuracy. Unfortunately, the four-pixel mode has a maximum range of 165 cm limiting its capabilities when used to detect movement. Fortunately, we are not using the ToF sensor to detect movement, so this would not have been an issue for our system. This ToF sensor requires a supply voltage that lies in the range of 4.75 V and 5.25 V. The TeraRanger Evo Mini is a fantastic ToF sensor, but unfortunately, it is rather expensive as its price ranges from $43 to $51. While this is not terribly expensive, it is significantly more expensive than our team had in mind for a ToF sensor. Due to this, we did not plan to use the TeraRanger Evo Mini.

3.3.5.2 TFmini Plus Micro Range Finder

The TFmini Plus also utilizes a laser diode as a LiDAR distance detection module. This sensor emits light at a central wavelength of 850 nm placing it in the near infrared zone just outside of the visible spectrum. As we have discovered before, LIDAR sensors are fantastic for larger ranges and this sensor does not disappoint as it can measure ranges from 10 cm up to an astonishing 1200 cm. This ToF sensor is without a doubt capable of range finding at distances much larger than any of the other ToF sensors we are considering. Unfortunately, the TFmini Plus is also much more expensive than we plan to spend on our ToF sensor. The supply voltage required for this ToF sensor is between 4.5 V and 5.5 V. At $51, the TFmini Plus was one of our more expensive options. This sensor also claims to be IP65 waterproof which would certainly have been beneficial for a system when worn outdoors on rainy days.

3.3.5.3 Seeedstudio Grove TF Mini LiDAR ToF Distance Sensor

The TF Mini LiDAR also uses a laser diode as a LiDAR range finder. The central wavelength of light emitted by this sensor is also 850 nm just like the TFmini Plus. That is not the only similarity though, as the Grove TF Mini LiDAR is also capable of measuring ranges from 10 cm up to 1200 cm. At $40, this sensor seemed to be just as good as the TFmini Plus, but at a better value. The TF Mini LiDAR requires a supply voltage between 4.5 V and 6 V. Unlike the TFmini Plus, this sensor does not claim any water resistance, but that was not a key factor in our ToF sensor selection process. While we did not plan to incorporate a LiDAR sensor in our system, if we had chosen to, this sensor would have been our top choice.

3.3.5.4 Sharp GP2Y0A21YK0F

The Sharp GP2Y0A21YK0F utilizes an infrared LED for its range finding. The light emitted by this sensor has a central wavelength of 870 nm which is also definitely in the near infrared zone. With a distance measuring range of 10 cm up to 80 cm, this sensor would only be capable of accurately acquiring a starting distance for nearby surfaces. While the limited range of this ToF sensor is not necessarily a deal breaker, a further upper range would have suited our system's needs more appropriately. This ToF sensor requires a supply voltage that can range from 4.5 V to 5.5 V. The Sharp GP2Y0A21YK0F cost ranges from as little as $5.91 up to as much as $11.96. The cost per unit is significantly cheaper when purchasing large quantities, but our system only required one ToF sensor, so the cost would have been at the higher end. The cheapest we had found this sensor at is $10.43 for a single unit. This ToF sensor is significantly cheaper than either of the laser diodes previously mentioned. Due to the low cost, the Sharp GP2Y0A21YK0F was a serious contender as our ToF sensor. Unfortunately, its limited range was not suitable for our system to function as desired.

3.3.5.5 Grove Time of Flight Distance Sensor (VL53L0X)

The Grove VL53L0X utilizes an infrared laser diode for its range finding. The central wavelength emitted by this ToF sensor is 940 nm just like the TeraRanger Evo Mini. This ToF sensor is capable of measuring up to 200 cm which is a decent distance. While significantly less than the TF Mini LiDAR's maximum range, 200 cm should be enough for the starting distance our system requires. That being said, upon further examination, the product listing states that the recommended measure distance should be between 3 cm and 100 cm, leading us to believe that the accuracy is significantly reduced above 100 cm. Due to this, the Grove VL53L0X may not be suitable after all. The Grove VL53L0X has a working voltage of either 3.3 V or 5 V. The cost of this sensor ranges from as low as $5.80 to as high as $7.25. As mentioned previously, we only require one ToF sensor for our system, so the Grove VL53L0X would cost us $ 7.25. This sensor was the cheapest we had seen thus far and had a slightly better range than the Sharp GP2Y0A21YK0F. These two factors made this ToF sensor a top contender for our system as well.

3.3.5.6 Grove Ultrasonic Distance Sensor

Unlike all the previously mentioned ToF sensors, the Grove Ultrasonic Distance Sensor does not utilize light to measure distance. Instead, as the name implies, it utilizes ultrasonic waves to acquire distance measurements. The immediate downside of this factor is that sound waves do not travel as quickly as light waves and thus the response time is inherently slower. This ToF sensor can measure at distances that range from 3 cm up to 350 cm. With a shorter maximum measurement distance than the laser diode ToF sensors, yet a longer maximum measurement distance than the LED ToF sensors, the Grove Ultrasonic Distance Sensor functions at a perfectly suitable range for our system's purposes. As for the voltage support, this sensor is compatible with both 3.3 V and 5 V. At a cost of $3.95, this ToF sensor was incredibly affordable and a great choice for our system overall.

3.3.5.7 WWZMDiB HC-SR04 Ultrasonic Sensor Module

The final ToF sensor that we considered, the HC-SR04, is another ultrasonic sensor. This range finder is capable of measuring distances that range from 2 cm up to 450 cm. This is an incredible range, especially for an ultrasonic ToF sensor. With the maximum measurement distance of 450 cm, this ToF sensor is even better than the previous ultrasonic sensor, the Grove Ultrasonic Distance Sensor. The HC-SR04 requires a voltage of 5 V, which is slightly more limited than the previous ultrasonic sensor. This sensor seems to only be available as a set of at least two units for a cost of $7. With this in mind, each individual ToF unit costs $3.50. This is an incredibly economical price for a ToF sensor. Aside from the lack of flexibility for the required voltage, the HC-SR04 seemed to be the best choice for a ToF sensor. In addition to this, our team happened to have a spare HC-SR04 already, so there was no need to purchase one.

3.3.5.8 Time-of-Flight (ToF) Sensor Comparison

When choosing the proper Time-of-Flight sensor for our system, we primarily considered the cost, size, and range measurement capabilities. All the ToF sensors we considered were rather small and thus the size was no longer a deciding factor. Table 3.3.1 below lists all the ToF sensors we compared as well as some crucial specifications we had to consider. We compared the measurement range, the operating voltage, the average current, and the cost for all these ToF sensors. Unfortunately, none of the LED based sensors were capable of measuring far enough for our needs. Most of the laser diode based sensors were capable of measuring distances much further than we need, but they were also rather expensive. With the capability to measure just far enough, the ultrasonic sensors seemed perfect for our auto-focusing system. The ultrasonic sensors also happened to be the most economically sound choices for ToF sensors at less than $10 each. Ultimately, the ultrasonic ToF sensor we selected to use also happened to be one that we already had available which meant we did not have to purchase this part at all. Of course, the response time was slower than any of the LED or laser diode sensors, but it was still be sufficient for our auto-focusing system.

Sensors	Sensor Type	Measurement Range (cm)	Operating Voltage (V)	Operating Current (mA)	Cost
TeraRanger Evo Mini	Laser Diode	3 - 330	4.75 - 5.25	50	$43

TFmini Plus	Laser Diode	10 - 1200	4.5 - 5.5	110	$51
TF Mini LiDAR	Laser Diode	10 - 1200	4.5 - 6	120	$40
Sharp GP2Y0A21YK0F	Light-Emitting Diode	10 - 80	4.5 - 5.5	30	$10.43
Grove VL53L0X	Light-Emitting Diode	3 - 100	3.3 or 5	19	$7.25
Grove Ultrasonic Distance Sensor	Ultrasonic	3 - 350	3.3 or 5	8	$3.95
HC-SR04	Ultrasonic	2 - 450	5	< 5	$0

Table 3.3.1 Time-of-Flight Sensor Comparison Table

3.4 Lenses

Our system required an adjustable lens system capable of focusing on various ranges. To accomplish this, the focusing power of the system had to be capable of varying between -1.5 D and +2.5 D. There are a variety of systems and types of lenses that could have been utilized to accomplish this. Liquid lenses, flexible lenses, and traditional glass or plastic lenses could have been used in the system. Each of these lenses can produce an adjustable optical power through different means.

In addition to this, the number of lenses utilized can influence the impact of different kinds of aberrations. By using more lenses or various types of lenses in conjunction, the intensity of the aberrations that may be present can be significantly reduced.

3.4.1 Lens Shape

The shape of a lens is one of the main factors that determines its optical power. Whether light converges, diverges, or neither after passing through a lens depends on the shape of the lens. The shape of the lens impacts the vergence of the light by gradually changing the angle of incidence gradually. This causes light to refract at various angles focusing it as desired. While most of these shapes are based on spherical curvature, there are instances in which that is not the case, such as the cylindrical lens which only curves light in one direction allowing for light to be focused along a line instead of at a point. For lenses that utilize spherical curvature, Equation 3.4.1 can be utilized to calculate the optical power (P) given the radius of curvature of the first surface (R_1), the radius of curvature of the second surface (R_2), and the lenses refractive index (n_2) are all known. The refractive index of the original medium (n_1) can safely be assumed to be 1 when the lens is placed in air but will vary if submerged in a liquid or surrounded by another medium. For a thick lens, the full Lensmaker's equation (Equation 3.4.2) is necessary in which the thickness (d) of the lens is included in the calculation. [31]

$$P = (n_2 - n_1)(\frac{1}{R_1} - \frac{1}{R_2}) \quad (3.4.1)$$

$$P = (n_2 - n_1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - \frac{(n_2-n_1)^2 d}{n_2 R_1 R_2} \quad (3.4.2)$$

Planar lenses, as seen in Figure 3.4.1(A), are rather straightforward; both sides of the lens are flat. Since neither side of the lens has any curvature, these kinds of lenses do not converge, nor diverge any light which is normal to the surface, also known as the optical axis. Light that enters the lens at any angle other than the optical axis will still refract or reflect of course due to the change of refractive indices of the mediums that light is traveling through. These lenses are not typically used for focusing purposes, instead they can be used for other purposes such as windows, waveguides, holography, polarization control, and optical filtering. [32]

A plano-convex lens is a lens in which one side is completely flat with no curvature, while the other side has a convex curvature. Figure 3.4.1(B) demonstrates how this type of lens has a positive optical power as it causes the light to converge onto a single focal point[33]. The larger the radius of curvature, the higher the optical power. The optical power is inversely proportional to the focal length. As such, a higher optical power of the lens will achieve a shorter focal length. The plano-convex lens has a constant focal length regardless of orientation. Regardless of whether the flat side or the convex side is pointed towards the light source, the focal length will remain the same. That being said, the orientation does impact the intensity of aberrations. By placing the light source on the convex side of the lens, aberrations can be significantly reduced, and an incredibly sharp focus can be achieved. The asymmetrical aspect of these lenses is beneficial at reducing spherical aberrations when the light source and image are at unequal distances from the lenses. [33]

A plano-concave lens also has one flat side and one curved side. The difference here is that the curved side is concave, resulting in negative optical power. Due to the negative optical power, collimated light that passes through diverges as seen in Figure 3.4.1(C). This divergence means that the light expands instead of focusing to a point. The negative optical power corresponds with a negative focal length which "focuses" onto a virtual image on the same side as the light source.

The diverging light appears to originate from the virtual image. [33] These lenses are typically utilized for beam expansion or added to an existing optical system to increase the current focal length. Similarly to a plano-convex lens, the optical power remains the same regardless of the orientation of the lens, while the orientation does impact the intensity of aberrations as well. The light source should be placed on the concave side for a plano-concave lens to reduce aberrations. [34]

Biconvex lenses have two convex sides as seen in Figure 3.4.1(D). Each side adds a positive optical power, subsequently resulting in an overall positive optical power. As mentioned previously, a positive optical power causes collimated light to converge after passing through the lens. Spherical aberrations are significantly reduced by these kinds of lenses, because of the symmetry of two convex sides. [34] While it is not necessary for a biconvex lens to have the same radius of curvature on both sides, doing so will significantly reduce distortion as well as spherical and coma aberrations. [33]

Biconcave lenses have two concave sides as seen in Figure 3.4.1(E). Each of which has a negative optical power and thus results in an overall negative optical power. This negative optical power means that collimated light diverges, expanding after passing through the lens. Another form of divergent lens with a negative focal length thus “focusing” onto a virtual image on the same side as the light source. [34] These hold similar functions as plano-concave lenses but are typically stronger due to both sides being concave. Similarly to biconvex lenses, both sides do not have to have the same radius of curvature, but typically are as it reduces spherical aberrations. [35]

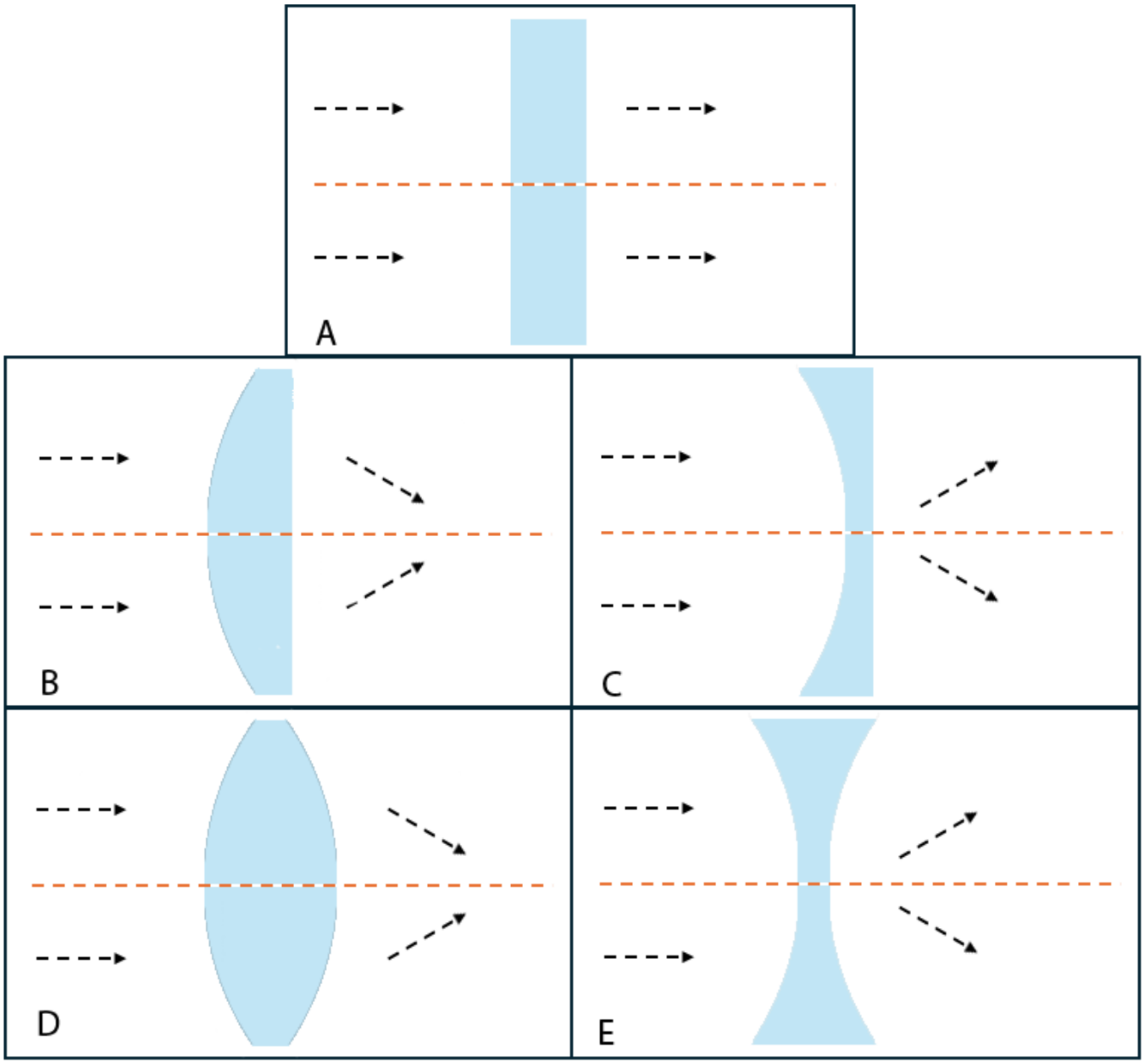

Figure 3.4.1 Typical Lens Shapes

Meniscus lenses utilize the divergent nature of a concave lens in conjunction with the convergent nature of a convex lens to have a resulting optical power that is either positive or negative. A meniscus lens has a concave side and a convex side. Depending on the radius of curvature that each side holds, the lens will either converge or diverge.

For a positive optical power to occur, the concave side must have a larger radius of curvature than the convex side. [34] This positive meniscus lens is also known as a concavo-convex lens. Due to the asymmetrical nature of the positive meniscus lens, the center is thicker than the ends of the lens. Since this is also a convergent lens, it is typically used in conjunction with other lenses to shorten the focal length of an optical system. [34]

For a negative meniscus lens, the convex side must have a larger radius of curvature than the concave side. This lens has a negative optical power and is also referred to as a convexo-concave lens. This divergent lens is typically used in lens systems to increase the focal length. It can also be utilized to minimize spherical aberrations and increase the resolution of a system. [34]

While uncommon, a meniscus lens can also be designed to have zero optical power. The convex and concave sides would essentially cancel each out keeping the focal length the same as it was. These kinds of lenses would still alter how light interacts with the system and could potentially influence the effect of different types of aberrations.

Aspherical Lenses are unique lenses typically designed for extremely specific purposes. They do not have a uniform curvature as would typically be expected of a lens. If the surface of a lens is not spherical, then it could be considered aspherical. Spherical lenses have rotational symmetry and a constant radius of curvature from the center of the surface to the edge. An aspherical lens's surface may still have rotational symmetry, but its radius of curvature varies from the center to the edge. Aspherical lenses can improve the performance of optical systems without adding more elements, allowing for a more compact system. Unfortunately, due to their unique shapes, there are additional obstacles when it comes to manufacturability. [36]

Cylindrical Lenses are unique in that they only have curvature in one axis instead of both axes. Since the curvature is only on one axis, the light is focused as a line instead of a point. These kinds of aspherical lenses can also have a positive or negative optical power. To achieve this, they can also come in various shapes including plano-concave, plano-convex, biconcave, and biconvex. [37] In addition to the typical circular style that is common for spherical lenses, cylindrical lenses are also available in a rectangular style as seen in Figure 3.4.2. It may be obvious, but cylindrical lenses serve different purposes than the traditional spherical lens. Since they only alter the optical power of one axis. They are often utilized to create laser lines, adjust an images height while leaving its width unchanged, or for correcting astigmatisms. [38] These lenses are used to diagnose an astigmatism using the Jackson Cross Cylinder Test. This test consists of placing two equal but opposite power cylindrical lenses to find the corrective focus that reduces the astigmatism the most. [39]

Figure 3.4.2 Cylindrical Lens

Fresnel lenses were originally utilized in lighthouses to direct light without the losses that the existing metallic produced. A Fresnel lens is another form of aspherical lens as it consists of many concentric rings that direct light in parallel, forming a large beam of collimated light. The main advantages of a Fresnel lens are its compact size and light weight. A traditional spherical lens could be utilized to produce collimated light, but the lens would have to be very thick depending on its radius of curvature. The Fresnel lens in Figure 3.4.3 is composed of many concentric rings. This shape allows each ring to be much thinner and have a unique radius of curvature, producing the desired collimated light. [40]

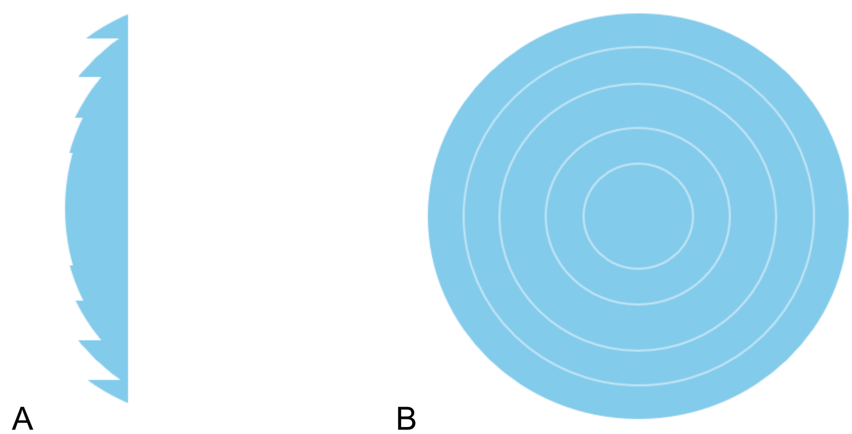

Figure 3.4.3 Fresnel Lens
(A) Side View
(B) Front View

3.4.2 Traditional Lenses

Traditional lenses are typically made of an optical-grade glass or plastic. These lenses are made into a fixed shape that cannot be adjusted afterwards. These are the most widely known and are utilized in many technologies such as eyeglasses, microscopes, cameras, and other optical devices. The fixed shape of the traditional lens provides the advantage of constant optical power as well as high durability. Constant optical power is unfortunately also a disadvantage as there is no flexibility there and would require additional lenses to adjust the optical power. Fortunately, these lenses can be shaped in many different forms to accomplish their desired goals.

As mentioned previously, glass and plastic are the primary materials utilized to produce traditional lenses. Glass and plastic lenses each have unique manufacturing processes. Glass is ground down and polished to the desired curvature and shape. Plastic, on the other hand, is typically injection molded. Each of these materials has its own set of advantages as well as disadvantages. [41]

To begin with, glass has hundreds of available materials for making optics, while plastic is limited in materials to choose from. This limits the flexibility available in the process of achieving specific optical properties. Glass is also significantly more durable than plastic in most cases. It can withstand wider temperature ranges, humid environments, and is much less susceptible to scratching. Perhaps the greatest advantage that glass holds is its optical clarity of; when shaped properly, they offer minimal distortion and higher accuracy in terms of desired results. Glass typically has a higher refractive index than plastic, allowing for the production of thinner lenses with the same optical power. This advantage is incredibly beneficial in the cases where the space in which the optics must be help is limited. [41]

Plastic on the other hand, can be two to four times lighter than glass, making them more comfortable in applications in which they must be worn or carried such as eyeglasses. While plastic is more susceptible to scratching, it also has much more impact resistance. A plastic lens that is dropped may acquire a few new scratches, but it is unlikely to shatter. A glass lens, on the other hand, would likely shatter to pieces or at the very least be chipped upon impact with the ground. What plastic lacks in optical clarity, it makes up for in the ease of its manufacturability. For starters, plastic is significantly cheaper than glass, allowing for much higher production at lower costs. Since plastic is injection molded, the lenses made using the same molds are incredibly consistent in quality. The use of a mold also allows for much more unique designs such as Fresnel lenses. These unique designs are much harder to acquire with the grinding and polishing process required with glass lenses. Typically, lenses must be mounted onto an optical system through the use of other mechanical mounting hardware. While this can still be accomplished with plastic lenses, they can also be designed to include the mounting hardware in the mold, skipping the need for a separate mounting hardware. [41] While glass typically has a higher refractive range than plastic, there are modern options for plastic now that also allow very higher refractive indices. Glass can have refractive indices ranging from approximately 1.5 to approximately 1.9 while plastic can have refractive indices that range from approximately 1.5 to approximately 1.75. Glass certainly still has the advantage when it comes to quality, but plastic certainly has many advantages, especially when considering affordability.

3.4.3 Flexible Lenses

Flexible lenses are made of soft materials that can be physically adjusted to alter the radius of curvature on one or both sides of the lens. By adjusting the radius of curvature, the optical power of the lens is also adjusted, allowing for a lens with a variable focal length. Through the use of a flexible lens, the number of lenses necessary in a system can be reduced and the system can be made lighter and more compact. In addition to this, they are much simpler mechanically than having multiple lenses moving back and forth to produce the same effects. This concept is similar to how the human eye functions as the muscles in your eye adjust the thickness and curvature of the eye for accommodation to occur.

Flexible elastomers can be utilized for lenses with adjustable curvatures. By applying a symmetrical amount of strain around the elastomeric lenses, the optical power can be adjusted without impacting other optical elements of the lens. This is a mechanical means of adjusting the optical power of the lens. [42]

Liquid lenses are a rather simple idea: a lens is made with a liquid core. One face of the lens is typically made of a hard, nonflexible material like glass or plastic, while the other is made of a more flexible material, such as an elastomer. [43] Through the application of mechanical pressure, the flexible material can have its radius of curvature altered, thus changing the optical power of the lens. Alternatively, an electric field can be applied to the liquid, increasing the pressure and altering the curvature as is done in electrowetting. [44] While typically, one of the surfaces is made of a less flexible material, that is not a requirement as both surfaces could be made of a flexible material and the optical power could still be adjusted.

3.4.4 Lens Coatings

Some lenses have coatings on them that serve a variety of purposes and impact different optical elements. While lenses do not require a coating to function, their effectiveness can be significantly improved with a coating present. These coatings are often applied utilizing the sol-gel method in which molecules are hydrolyzed to produce a hardened solid-state polymeric oxide network. [45] Essentially, a liquid is hardened into a solid coating on a material.

Anti-reflective coatings are applied to lenses to reduce reflectance as well as glare. By reducing the reflectance, the transmission of light is increased providing a clearer image, especially in lower light situations. As light interacts with a medium, some with transmit through and some will reflect off. The goal of an anti-reflective coating is to promote more transmission. Equation 3.4.3 is a simple reflectance (R_1) formula in which the light travels from one medium, let us say air, to another medium at normal incidence. The refractive index of the air is n_{air} and n_s is the refractive index of the next medium. By utilizing this medium, it becomes apparent that the larger the difference in the refractive indices of the two mediums, the larger the reflectance. By including a layer with a refractive index n_f greater than n_{air}, yet lesser than n_s, a buffer is created allowing a smoother transition between mediums and reducing the reflectance. Equation 3.4.4 would be the resulting formula using the new layer. [46]

$$R = \frac{(n_a - n_s)^2}{(n_a + n_s)^2} \tag{3.4.3}$$

$$R = \left(\frac{n_{air} n_s - n_f^2}{n_{air} n_s + n_f^2}\right)^2 \tag{3.4.4}$$

Scratch-resistant coatings are just as they sound, coatings that make are more difficult to scratch. Scratches and other forms of physical damage deteriorate the optical performance of lenses. These coatings are commonly applied to lenses through a dip-coating process. Glass, while already more scratch resistant than plastic, is still highly susceptible to being scratched rather easily. Corondium and Ormosils are scratch resistant materials that can be applied to glass and plastic, respectively. These coatings are much more durable that the original lens, ensuring consistent optical performance. [47]

UV protection coatings serve the purpose of either absorbing or reflecting ultraviolet light. They are applied to materials using the sol-gel method with the goal of reducing the effect that UV radiation has on different materials. [48] These are often applied to sunglasses as well as prescription lenses to help protect an individual's eyes. The coating reduces the amount of UV light that transmits through the lenses, thus preventing damage which could lead to loss of vision. While the coating reduces the transmission of ultraviolet light, it has little to no effect on the visible spectrum depending on the specific coating. This is important as increased transmission of the visible spectrum is ideal for a clear image.

Hydrophobic coatings are great for developing self-cleaning and anti-icing surfaces. The coatings are typically applied using the sol-gel method. These coatings are utilized for many applications including solar panels, our system, and optical instruments. The hydrophobic surface prevents obstructions from remaining on the surface as well as enabling the surface to be cleaned much more easily in the event that an obstruction remains on the surface. [49]

Fogging is a common occurrence everywhere; it occurs when the temperature is lower than or equal to the dew point of water vapor. Condensation then occurs on solid surfaces and fogging occurs. Anti-fog coatings strive to prevent or at the very least reduce the amount of fogging that occurs as it can highly reduce the effectiveness of an optical system. Anyone who wears our system or prescription glasses on a daily basis would be able to elaborate on the inconvenience of fogged up lenses. Fogging highly diffuses light, reducing the transmission as well as obscuring the image. This can lead to dangerous situations in laboratories and on the road. While there are mechanical methods, such as introducing an external voltage to control the temperature of a material, coating the material is a much simpler method. This can be achieved with two types of coatings. The first is a coating with chemical properties that hinder the fogging process. The second type of coating relies on microstructures on the surface that promote the shedding of the condensed droplets, so they do not build up as fog. [50]

All these coatings have unique benefits, but none were absolutely necessary for our system to function properly. That being said, the AR and UV coatings would have been the most beneficial for our purposes. The AR coating would have been ideal for our color identification system as it could have improved the transmission of the different wavelengths for each color. The UV coating could have been beneficial for the lenses the user would see through as it would have prevented any damage that the ultraviolet light could cause.

3.4.5 Lens Systems

The number of lenses in a lens system depends highly on what the system is meant to accomplish. If the purpose is simply to magnify or alter the optical power a set amount, then a single lens will easily accomplish the task. This single lens system is simple, typically light weight and likely cheaper as there are less parts involved. However, the system may be fraught with optical aberrations and will be incredibly limited in its capabilities. Magnifying lenses and prescription lenses are great examples of single lens systems that accomplish their purpose well, since they have simple requirements, to magnify or adjust optical power a fixed amount. As the purposes of the system become more complex, the number of lenses increases based on the level of precision that is required. With multiple lenses, the effective focal length of the system is adjusted based on the optical powers of each lens as well as the distance between the lenses. By using Equation 3.1.2, the Lensmaker's equation, we can estimate the power of two lenses by thinking of them as one larger, thick lens. As more lenses are added to the system, the optical power and effective focal length will continue to change as well. A single lens typically cannot account for all kinds of optical aberrations. To correct this, different lenses of different optical powers and materials are utilized to correct the specific types of optical aberrations.

A complex lens system will typically have multiple lenses that all work in conjunction to accomplish the purpose of the system. Multiple lenses allow for variable focal powers and improved image quality with a reduction of optical aberrations. Occasionally more lenses are also added that counteract issues that other lenses in the same system might introduce such as chromatic aberration.

For our lens system, at least two lenses were necessary to produce the variable focal length necessary for auto-focusing. To reduce the complexity, the lens system that the user will see through is a two-lens system. The lens system for the CMOS sensor, on the other hand, is a three-lens system including the provided CMOS module lens. One lens is utilized as a focusing lens and the remaining two lenses are utilized to provide the variable optical power.

3.4.6 Lens Selection

When choosing lenses for our auto-focusing system, our largest restrictions were the size, weight, and shape. Since our system is meant to be worn, it was preferable to make our system as light and compact as possible. The auto-focusing feature of our system is achieved through the physical movement of the lenses, adjusting the distance between them. To make this as compact as we can, we selected lenses with relatively high positive and negative optical powers. Both converging and diverging lenses were necessary to accomplish this. The use of both converging and diverging lenses also produced an image with a positive orientation. We took into consideration the variety of lenses different companies had available.

3.4.6.1 United Scientific Lenses

Beginning with United Scientific, they offer lenses of many focal lengths, but limited shapes. Aside from the lens kits, they only offer biconvex or biconcave lenses. All their lenses are made from plate glass, a material generally used for windows. In which seems to have a refractive index that could range from 1.5 to 1.9. [51] This lack of a precise refractive index could reduce the accuracy of our auto-focusing system.

United Scientific's lenses have diameters that range from 38 mm to 100 mm. The biconvex lenses have focal lengths that range from 50 mm up to 500 mm. Meanwhile, the biconcave lenses are less straightforward. The lenses are listed as having focal lengths that vary from 50 mm up to 500 mm. United Scientific has many lenses available at different focal lengths which is certainly beneficial for acquiring more precise focusing.

Unfortunately, in an attempt to acquire accurate quotes, an account could not be created and thus the estimated prices could not be viewed. This uncertainty was a large hinderance that had a heavy impact on the decision-making process for lenses.

3.4.6.2 Eisco Lenses

Eisco also produces both converging and diverging lenses. The shapes available to choose from are biconcave, plano-convex, and biconvex. Unfortunately, these lenses do not specify their exact materials. Instead, the product listings simply state that they are “optically worked” glass lenses. Due to this, the exact refractive index of these lenses is unknown, but can be assumed to be approximately 1.5 as glass typically is.

When considering the options for diverging lenses that Esco offers, the diameters range from 38 mm to 75 mm. The focal lengths available are incredibly broad as they vary from 50 mm up to 1000 mm. While the range is large, the variety of focal lengths is actually more limited than the United Scientific lenses. The converging lenses vary in diameter from 25 to 75 mm, allowing for some rather small lenses. The focal lengths of these lenses range from 50 mm up to 1000 mm as well. The large variety of focal lengths is incredibly beneficial.

Esco’s lenses are reasonably priced as well. The cheapest lenses cost approximately $9 while the most expensive cost approximately $20. Fortunately, the lenses with smaller diameters seemed to be the cheapest as well, which was great, since we planned to keep our system as compact as possible.

3.4.6.3 Edmund Optics Lenses

Edmund Optics is a highly reputable source for all kinds of optical equipment. They offer an incredible variety of types of lenses in many different shapes that serve an assortment of purposes. Of course, quality does come at a cost; Edmund’s Optics lenses are not exactly the most affordable. Every lens that Edmund Optics has available also has a list of all the lens specification, including material, lens thickness, and coating if there is one. This information is crucial for the accuracy of a lens system. It is certainly something to consider when choosing exact lenses.

Edmund Optics offers all sorts of AR coating options such as MgF2, NIR I, and NIR II just to list a few. While these options are available, they significantly increase the costs, so we are primarily considering the uncoated options to reduce our expenses. Of the uncoated options, there are plenty of diverging and converging lenses listed. Starting with the diverging lenses, their diameters range from 3 mm to 50 mm. These have focal lengths that range from 6 mm up to 100 mm. The converging lenses have diameters that range from just 1 mm to 200 mm, which is an incredible range in sizes. These lenses have focal lengths that range from 0.6 mm up to 750mm.

The range of options that Edmund Optics offers is incredible. They have lenses that are incredibly small and absolutely perfect for a compact optical system such as ours. While great in quality, Edmund Optics lenses are significantly costlier, especially the most compact ones. The prices seem to range from as low as $30 to as high as $750. That is not even considering the coated options. If we had decided to go with lenses from Edmund Optics, we would only have utilized a few for the most compact aspects of our system, such as the lens system that was necessary for the CMOS sensor.

3.4.6.4 Lens Comparison Table

Table 3.2.1 below compares most of the shapes, diameters, focal lengths, and costs of the optical lenses that United Scientific, Eisco, and Edmund Optics offer. Edmund Optics has such an expansive library of available lenses that most of the lenses were excluded based on the diameter of the lenses. The sizes that we deemed unfit for our systems purposes are not listed. Our auto-focusing feature consisted of two two-lens systems, one that the user can use to adjust their focus and the other which can adjust the focus on the CMOS sensor. For the lens system that the user sees through, lenses with a diameter of 25, 38 or 50 mm were preferred. In addition to this, we required a negative and a positive lens in each system to keep the lens system compact. More specifically, the negative lens had to be more powerful than the positive lens to cover the optical power range of -1.5 D to +2.5 D that we desired. Shorter focal lengths would have also resulted in a more compact system as they have larger optical powers. For this reason, we primarily considered lenses with focal lengths at 200 mm or less. Some lenses that meet these criteria are highlighted in blue on Table 3.4.1. As for the lens system necessary for the CMOS sensor, Eisco had all the lenses necessary for this at affordable prices.

As for the lenses necessary for the CMOS sensor's lens system, they had to meet the same requirement, aside from the diameter size. The size of the CMOS sensor we chose determined if we could consider lenses with a smaller diameter. The smaller the sensor, the smaller the lens of course. For the CMOS lens system, we also considered the lenses highlighted in green on Table 3.4.1. Unfortunately, these smaller lenses are much more expensive. Eisco was our best choice for this lens system, unless it was absolutely necessary that we needed smaller lenses. Our top choice for the lenses were the Eisco biconvex lens with a diameter of 38 mm and a focal length of 100 mm and the Eisco biconcave lens with a diameter of 38 mm and a focal length of 50 mm. These two lenses are marked in green on Table 3.4.1.

Brand	Lens Shape	Diameter (mm)	Focal Lengths Available (mm)	Cost (USD)
United Scientific	Biconcave (negative)	38	50, 100, 150, 200, 300, 350, 400, 450, 500	Unknown
		50	50, 100, 150, 200, 250, 300, 350, 400, 450, 500	Unknown

		75	200, 300, 350, 400, 450, 500	Unknown
		100	100, 300, 350, 400, 450, 500	Unknown
	Biconvex (positive)	38	50, 100, 150, 200, 250, 300, 350, 400, 450, 500	Unknown
		50	50, 100, 150, 200, 250, 300, 350, 400, 450, 500	Unknown
		75	150, 200, 300, 350, 400, 450, 500	Unknown
		100	75, 100, 300, 350, 400, 450, 500	Unknown
Eisco	Biconcave (negative)	38	50, 100, 150, 200, 250, 300	$10 - $14
		50	50, 100, 150, 200, 250	$11 - $20
		75	100, 150, 200, 250, 300, 500, 1000	$12 - $18
	Plano-Convex (positive)	25	50, 71	$9 - $10
		50	100, 150, 200	$10 - $13
	Biconvex (positive)	38	50, 100, 150, 200, 250, 300	$8 - $16
		50	50, 100, 150, 200, 250, 300	$9 - $18
		75	100, 150, 200, 250, 300, 500, 1000	$11 - $15
Edmund Optics	Plano-Concave (negative)	3	6, 9	$50
		6	6, 9, 12, 15, 18	$30
		9	9, 12, 18, 27	$30
		12	12, 15, 18, 24, 48	$30
		20	30, 40, 50, 100	$31
		25	25, 35, 50, 100	$32
		50	100, 125	$48
	Biconcave (negative)	6	6, 9, 12	$28
		9	9, 12, 18	$29
		12	12, 18, 24	$31
		20	20	$31
		25	25, 50, 100	$33
	Plano-Convex (positive)	3	3, 4.5, 6, 7.5, 9, 12, 15	$47 - $52
		6	6, 7.5, 9, 10, 12, 15, 18, 20, 21, 24, 25, 30, 36, 48, 60, 72	$26 - $27
		9	9, 10, 12, 13.5, 15, 18, 20, 22, 25, 27, 36, 45, 54, 72, 90	$27 - $28
		12	12, 15, 18, 20, 24, 25, 30, 36, 42, 48, 50, 54, 60, 72, 84	$29 - $30
		20	20, 24, 30, 35, 40, 50, 60, 70, 80, 100, 150	$29 - $31

		25	25, 30, 35, 40, 50, 60, 75, 85, 100, 125, 150, 175, 200, 250, 300, 400, 500, 750	$29 - $31
		50	50, 75, 100, 125, 150, 175, 200, 250, 500	$43 - $48
	Biconvex (positive)	3	3, 4.5, 6, 9	$50
		6	6, 9, 12, 18, 24, 30, 36	$29
		9	9, 13.5, 18, 27, 36, 45	$30
		12	12, 18, 24, 30, 36, 48, 72	$30
		20	20, 25, 30, 40, 50, 60, 80	$32
		25	25, 30, 35, 40, 50, 75, 100, 125, 150, 175, 200	$32
		50	50, 100, 150, 200, 250	$48

Table 3.4.1 Lens Comparison Table

3.5 3D Printer Filament

For our system, we required custom designed frames to hold and connect various components. To accomplish this, we utilized a 3D printer to produce all the custom parts that we needed. Since a large portion of the system was 3D-printed, it was essential that we used the correct material that would give us the stability necessary for proper optical alignment. The 3D material had to be strong and durable, while not being brittle. Luckily, there were many 3D printer filament options available to choose from.

3.5.1 Polylactic Acid (PLA)

Polylactic Acid, PLA, is one of the two most popular filaments used in 3D printing. PLA is a biodegradable thermoplastic typically produced by renewable resources. It is typically the first choice for beginners as it is incredibly easy to use for printing. As the starter filament, it is a rather strong material. It produces very few fumes when melted making it one of the safer filament materials to use indoors. Like most popular filaments, it is also recyclable which is always great. Unfortunately, PLA is very brittle and cracks if bent. PLA is often used for figures, toys, and containers. [52]

3.5.2 Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile Butadiene Styrene, ABS, is the second most popular filament used in 3D printing. ABS is a petroleum-based thermoplastic that can be recycled but is not biodegradable. As a stronger filament, ABS is a more durable material. ABS has some flexibility to it which prevents cracking when bent, but can also result in warping, especially in larger prints. Unfortunately, ABS filaments do produce intense fumes when melted. These fumes can be hazardous to an individual's health without the proper ventilation. Having the 3D printer within an enclosed housing can reduce the inhalation of harmful fumes. ABS is also considered to be slightly harder to work with than PLA. ABS is commonly used for electronic housings, interlocking parts, and tool handles, making it a good option to consider. [52]

3.5.3 Polyethylene Terephthalate Glycol-Modified (PETG)

Polyethylene Terephthalate Glycol-Modified, PETG, is a polymer in the polyester family. It is a thermoplastic that is modified with glycol. Similarly to ABS, PETG is recyclable, but not biodegradable. PETG is even stronger and more durable than ABS. It also has a higher heat resistance and some weather resistance making it suitable for the outdoors. While tougher than PLA, PETG does not have a warping tendency. Unfortunately, PETG also produces dangerous fumes and should be utilized in a proper ventilated environment. Another disadvantage of PETG is that it has poor first-layer adhesion which can cause issues while printing. These issues can be easily overcome by applying a layer of blue tape for it to adhere to. PETG is often used for printing semi-transparent objects. [52]

3.5.4 Thermoplastic Polyurethane (TPU)

Thermoplastic Polyurethane, TPU, is a urethane-based elastomer with similar qualities to rubber. TPU is not the easiest material to print with and should not be used by beginners. This is another filament that is recyclable, but not biodegradable. Very few fumes are produced when printing with TPU, which makes it much safer to use indoors. TPU has high flexibility without sacrificing durability or strength. The material is also both UV and weather resistant. The main disadvantages of this filament are that it cannot be used by all 3D printers, and it is typically much more expensive than the previously mentioned filaments. TPU is typically used to make shock absorbers and other protective housings. [52]

3.5.5 Nylon-6 (Nylon)

Nylon filament is an extraordinarily strong and durable material that works well for moving parts. When printed thinly, it is very flexible and can be used as a hinge of sorts. Unfortunately, it seems that Nylon is not simple to work with and thus is not recommended for beginners. It may also produce dangerous fumes and should only be used for printing in well-ventilated environments. Nylon is highly susceptible to warping requiring an enclosure to reduce how much warping occurs. [53]

3.5.6 3D Printer Filament Material Comparison

By comparing the five filaments researched, it seemed that ABS and PETG were the best two options for our purposes. Both of these materials are strong, tough, and durable, which will be necessary for our system. PLA is the only biodegradable option, which is great, but it is also one of the most brittle option. Because of this, we did not initially believe it would be suitable for our system. TPU and Nylon both seemed like great options as well. In terms of reliability, TPU and Nylon would both hold up well, but they are also the hardest filaments to print with which would have likely caused more complications throughout. Since they are not beginner friendly, we did not considering them very much. Table 3.5.1 compares various properties of the five filament materials listed above. By comparing the option, ABS and PETG were clearly the best options, but some practice and proper ventilation were required when printing.

Property	PLA	ABS	PETG	TPU	Nylon
Print Nozzle Temperature (°C)	180- 230	210 - 250	200 - 260	190 - 245	240 - 270
Print Bed Temperature (°C)	20 - 60	80 - 110	80 - 90	60 - 90	70 - 90
Bed Adhesion	Moderate	Moderate	Poor	Poor	Poor
Fumes	Low	High	High	Low	High
Strength	Moderate	Good	Very Good	Very Good	Very Good
Flexibility	Poor	Moderate	Good	Good	Good
Biodegradability	Partial	None	None	None	None

Recyclable	Yes	Yes	Yes	Yes	Yes
Ease of Use	Very Easy	Moderate	Moderate to Difficult	Difficult	Difficult

Table 3.5.1 3D Printer Filament Property Comparison

3.5.6 3D Printer Filament Selection

With the properties compared, the next step was to compare the costs of various brands. Table 3.5.2 compares the costs of the filament materials available from various vendors. With ABS and PETG as the best options for our system, it is clear that Elegoo has the most affordable filaments for sale. With the costs within $2 of each other of 1 kg of filament, both ABS and PETG are great choices. PETG is both more durable and cheaper than ABS making it the choice we chose to move forward with. Unfortunately, it had poor bed adhesion, which led to many failed prints at first and inconsistencies. The poor adhesion was overcome through the use of a glue stick but was still difficult to work with reliably. Due to this, we chose not to purchase more PETG filament after the first roll. Instead, we chose to purchase PLA, a more reliable and beginner friendly filament. That being said, most components that involved optical alignment were still printed with the PETG filament and the rest of the parts were printed using the PLA filament.

Brand	PLA (1 kg)	ABS (1 kg)	PETG (1 kg)	TPU (1 kg)	Nylon (1 kg)
Overture	$13.99	$19.99	$14.99	$27.99	$37.99
Creality	$13.99	$20.99	$12.99	$25.99	$49.99
Polymaker	$21.99	$21.99	$21.99	$29.99	$39.99
Bambu	$19.99	$19.99	$19.99	$35.09	$36.54
Elegoo	$15.99	$16.99	$14.99	$24.99	N/A

Table 3.5.2 3D Printer Filament Cost Comparison

3.6 Motors

In the selection of motors for our design, several factors were considered such as: size, weight, and positional accuracy. We evaluated two types of motors: stepper motor and servo motor.

3.6.1 Stepper Motor

Stepper motors are a well-known motor and are commonly applied in robotics and 3D printers. There are several types of stepper motors such as: permanent magnet stepper motors, variable reluctance stepper motors and hybrid stepper motors. Of them the most common is the Hybrid Stepper Motor, which is widely used for its excellent balance of speed, torque, and accuracy. The stepper motor has no feedback feature as it works in an open-loop circuit, which is a step back if we were to look at a route of needing feedback from both motors to compare position. A great advantage that comes in handy with our design is that the stepper motor shows good torque at low speeds. Considering we are motorizing lenses that can break when dropped, we needed low speed.

In terms of size, stepper motors are typically available in smaller sizes than other types of motors and since we are working with a space-constrained environment this was a benefit. It also appears to be the least expensive when it comes to the motors we researched on. Comparing the torque vs speed of the stepper and servo motors, as the graph in Figure 3.6.1 shows, at lower speed the stepper motor shows higher torque, meanwhile the servo motor shows lower and more constant torque than stepper. Stepper motors often encounter limitations in high-speed applications due to insufficient torque, leading to a potential loss of position. [54] But, for our design purposes we did not need high speed as that could detriment our design if we were to use high speed (>2,000 rpm). On the downside if we had chosen a stepper motor, we would have had to incorporate drivers, as they would have helped us get precise movement of the lenses using a written code to operate it. This could have impacted our design as that would have meant additional overall costs.

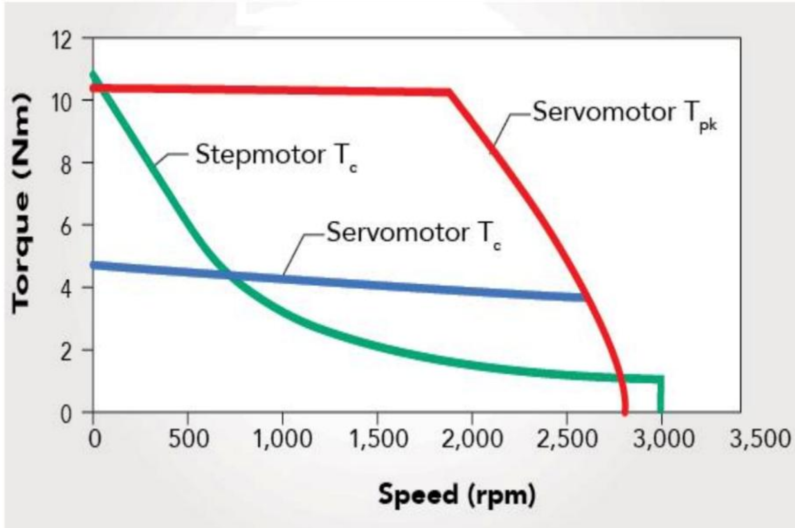

Figure 3.6.1 Torque vs Speed of Stepper Motor and Servo Motor

3.6.2 Servo Motor

A servo motor is a specialized motor that provides precise control of angular position, velocity, and acceleration. Servo motors can be categorized by: AC servo motors or DC servo Motors. The AC servo operates on alternating current and is used in industrial applications. While DC operates with direct current and is used in smaller applications. This type of motor can be more energy-efficient in some cases, and they provide smooth motion with reduced vibration and noise.

When performance is a priority, servo motors demonstrate superior capabilities [54] compared to stepper motors. Our next factor to take into consideration is the cost of the motor, it is commonly known that servo motors can be more expensive than steppers as they have more complex features. However, the critical metric for our design is positional accuracy. Servo motors utilize closed-loop control, incorporating feedback to maintain precise positioning without additional components. [54] We took into consideration that if we wanted this feature in our servo motor it would cost significantly more. As our design required input from a sensor for position instructions, having a servo motor that can connect to an MCU was more beneficial than any of the other motors. Another feature of the servo motor is it can rotate in both directions, forward and backwards.

3.6.2.1 MG90S

The MG90S servo is an analog micro servo with metal gears. It operates at a range of 4.8V-6.0V. Its control signal is a PWM (Pulse Width Modulation) which is capable of being programmed by any PWM capable pin in an MCU. It has a 3-pin connector, a ground pin, voltage pin, and signal pin. It’s commonly applied to small robotics, and lightweight mechanisms. An advantage of this motor is there is a 360 rotational motor in the market, beneficial for our design.

3.6.3 Motor Selection

Taking into consideration the research found on stepper motors and servo motors, we decided on the servo motor for our design. Considering we required three motors we chose to focus on low-cost and light weight servo motors. Since we were selecting a servo motor, we consider a few options before we made a decision.

3.6.3.1 NEMA 17 Stepper Motor with Lead Screw

The NEMA 17 is a stepper motor that works in an open loop system and is generally used in robotics and 3D printing. The NEMA 17 was a good option based on our design criteria, because it typically has a 1.8° per step. Considering we required movement of small increments for our lenses this motor was a great option. NEMA 17 would have required us to add a driver to our design, some compatible drivers are the A4988 and the DRV8825. On the downside the NEMA 17 has a load capacity of around eleven pounds.

3.6.3.2 NEMA 23 Stepper motor with Lead Screw

The NEMA 23 is a stepper motor that compared with the NEMA 17 it foreshows much higher load capacity and higher torque. This comes at a price, since this motor is a lot more expensive than the NEMA 17. It has a lead screw pitch of 4mm that leads to it having a higher torque. This motor also would have required a driver to be programmable. A couple examples of compatible drivers are the DM542 and the DRV8711.

3.6.3.3 Lead Screw Actuator

An actuator is a type of linear movement system that consists of a stepper motor and other components to function. It has a lower step size angle than the other two motors. On the other hand, it has a load capacity of 3.3lb, much less than the other motors. Its greatest setback is the general cost for a lead screw actuator, ranging in the pricier side.

3.6.3.4 NEMA 8 Stepper Motor with Lead Screw

The NEMA 8 is a stepper motor of relatively small size compared to other NEMA stepper motors. It is a bipolar stepper motor that, considering its small size, can hold a torque of 5 oz-in to 10 oz-in. This motor is ideal for applications where there is limitation on space, and excellent where small precise movement is required. Meanwhile it does not offer such high torque as other stepper motors can and is not the best option in fast speed application as the torque tends to be lower when speed is higher.

3.6.3.5 Stepper and Servo Motors Comparison and Selection

In Table 3.6.1 we are comparing the stepper motors we had done further research into. To pick a motor we took into consideration all our requirements and looked at what features work best for our design. We were focusing on what motor we could program to move precisely, at a reasonable speed in a linear motion, its weight and the cost of the motor. Based on the research results we selected the MG90S servo motor as our designated motor.

Parameters	**NEMA 17 Stepper Motor**	**NEMA 8 Stepper Motor**	**MG90S Servo Motor**	**MG996R**
Type	Bipolar	Bipolar	Bipolar, 360 Degrees Rotation	Integrated System
Step Angle	1.8 ° (200 steps/rev)	1.8 ° (200 steps/rev)	Increments of 1° to 2°	0.9 ° (400 steps/rev)
Lead Screw Pitch	2 mm	0.5 - 2 mm	N/A	5 mm
Cost	$15-$30	$30-$60	$3-$7	$50-$100
Load Capacity	5 kg	2-10 kg	1.8kg*cm	1.5 kg
Compatible Driver	A4988 DRV8825	DRV8834 DRV8825 A4988	Comes in the design	Comes in the design
Motors Dimensions	Width: 43.2 mm Height: 43.2 mm	Width: 20 mm Height: 20 mm	Width: 22.8mm Height: 12.2mm	Width: 38-76 mm Height: 51-152 mm
Weight	280g- 450g	100g-150g	13.4g	55g

Table 3.6.1 Stepper and Servo Motor Comparison Table

3.7 Logic Devices

With our system needing machine capabilities for capturing photos, monitoring different sensors, controlling motor movement, and image analysis, a programmable logic device was necessary. In terms of our required needs, we believed the devices to consider were a Field Programmable Gate Array (FPGA) or a Microcontroller Unit (MCU).

3.7.1 Field Programmable Gate Array (FPGA)

A Field Programmable Gate Array (FPGA) is a high-powered configurable logic device that allows for customizable hardware architecture. Breaking down its capabilities, as stated before an FPGA enables users to create custom circuits and modify them as needed unlike the MCU. This is because the building block, logic cells aka logic blocks, all operate independently from one another which allows for them to be reconfigured as needed. Because of this ability, FPGAs are highly capable of parallel processing and ideal for tasks that have excessive amounts of data like video processing or real-time tasks. It is also faster than the average processing speed as it can offload heavy computations from a CPU by completing them directly in the hardware. But this does call for much higher power consumption and in low-power or compact power systems, this could have been a problem.

This customization is both the FPGA's greatest strength and weakness as it must be programmed specifically before use with a hardware description language (HDL) like Verilog or VHDL. This requires specific knowledge of programming in these languages as there is a larger learning curve and debugging is much more difficult. They are not as user friendly as the higher-level languages such as C/C++ that you would code for an MCU. It also does not have a non-volatile memory so it cannot hold a programmed code once it has been turned off. It needs to be reconfigured every time it turns on. [55]

3.7.2 Microcontroller Unit (MCU)

A Microcontroller Unit (MCU) is a small integrated circuit that can function like a computer. On the board there is a processor core (CPU), memory, and typically various peripherals. The CPU is the main part of the board responsible for conducting and executing instructions given through code in memory. There is quite a broad range of several types of cores which affect the performance, speed, and power efficiency of the MCU. The memory is built in and consists of flash memory which stores the program code even after the MCU is powered off, a random access memory (RAM) which temporarily stores variables and data when executing the program, and electrically erasable programmable read-only memory (EEPROM) which stores small data bits that is retained through power cycles such as configuration settings. There are various peripheral and input/output capabilities. A MCU typically has multiple GPIO pins for interface with external parts/technologies like buttons, sensors, motors, LEDs, etc. It has analog-to-digital converters (ADC) and vice versa (DAC) as well as communication interfaces such as UART, I2C, SPI, and built-in timers.

A MCU is overall a much more user-friendly choice. It can have built-in support for coding and debugging as it can connect to interfaces such as JTAG or SWD which allows you to analyze the system as the code runs. They are widely supported in different common IDEs and there are so many prebuilt software libraries with common tasks which make developing a program much easier. It also supports real-time operations and can be more low power usage friendly as it supports multiple different low power modes and is more suitable for wearable/wireless and more portable designs. [56]

Though on the other hand, in comparison to a FPGA, the fixed architecture on MCUs restricts the overall capabilities and personalization available. They have more limited resources when it comes to processing power and memory which makes high-speed data processing or real-time processes a challenge. This calls for more careful optimization and system design. Table 3.7.1 below provides direct simplified comparisons between the two options.

Criteria Factors	**MCU**	**FPGA**
More budget friendly option	✓	
Lower power consumption	✓	
Higher real-time performance		✓
Uses high-level programming languages	✓	
Suitable for simple control tasks	✓	✓
Suitable for complex tasks		✓
Fast development time	✓	
Suitable for parallel processing		✓
Flexible and/or custom hardware design		✓
Real-time performance		✓
Peripheral add-on capabilities	✓	

Table 3.7.1 MCU vs. FPGA Comparison Table

Overall, the best choice for our project given the comparison above was the MCU. Although the FPGA would have given us much more processing power and the ability to multitask more efficiently. The added limitation of only being able to code in custom hardware logic typically specific languages such as VHDL or Verilog and the fact that we needed multiple connectors for a camera, motors, and different sensors, the MCU overall covered our general requirements. Additionally, even though we would have had more computing power with the FPGA we still have more than enough with the MCU.

3.7.3 Microcontroller Boards

When it came to selecting an MCU board there were many components to consider and factor in when choosing the best fit. In general, for our specific project, we needed to look at processing power, camera interface, number of I/O ports, memory size, and power consumption. We researched several boards.

3.7.3.1 Raspberry Pi 4

The Raspberry Pi 4 was a potential option due to its impressive high processing power, capable of handling the complex task of image processing efficiently. It also has versatile connectivity options, including a dedicated CSI camera interface, plenty of CPIO pins to accommodate several peripherals, USB 3.0 ports, up to 8GB of RAM configurations, and built-in Wi-Fi/Bluetooth. It definitely is more on the expensive side in comparison to simpler microcontroller boards that might not have some components like the Wi-Fi and Bluetooth options. These might be unnecessary, and we could have saved money with a simpler board. The higher processing power also meant that this board was less ideal for portable, battery-powered applications like our wearable glasses as battery life was shortened as a result. It also lacks real-time processing capabilities which left room for potential problems in the design process. Timing was also hindered by its reliance on a full Linux OS which resulted in longer boot times. [57]

3.7.3.2 Espressif ESP32-S3

The ESP32 is focused on low-power applications and is more battery-powered/wearable friendly. This is because it has many battery-extending power modes. But in comparison, it definitely has much more limited processing power in comparison to the other types of MCUs such as the Raspberry Pi 4 which was a potential dealbreaker since we are dealing with image processing which often requires high computational power. It offers the Wi-Fi/Bluetooth connectivity option and real-time performance for time sensitive applications as well as a built-in analog-to-digital converter which makes it easier to work with analog sensors without adding additional hardware. The ESP32 is much more of a budget-friendly option and its smaller size works better with our more compact design build for the glasses. But the biggest tradeoff is its smaller memory, averaging around 512KB SRAM and 16MB external PSRAM, and less camera interface support. [58]

3.7.3.3 Seeeduino Lotus

The Seeeduino Lotus is a potential Arduino-compatible board that's biggest strength is its compact size and easy integration with a sensor that we could have utilized for this project. This could have sped up prototyping, especially with the large libraries available within the Arduino ecosystem. Along with this, the board is extremely inexpensive overall and still offers both digital and analog I/O pins and USB integration. Its biggest drawbacks come with the cost of low memory, offering only 2KB of SRAM and 32KB flash memory, and very limited processing power. This board has the lowest processing power of the previous boards we had looked at; it is not very suitable for more power-heavy tasks like image processing, which is a huge component of our project. It also lacks a camera interface which means it would have been difficult to incorporate capturing and processing images. [59]

3.7.3.4 Raspberry Pi 5

The Raspberry Pi 5 is the newest released version of the Raspberry Pi boards. It is a large step up from the Raspberry Pi 4 in terms of processing power along with slight improvements in its overall capabilities. It now is equipped with a Quad-core ARM cortex-A76 CPU running at 2.4 GHz in comparison to the 1.5GHZ on the Raspberry Pi 4. It has roughly similar options for memory and graphics with slight improvements to offer faster and more efficient video support. It now offers faster 4-8GB LPDDR4X-4267 RAM and the new VideoCore VII GPU that supports dual 4k displays at 60 frames per second an improvement from the Raspberry Pi 4's 30 frames a second. It offers the same connectivity to ethernet and Bluetooth with slight increases in range and faster speeds. It does come with dual camera/display connectors allowing for multiple camera connections instead of a single one which could have been quite useful for this project if we had decided to utilize more than one display/camera. A drawback for this board is its much larger requirement for power, going from a 15-watt requirement to a 27-watt requirement. This increase in the level of power also calls for a more complex cooling system. Given the need for the project to be light and compact, this could have brought accessibility issues. But overall, the biggest concern with this board was its pricing. It is much more expensive than the other boards listed here and its additional need for cooling and power could have caused some avoidable additional expenses. The Raspberry Pi 5 is a very heavy-processing board with overall very efficient and vast capabilities. In comparison to Raspberry Pi 4, it is the better board, but it was not necessarily the best board for this project given price and power requirements. [60]

3.7.3.5 Raspberry Pi Pico

The Raspberry Pi Pico is another version of a Raspberry Pi board that is designed for embedded systems and IoT applications. It has a dual-core ARM Cortex-M0+ processor capable of running up to 133 MHz. Its build makes it good for handling a multitude of real-time tasks and its small size makes it super convenient for portable devices. It has 264KB of SRAM and 2MB of flash memory along with twenty-six multi-functional GPIO pins, three of which are analog inputs. It features many connectivity options with its 2 SPI, 2 I2C, 2 UART interfaces and it supports programmable input/outputs which showcases its wide flexibility. It can operate on fairly low power between 1.8-5.5V and has added features like LEDs, temperature sensors, and a 12-bit ADC for analog conversions to digital. It benefited us in terms of power the most since it operates with specific sleep modes which could have helped us maximize the battery life. Although Pico does not support the most complex image processing, it does have enough power to do simple image processing quite efficiently. The main concern was that it wouldn't have enough processing power for our project. [61]

3.7.3.6 Microcontroller Boards Comparison and Selection

The features of these microcontroller board options are meticulously compared below in Table 3.7.2.

Features	**Raspberry Pi 4**	**ESP32-S3**	**Seeeduino Lotus**	**Raspberry Pi 5**	**Raspberry Pi Pico**	**ESP32-WROOM 32D**
Processor	Quad-core Cortex-A72 64-bit SoC, up to 1.5GHz and VideoCore VI	Dual-core Xtensa LX7, up to 240 MHz	ATmega328P, 8-bit AVR running at 16 MHz	Quad-core Cortex-A76 64-bit SoC, up to 2.4 GHz and VideoCore VII	Dual-core Arm Cortex-M0+ processor, up to 133 MHz	Xtensa dual-core 32-bit LX6 microprocessor, up to 240MHz
Memory	Option of 2GB, 4GB, 8GB LPDDR4-3200 SDRAM	512KB SRAM, 384KB ROM, 16MB of flash	32KB flash, 2KB SRAM, 1KB EEPROM	4GB and 8GB LPDDR4X	264kB on-chip SRAM, 2 MB flash, external memory support	520 KB SRAM, 448 KB ROM, 4 MB flash memory
Connectivity	2 USB 3.0 ports, 2 USB 2.0 ports, 1 micro-HDMI ports, 2.5mm audio jack and HDMI	USB 1.1 with OTG, SPI/I2C/I2S/UART/CAN interface support, camera	Micro USBs, support UART, I2C, and SPI	2 USB 3.0 ports, 2 USB 2.0 ports, 1 micro-HDMI ports, 2.5mm audio jack and HDMI audio output, 2-	USB 1.1 micro-USB, 26 multi-function GPIO pins, 3 analog inputs, support I2C, SPI, and UART	USB 1.1, support UART, I2C, and SPI

	audio output, 2-lane MIPI CSI, 2-lane MIPI DSI, 40-pin GPIO header	interface support		lane MIPI CSI, 2-lane MIPI DSI, 40-pin GPIO header		
Network	Gigabit Ethernet, 2.4GHz and 5.0GHz IEEE Wi-Fi, Bluetooth 5.0, BLE and mesh support	2.4 GHz IEEE Wi-fi, Bluetooth 5.0, BLE and mesh support	No wireless capability (can be added externally)	2.5 Gigabit Ethernet, 2.4GHz and 5.0 GHz Wi-fi, Bluetooth 5.0 and BLE support	No wireless capability (can be added externally)	2.4 GHz IEEE Wi-fi, Bluetooth 5.0, BLE and mesh support
Peripherals	MicroSD Slot, USB-C, 5V/3A DC input	45 GPIOs, 14-bit ADC up to 20 channels, 2 DAC channels, 22 timers, 14 touch sensing GPIOs	12 grove connectors, 14 digital pins, 6 analog inputs, 6 PWM outputs, USB power supply	MicroSD slow, PCle 2.0 interface, USB-C	16 PWM channels, USB power supply, SWD interface	34 GPIO's, ADC, DAC, UART, SPI, I2C, PWM, I2S.
Dimensions	85.6 mm x 56.5 mm	15 mm x 25.5 mm	68 mm x 53 mm	85.6mm x 56.6 mm	21 mm x 51 mm	18mmx25.5mmx3.1mm
Price	2GB–$35-45, 4GB–$55-65, 8GB –$75-85	4MB-$3-6 8MB-$5-10	$12-15	4GB-$60-70 8GB-$80-90	$4-6	$3-$6

Table 3.7.2 MCU Board Comparison Table

The Raspberry Pi 4 was ultimately chosen as one of our MCU board due to its balance of processing power and versatility with peripherals. It already has a Bluetooth module and its compatibility with our chosen camera module was also a large deciding factor. The ESP32 was chosen for our main PCB because of its compatibility with Arduino, enabling easy programming of the various peripheral systems that we used, and its low power consumption.

3.8 Programming Languages

When it came to selecting a programming language, there were many factors that we had to take into consideration, like our system needs as well as compatibility with our MCU board. We had to look at our projects' real-time needs, hardware access requirements, development timeline, and just overall complexity of the system to determine which language had a good balance of strengths and trade-offs. We compared the popular languages Python, C++, Java, C, and assembly language.

3.8.1 Python

Python is a high-level programming language that is well-suited for diverse applications due to its fast development, ease of learning, and extensive pre-existing library support. It is utilized in fields such as web development, data science, embedded systems, and is popular in prototyping and iterative development. It has a broad ecosystem that is compatible with the Raspberry Pi series MCUs.

The biggest pro is Python's large community support and compatibility with image-processing libraries like OpenCV which we will be using for the tasks of edge detection and color analysis. Additionally, Python also has supportive libraries, RPi.GPIO and pigpio which can be used to control GPIO pins on the Raspberry Pi. The only drawback was that this programming language is definitely slower in execution than more popular languages such as C++ and C. This can limit how efficient our image processing or real-time our motor control ends up being. Overall, Python was a solid choice given how easy it is to develop and integrate with hardware components but its lower performance in processing speed would have required a balance. [62]

3.8.2 C++

C++ is a high-performance programming language that is popular in systems where speed and resource efficiency are a top priority. It is known for its object-oriented structure and hardware capabilities. It lets programmers interact directly with hardware and works with libraries like OpenCV and pigpio for image processing and pin manipulation.

One benefit of C++ is that it is compiled directly to machine code which not only allows for a faster execution time, but it uses much less memory. Since we are working with image processing, saving power and memory usage were both big advantages. C++ also has fine-grained memory management capabilities which also helps with execution efficiency. For our project, we required our motor adjustments and analysis of the CMOS sensor to be as real-time as possible to be more accurate. On the other end, C++ code is not as compact and easy to develop as programming languages like Python. It has a larger complexity and with it a bigger learning curve when it comes to development. The tradeoff in our decision was between efficiency versus complexity. [63]

3.8.3 Java

Java is an object-oriented programming language known for its portability, security features, and strong library support. Code can run across many different platforms without much effort with the Java Virtual Machine (JVM) which makes it very suitable for a system that needs to work with so many different parts and sensors. Java’s large library has strong support for network communication, file handling, and graphical user interfaces.

Benefits of using Java include its garbage collection feature which helps to make memory management easier and reduce memory leaks. Similar to C++ and Python, Java also supports OpenCV and pin handling libraries to access GPIO pins. On the other hand, Java is not as fast as C++ or C due to its JVM, so it also struggles in more real-time necessary tasks. It is also much more consuming in memory in comparison to other programming languages. Overall, it was a strong choice considering ease of development and system stability were top priorities. [64]

3.8.4 C

C is a popular, low-level programming language that provides direct access to hardware and system resources. It is well-known for its code simplicity and efficiency which makes it ideal in performance-critical embedded systems. C is able to work closely with hardware which allows for more detailed control over memory and processing. This helps with real-time control tasks due to its extensive support for low-level operations.

Some advantages of C include its execution speed, which is faster than both Python and Java. This is due to C compiling directly to machine code. C also has access to large libraries like WiringPi and pigpio that helps with interfacing with hardware. The biggest drawback being its memory management as it does not have any sort of automatic features like garbage collection which makes it at higher risk for memory leaks, buffer overflows, or any sort of memory error. It also is not as abstract as other programs which means it requires more code to create more complex functionality. Overall, C was a strong choice with its easier hardware access and high performance but the code complexity was a major drawback. [65]

3.8.4 Assembly Language

Assembly language is a low-level programming language that allows direct control over hardware by mapping close to the processor's instruction set. This makes it super-efficient in terms of performance-critical applications and allows it to be highly optimized since programmers have "fine-grained" control over the CPU.

The biggest advantage is its efficiency/speed since the code can be executed significantly faster than other higher-level languages. This makes it ideal for real-time applications. On the other hand, it lacks any real portability and has a steep learning curve. Assembly code is always specific to whatever microcontroller or processor we use which means it has to be rewritten for different hardware. This adds on a lot of development time to code. [66]

3.8.5 Programming Languages Comparison

Table 3.8.1 lists and compares all the programming languages that were considered for our system.

Features	**Python**	**C++**	**Java**	**C**	**Assembly Language**
Abstraction Level	High	Medium	High	Low	Very Low
Performance	Moderate, interpreted slower for real-time applications	High, compiled, allows direct memory management	Moderate, JVM-based, slower than C/C++ for embedded uses	High, compiled, very efficient for embedded systems	Very high, directly mapped to hardware instructions
Ease of Use	Very easy	Moderate	Moderate	Moderate	Difficult
Memory Management	Automatic garbage collection	Manual Control	Automatic garbage collection	Manual Control	Direct control
Real-Time Capabilities	Low, lacks real-time processing	High, supports real-time and deterministic applications	Low, not ideal due to JVM overhead	High	Very High
Hardware Access	Limited	Good	Limited	Very Good	Excellent

Error Handling	High-level exceptions and try-except blocks	Strong exception handling, low -level debugging issues are complex	High-level exception handling	Limited to basic error codes	Minimal, no built-in error handling
Development Speed	Fast	Moderate	Moderate	Fast, for low-level tasks	Slow
Libraries of Support	Extensive data processing, limited with hardware control	Extensive for both high- and low-level embedded libraries	Extensively for only high-level applications	Extensive for low-level and embedded devices	Very limited
Examples of Boards	ESP32, Raspberry Pi	ESP32, Raspberry Pi, Arduino	Limited, typically Raspberry Pi	Most microcontrollers, ESP32, STM32, Arduino	Any board that has assembly-compatible architecture

Table 3.8.1 Programming Languages Comparison Table

Python was chosen as our final programming language due to its vast libraries that we will be using such as the OpenCV and NumPy for both image processing and Sobel filter calculations. The ESP32 was used as well as an Arduino IDE which uses C primarily.

3.9 Integrated Development Environment (IDE)

An integrated development environment or IDE is a software application that provides several tools to aid in programming and software development. It typically consists of some sort of code editor, compiler/interpreter, debugger, and other automatic tools to help develop, test, and debug code. It is important to consider many things when picking an IDE. You want to pick the best option to maximize ease of programming and development time. Key factors to look into are the programming languages it supports, available debugging tools, capabilities with integration of hardware, additional add ins via plugins, and an overall IDE that matches the project requirements. We looked at several IDEs below to select one.

3.9.1 Visual Studio Code (VS Code)

Visual Studio Code or VS Code is an open-source code editor created by Microsoft that is used in many fields like web development, data science, and embedded systems programming. It supports multiple programming languages and gas extra features like syntax highlighting, code autocompletion, debugging, and Git integration for GitHub. It is extremely customizable with tons of extensions to add in specific languages, tools, and frameworks so it can adapt to whatever the project needs. It runs on Windows, macOS, and Linus and in terms of embedded development, VS Code's best extensions are PlatformIO, Arduino, and ESP-IDF which adds in special capabilities to interact with microcontroller boards like the ESP32, STM32, and Raspberry Pi Pico. [67]

3.9.2 Thonny IDE

Thonny IDE is a beginner-friendly integrated development environment designed specifically for Python. It has a simple designed interface that enables a step-through debugging where it shows each line being executed which helps with understanding the code flow. It also supports features like variable value tracking which makes it easy to track data changes. It is very practical for microcontroller projects, especially with boards using MicroPython like the Raspberry Pi Pico or ESP32. It has built in support for MicroPython allowing for direct upload of code onto the board and the IDE also includes a built-in Python REPL (Read-Eval-Print Loop) which allows for interactive coding and debugging. It also allows for package management with adding libraries, so it is extremely useful in projects that need additional outside functionality. The biggest downside it doesn't offer much in terms of advanced features like other IDEs it focused on embedded support and beginner-friendly simplicity. [68]

3.9.3 JetBrains PyCharm/CLion

PyCharm and CLion are specialized integrated development environments designed by JetBrains, each focused on specific programs with PyCharm for python development and CLion for C and C++. Both IDEs offer tools to help streamline code, debugging, and testing which makes them good for projects focused on efficiency or code reliability.

In terms of PyCharm, the IDE offers an extensive amount of Python support including things like intelligent code assistance, refactoring tools, a built-in debugger, and support for popular data science and machine learning libraries like NumPy and Tensor Flow. It has virtual environment support and package managers like pip to help regulate the dependencies, which makes it a good choice for projects with heavy data-application or ones needing a lot of flexibility.

On the other hand, CLion is focused on C and C++ and comes with advanced code analysis, a debugger, and cross-platform support for Windows and Linux. It is super useful in embedded development and system-level programming as it integrates easily with version control systems, testing frameworks, and build systems like CMake.

Since they are by JetBrains, both PyCharm and CLion also have addition JetBrain plugins that make it possible to add embedded toolchain support or even specific microcontroller workflows. The only real negative with these two is the IDEs are quite difficult in comparison to more user friendly ones. [69]

3.9.5 Jupyter Notebooks

Jupyter Notebook is an open-source, web-based interactive computing environment that is used in data science, machine learning, and scientific research. It supports a variety of programming languages although the most common is Python. The user-interface allows code to be run in small blocks or cells rather than the entire code which helps with debugging. The IDE’s biggest strength is its visualization capabilities. It integrates with libraries such as Matplotlib, Seaborn, and Plotly which generate and display visual data directly within the notebook. On the other hand, it has a lot of limitations on more complex projects. The cell-based structure means it could lose data or run into errors if run in the wrong order and it also is not meant to run directly with embedded systems. There would need to be additional tools or frameworks to connect Jupyter Notebook code to the microcontroller unit we are using. Overall, it is very strong in terms of analyzing data from our sensors like the camera to help with color detection tasks but not the most convenient when working with hardware boards. [70]

3.9.6 MATLAB

MATLAB or Matrix Laboratory is a high-level programming environment and language meant for numerical computing, data analysis, and algorithm development. It is widely used in engineering, scientific research, and academic fields due to its strength in mathematical computations. It has a diverse range of different libraries with build in functions for things like signal processing, image analysis, machine learning, and control system designs. Its very user friendly with its own editor, debugging tools, visualization capabilities. MATLAB even has specialized toolkits for things like image processing which simplifies the analysis of images pixel by pixel which would be beneficial in simplifying our system code. The only drawback is MATLAB’s licensing costs can be quite expensive for users. It is also very computationally heavy so the code may need quite a bit of optimization to be able to run on a MCU. [71]

3.9.7 Arduino IDE

Compatible with our ESP32 is a software used to write, compile, and upload code to Arduino and other microcontrollers. It supports a simplified version of C/C++ programming, making it accessible for beginners. The IDE includes a text editor for writing code, a message area for errors, a console, and a toolbar with buttons for common tasks such as uploading and verifying code. It features a serial monitor which allows users to communicate with their board and view sensor data or debug messages in real time. It supports a wide variety of libraries and hardware boards, making this flexible for electronics projects.

3.9.8 IDE Comparison and Selection

A comprehensive comparison between the various IDE options can be seen in Table 3.9.1.

Features	**Visual Studio Code**	**Thonny IDE**	**JetBrains PyCharm/ CLion**	**Jupyter Notebook**	**MATLAB**	**Arduino IDE**
Primary Use	General code editor with large language support	Beginner Python IDE	Python or C/ C++ development	Data science, interactive computing	Numerical computing, simulation, and algorithm development	Writing, compiling, and uploading code to Arduino and other microcontrollers.
Supported Languages	Most languages (Python, C/ C++, Java, etc.)	Python	Python or C/ C++	Python and others via extensions	MATLAB	C/C++, MicroPython, Lua, JavaScript and more.
Ease-of-use	Medium – requires setup for extensions	High – intuitive user interface made for beginners	Medium – some advanced features that have high learning curve	High – data analysis Medium – general programming	Medium – needs familiarity with MATLAB syntax	Very user-friendly.
Hardware support	Yes, with extensions	Limited, only Python libraries	PyCharm: limited, CLion: Strong support	Limited	Strong hardware toolboxes	Strong hardware support
Debugging Tools	Advanced debugging	Basic Python debugging	Advanced debugging	Limited	Integrated debugger and simulation tools	Basic serial monitor and plotter.

Visualization	Moderate	Minimal	Moderate	Excellent	Excellent	Excellent
Cost	Free	Free	Paid	Free	Paid (expensive)	Free
Embedded System	Strong	Limited	PyCharm: limited, CLion: strong	Limited	Strong	Strong
Learning Curve	Moderate	Low	Moderate-to-High	Low	Moderate	Low

Table 3.9.1 Integrated Development Environment Comparison Table

Due to its vast collections of extensions which make integration of different codes and libraries much easier to manage, Visual Studio Code was our selected integrated development environment to code the Raspberry Pi 4. Meanwhile our ESP32 was coded using the Arduino IDE software because of its hardware support capabilities and ease-of-use.

3.10 Communication Protocols

Communication protocols are standardized rules and conventions that allow devices to exchange or communicate information. The focus being on how data is transmitted, received, and then processed to ensure compatibility and understanding between devices with different hardware or software components. These protocols can be split into two main large categories: wired and wireless. This is just dependent on what medium the data is being transmitted either through a physical connection or non-physical connection.

3.10.1 Wired Communication Protocols

Wired communication protocols consist of communication via a wire medium. Wired communication is known to be more secure than wireless as it requires physical connection between devices. The most well-known transmission mediums are coaxial cable, wired pair and optical fiber. This type of communication is widely used in electronics and can have different protocols. For our research we focused on three main wired communication protocols: I2C, UART and SPI. [72]

3.10.1.1 Inter-integrated circuit Protocol (I2C)

I2C is a synchronous serial communication method that supports multiple master and slave devices over a single-ended packet-switched serial bus. The system consists of several master and slave devices connected via this bus. [72] An analogy to better understand the relationship between a master and slave device is a school. The teachers are considered the master devices where they determine the flow of communication, requests for homework (data). While the students can be considered the slaves, as they follow the teacher's instructions, and turn in homework (data) as requested by the teacher. Communication is managed through a 20-bit frame structure, which includes a start bit, 7-bit address, a read/write bit, an acknowledgment bit, 8-bit data, another acknowledgment bit, and a stop bit. The master device generates the clock signal on the SCL line and initiates communication, meanwhile the slave responds with an ACK when the master is requesting a read or write. The slave is responsible for sending the data the master requested. I2C is of simple implementation and only requires two communication lines. However it has its limitations as it only allows 112 addresses on the bus, there is a limit amount of master and slave devices. [72]

3.10.1.2 Universal Asynchronous Receiver Transmitter (UART)

The UART protocol is a serial communication method that enables synchronous transmission in a wired medium. It incorporates a baud rate generator, a transmitter, and a receiver in its design. It typically uses two communication channels in full-duplex mode: one for transmission and the other for reception. This protocol is an overall simple as it only allows communication between two devices. This can be seen as a limitation as it only allows a point-to-point communication and both devices must agree on the communication speed beforehand, otherwise errors can occur. This protocol is commonly used in IoT platforms or Raspberry-Pi for supporting the Bluetooth features. [72]

3.10.1.3 Serial Peripheral Interface (SPI)

The Serial Peripheral Interface is a bus protocol that can support a full-duplex and a half-duplex communication mode. It incorporates a baud rate generator, a master device and slave devices. [72] Each device includes four data lines: the Serial Clock Line, Master Input Slave Output, Master Output Salve Input and a low-level active Slave Select. [72] SPI is known for having higher speed data transfer compared to UART and I2C, as it allows straightforward communication by having every slave device connected to its own SS pin. It does not require too many hardware components as it works with a four-wire system. This is applied commonly to short-distance communication therefore that is a limitation to look at. It can encounter other limitations; this protocol requires connections for every new device therefore it can run out of connections. SPI is not commonly applied to multi-master configurations as it can only allow a single master device. [73]

3.10.1.4 Wired Communication Comparison and Selection

When it comes to our design, we considered all the features from Table 3.10.1 to find the best fit for our requirements. To communicate between our main PCB and all the electrical components to our MCU. Based on it we incorporated I2C protocols as they give the better coverage considering the placement of most of our electronic components. We selected the UART connection for communication between the ESP32 and the Raspberry Pi 4.

Features	I2C	UART	SPI
Duplex Mode	Half Duplex	Full Duplex	Full Duplex
Maximum Number of Nodes	112	2	8
Maximum Coverage	≤ 25 m	≤ 50 cm	≤ 50 cm
Rate	100 Kbps - 3.4 Mbps	230 Kbps – 460 Kbps	10 Mbps
Topology	Bus (Various Masters-Various Slaves)	Point to Point	Bus (One Master-Various Slaves)
Power Consumption	Low	Low	Higher than I2C

Table 3.10.1 Wired Communication Comparison Table

3.10.2 Wireless Communication

Wireless communication protocols are standardized rules and formats what allow data transmission without physical cables. They are separated into types based on their range, data rate, power consumption, and overall use. The most common types are short-range wireless, local area wireless, wide area wireless, personal area network (PAN), and mesh network protocols, etc. For our specific system, we really only needed to use short-range wireless protocols meant for local devices so we will look at Wi-Fi, Bluetooth, Zigbee, and Infrared. [74]

3.10.2.1 Wi-Fi

Wi-Fi is a widely used wireless communication protocol that offers high-speed internet and LAN capabilities. This protocol allows multiple devices to connect to the internet, as well as share data within a local network. Devices like phones, laptops, any sort of smart device, or IoT devices utilize Wi-Fi constantly to do things like browse the web and stream from shared sources. Wi-Fi operates within the range of 2.4GHz to 5GHz and newer models such as Wi-Fi 6E working at 6GHz. It has a decent local range typically around 100 to 300 feet, but it can vary depending on if there is any interference in the environment. Data rates also vary a lot depending on the which standard is being used. Older versions like Wi-Fi 4 offer speeds up to 600 Mbps, while Wi-Fi 5 can offer speeds up to 1Gbps, and Wi-Fi 6 can go up to 9.6 Gbps. In terms of power consumption, Wi-Fi is definitely more power-intensive than most other lower-power protocols like Bluetooth, but it does typically come with power-reducing features if lower power usage is needed. [75]

3.10.2.2 Bluetooth

Bluetooth is a wireless communications protocol designed for short-range, low-powered connectivity between local devices. Typically, it is found in personal area networks (PAN) for devices like smartphones, laptops, wireless earbuds or headphones, and speakers to communicate with each other. Bluetooth operates around a 2.4 GHz frequency and has a range of about 30 to 300 feet. Data rates like Wi-Fi vary quite drastically depending on the version classic Bluetooth can go up to 3 Mbps while newer versions support a max rate of around 2 Mbps. The biggest advantage of Bluetooth is how low its power consumption is, which can have devices that have extremely long battery life with minimal battery power. This is what makes Bluetooth a common choice for IoT applications. Its biggest drawbacks are its limited range and vulnerability to interference. [74]

3.10.2.3 Zigbee

Zigbee is a wireless communications protocol designed specifically for low power, low data rate applications typically used in home automation, industrial controls, and other IoT systems. It is ideal for use in creating a mesh network which each device sends data through other devices to achieve a broad range of communication. Its ability to support multiple devices in a network makes it a great choice for large-scale IoT systems. It operates on a 2.4 GHz frequency band and a range of around 10 to 100 feet. It does have a low data rate with a max of only around 250 kbps which can be used to send small data packets like sensor readings, control commands, and status updates. It’s not a good choice for high-bandwidth applications due to their limited range but it is ideal for devices that need to operate for years without frequent battery changes like smoke detectors, doors locks, or motion sensors. [74]

3.10.2.4 Infrared

Infrared (IR) communication is a wireless communication protocol that uses infrared light waves to transmit data between devices. It enables a simple one-way transmission over short ranges like remote controls for TVs and also is used in data transfer applications like wireless keyboards. It does require a direct line of sight between both devices which limits them to being in proximity. The range, around 5 to 10 meters, is best for indoor use. Data rates vary by device, but they are slower than both Bluetooth and Wi-Fi. It can support moderate speed data transmissions, but it is not designed to support high-bandwidth applications. One of its biggest advantages is, like Zigbee, it has quite low power consumption. It also is immune to electromagnetic interference (EMI) which allows it to be a reliable choice in environments with lots of radio frequency. [74]

3.10.2.5 Wireless Communication Comparison and Selection

Comparisons between these technologies have been laid out below in Table 3.10.2. Bluetooth was ultimately chosen as our wireless communication option for its versatility and ability to connect to personal audio devices easily.

Features	**Wi-Fi**	**Bluetooth**	**Zigbee**	**Infrared**
Typical uses	High-speed internet, streaming media, general wireless networking.	Short-range communication for devices.	Low-power IoT applications.	Remote controls, data transfer over short distance.
Range	100 to 300 meters	30 to 300 meters	10 to 100 meters	5 to 10 meters
Data Rate	11Mbps to 9.6Gbps (depending on standard Wi-Fi 4 to Wi-Fi 6E)	~up to 3 Mbps (Bluetooth classic) ~up to 2 Mbps (Bluetooth Low Energy)	~up to 250 kbps	100 – 4000 bps (depends on application)
Power Consumption	Moderate to high (depends on usage)	Low	Very low	Very low
Frequency Band	2.4 GHz, 5 GHz, and 6 GHz (Wi-Fi 6E)	2.4 GHz	2.4 GHz	850 – 950 nm
Network type	Infrastructure	Point-to-point, point-to-multipoint	Mesh networking	Point-to-point (line-of-sight)

Table 3.10.2 Wireless Communication Comparison Table

3.11 Audio Devices

As implied in the name, the primary purpose of the system is to be as assistive to the needs of the wearer as possible. We knew that it would be imperative then to ensure that the device could connect to a speaker and communicate any necessary info to the user. However, the exact nature of that connection is what we had to research. We did not want the audio to be a given piece of the headset, rather the user can connect to one of their own audio devices and receive information that way. While ideally, we could have enabled different kinds of connections, we chose to focus on the merits between auxiliary connection capabilities and Bluetooth connections.

3.11.1 Auxiliary Connection

Auxiliary connections or Aux, commonly known as headphone jacks, are wired connections that enable direct streaming of audio signals to a destination speaker. The primary benefit here is that wired speakers tend to have superior sound quality and lack the frustration that sometimes comes with needing to pair a Bluetooth device. They also tend to have lossless analog audio transfer, and wired headphones are often cheaper compared to Bluetooth ones. However, the main drawback is the physical, wired connection. Our headset is already equipped with several subsystems that interlace over the user's head, making comfort and human-friendly design an extremely important issue to us. Reducing the amount of necessary wiring makes our design less cumbersome and aesthetically more pleasing [76].

3.11.2 Bluetooth Connection

Bluetooth relies on wireless connection to stream audio to a speaker. To do this, it must compress digital audio into an analog form and then decompress it again into a digital form at the destination. This process inherently makes Bluetooth audio lossy, but not to a point that is significantly noticeable for most users. Additionally, this form of wireless connection can win out over Aux connections due to the physical degradation that occurs from repeated plugging and unplugging of the connection. Therefore, while some of these issues with Bluetooth were of concern to us, it did possess a few key advantages, including the reduction in the overall amount of wiring wrapping around the user [76].

3.11.3 Audio Connection Comparison

After careful consideration, it was ideal for us to focus on prioritizing Bluetooth connectivity over Aux. While Bluetooth devices tend to be more expensive than

Aux devices, the growing ubiquity of them in the form of products such as Apple Airpods help alleviate this concern. Additionally, the primary factor driving this decision is the amount of extra wiring it would add to the overall system. Reducing this physical component helps make the system more streamlined. Our comparison of both approaches is listed below in table 3.11.1.

	Price	Sound Quality	Ergonomics	Range
Bluetooth	Typically greater	Typically worse	More comfortable due to lack of wiring	33-foot standard
Aux	Typically lower	Typically better	Less comfortable due to wiring	Dependent on wiring

Table 3.11.1 Audio Connection Comparison Table

3.12 Batteries

Our design required batteries for the MCU and motors. We selected our Raspberry Pi with the batteries included, therefore the research was for choosing batteries that would power our motors, colorimeter, and ESP32. To choose a battery we will take into consideration factors like battery life, rechargeability and cost. We wanted a battery that would last and not require constant recharging. For batteries that accomplish these factors we researched four different types of batteries.

3.12.1 Nickel-Cadmium (NiCd)

Nickel-Cadmium batteries are known for their durability and reliability, having excellent performance in low-temperature environments. NiCd batteries can handle high discharge rates, beneficial in applications such as power tools and emergency lighting systems. Its ability to supply consistent power output for extended periods was considered and became a driving force on what battery we selected. Despite these advantages, NiCd has its downsides. A major downside is the memory effect, that can lead to a gradual loss of capacity if the batteries are not completely discharged before recharging. [77]

3.12.2 Nickel-Metal Hydride (NiMH)

Nickel-Metal Hydride batteries are of higher capacity than NiCd, these batteries are also less toxic. The NiMH battery was first introduced in the 1990s and had a purpose of solving the toxicity problem that other Nickel batteries had. They are used in applications like electronics, hybrid vehicles, and renewable energy systems. They offer a much higher capacity and less chance of experiencing memory effect when compared to the NiCd. They can also store more energy than the traditional alkaline batteries, good for high-drain devices like power tools and digital camaras. However, they offer lower voltage than lithium-based batteries. [77]

3.12.3 Lithium-Ion (Li-ion)

Lithium-ion batteries are very common in portable electronics, electric vehicles, and renewable energy systems as they have a lightweight design. Their performance is influenced by factors such as temperature, charge cycles, and battery management systems, which help optimize lifespan and safety. Despite having great advantages, this type of batteries can cause concerns about the environmental impact. [77]

3.12.4 Lithium Polymer (LiPo)

Lithium Polymer batteries are a type of rechargeable battery that uses a polymer electrolyte instead of the liquid electrolytes found in traditional lithium-ion batteries. This battery is popular in applications such as drones, smartphones, and other portable electronic devices. They come in different shapes and sizes, offering space efficiency and weight reduction in our design. On the downside LiPo can be sensitive to overcharging and physical damage so there exists concerns about safety as they require careful handling and specialized charging protocols. [77]

3.12.5 Batteries Comparison and Selection

To select our power supply, we considered the parameters of the different batteries listed in Table 3.12.1. We primarily based our selection on our specific voltage and current requirements for our electrical components. For example, our motors, ultrasonic sensor, and colorimeter that each require a certain value for current; we need to have a specific power supply for these. Meanwhile the battery to power our Raspberry Pi is included with the purchase.

Parameters	NiCd	NiMH	Li-ion	LiPo
Voltage	1.2V per cell	1.2V per cell	3.6-3.7 V	3.7 V

Cycle Life	Moderate (500-1,000)	Moderate (300-500)	Long (5000-2,000)	Moderate (300-500)
Memory Effect	Yes	Minimal	None	None
Environmental Impact	Toxic Materials	Less Toxic	More eco-friendly	Requires disposal
Applications	Power tools, RC toys	Consumer electronics	Smartphones, EVs	Drones, portable devices
Cost	Generally lower	Moderate	Moderate to high	Moderate to high
Charging Time (depending on capacity)	1-2 hours	1-4 hours	1-3 hours	1-3 hours
Durability	High (can withstand many cycles)	Moderate (wears over time)	Moderate to high	Moderate (depends on handling)

Table 3.12.1 Batteries Comparison Table

3.13 Converters

A converter refers to a device, software, or mechanism that changes something from one form to another. There are many kinds of converters but for the purpose of our product design we took a deeper look at Data and Electrical Converters. While both converters' main goal is to transform inputs to outputs, they have different systems.

3.13.1 Data Converters

Data converters transform data from one format or type to another, usually digital to analog data. For our product design purposes we took a look at one of the most common data converters: ADC.

3.13.1.1 Analog-to-Digital Converters (ADC)

ADCs are converters that take a continuous analog signal and convert it into a digital signal that can be processed by digital devices such as microcontrollers, computers, or digital signal processors. They can be categorized into three main steps in their process. The first step is sampling, an ADC samples from a continuous signal at regular intervals. The frequency of these samples can be denoted as sampling rate or sampling frequency. The second step is quantization where the ADC assigns each sample a numerical value. These values will then be encoded, the final step, into a binary format. ADC's performance depends on a couple of parameters, such as resolution and sampling rate. The resolution of an ADC is the number of bits used to represent the output digital value, the higher the resolution the more precise the signal will be represented. [78]

3.13.2 Electrical Converters

Electrical Converters are devices applied to most electronic designs, and they convert electrical energy from one form to another. Among the most common power converters: AC to DC, DC to AC, AC to AC and DC to DC. These kinds of converters are commonly applied to applications such as: Electric Vehicles, Renewable energy systems, motor control and telecommunications.

3.13.2.1 Direct Current to Direct Current Converter (DC to DC converter)

A commonly known DC-DC converter is the Buck Converter which in Table 3.13.1 we took a better look at some examples. Based on this table and research discoveries we considered them for our final design.

Parameters	LM3671	MP2338	MP2307	D24V10F3
V_{out}	1.1 – 3.3V	5V	Adjustable	3.3V
V_{in}	2.7- 5.5V	6.5-28V	4.75-23V	3.9-36V
Manufacturer	Texas Instrument	Monolithic Power Systems	Monolithic Power Systems	Pololu
Temp	-40 to 85 ° C	-40 to 125 ° C	-40 to 85 ° C	-40 to 125 ° C
Efficiency	95%	90%	92%	80-93%

Table 3.13.1 DC-DC converter comparison table

3.14 Regulators

Electrical regulators are devices used in electrical systems to control and maintain stable output parameters, like current or voltage, despite possible variations in input or external conditions. These regulators are important to ensure a proper operation of electronic devices. There are many types of regulators, but we researched voltage regulators for our design purposes.

3.14.1 Voltage Regulators

Voltage regulators are very common types of regulators that help maintain a constant output voltage regardless of any changes in input or external conditions. There are two main types of regulators: Linear Voltage Regulators and Switching Voltage Regulators.

3.14.1.1 Linear Voltage Regulators

Linear voltage regulators are electronic devices that are applied to systems to maintain a constant voltage regardless of any changes in the environment or in the input. They work by dissipating excess power as heat and regulating the voltage using an active component, like a transistor, in the linear region of operation. Their design is simple overall as it does not require too many components. They can generate very little noise when compared to other types of voltage regulators. On the downside this dissipate heat as it transforms the excess voltage to heat which means it can get quite hot. Therefore, requiring consideration in the design process. In Table 3.14.1 we took a look at some possible regulators for our design and compared them. Based on our requirements regarding regulating the voltage on our motor driver, a linear voltage regulator may not have been the better option as this type of regulator can dissipate voltage in the form of heat, which could have become a complication in our design.

Parameters	**LD1117**	**MCP1700**	**AMS1117**	**MIC293000**
V_{in}	4.5 – 15V	2.3 – 6V	4.5 – 15V	Up to 26V
V_{out}	1.25-13.8V Adjustable	Fixed Value. Typically: 3.3V	Fixed and Adjustable. Max: 5V	Fixed and Adjustable
Max Output Current	800mA	250mA	1A	3A

Type	LDO (Low-dropout)	LDO	LDO	LDO
Thermal Protection	Yes	No	Yes	Yes
Noise	Moderate	Low	Moderate	Moderate

Table 3.14.1 Linear Voltage Regulators' Comparison Table

We selected the AMS1117 to handle the 3.3V required to power our ESP32 and our Colorimeter.

3.14.1.2 Switching Regulators

A switching regulator is a type of voltage regulator that uses electronic switching to convert input to a stable, constant output voltage. In comparison with Linear Voltage Regulators, the switching regulators generate less heat. They have much higher efficiency than most linear voltage regulators, making them ideal for systems that require high-current. A downside is that it can generate EMI (Electromagnetic interference) that will generate noise in the system, therefore consider that before selecting regulators. The cost of switching regulators is commonly more than of a linear voltage regulator. There are different types of switching regulators such as: Buck, Boost, Buck-Boost and Flyback. For design purposes we will look at the options listed in Table 3.14.2.

Parameters	**LM5161**	**LMR33630**	**LM2596**
V_{in}	4.5V- 100V	5V-36V	4.5V-40V
V_{out}	Adjustable 1.225V-15V	3.3V or 5V	Adjustable: 1.25V-15V
Output Current	1A	3A	3A
Efficiency	<95%	<90%	<90%
Type	Wide Input Buck Regulator	DC-DC Converter	Step-down Regulator
Manufacturer	Texas Instrument	Texas Instrument	Texas Instrument
Price	$5-$10	$5	<$5

Table 3.14.2 Switching Regulators' Comparison Table

We have selected the LM2596 to handle the 5V voltage required for the 3 servo motors and the Ultrasonic Sensor.

4 Standards and Design Constraints

Standards and design constraints have been essential for the progress of this project as they provide guides and boundaries that should be adhered to. Standards enable interoperability and ensure reliability. By following industry standards, we could incorporate existing technologies and utilize them to our advantage. Design constraints on the other hand promote innovation and resource management forcing us to think realistically and plan accordingly given. Given we had limited resources, including time, we had to make do with what we had access to. Standards and design constraints guided the progression of our project development by requiring us to prioritize certain aspects of the system over others that may not have been as critical. The framework produced by standards and design constraint ensures efficiency while simultaneously maintaining quality.

4.1 Standards

Standards set the norm for technological development. Standards are essentially agreed upon by procedures or specifications that should be used when designing new technologies. They allow for quality products to be developed by meeting essential requirements. There are standards for practically any aspect of technological development imaginable. It is thanks to standards that different systems and products are capable of working together. There are of course safety standards that require the consumer’s well-being to be taken into consideration as well as compliance-based standards that ensure no laws are broken throughout the production of a new product or technology. Perhaps, the greatest benefit of standardization is that it streamlines the process a bit. By following standards, certain aspects of new products in the industry can be developed through established practices, which are much more efficient than reinventing the wheel every time. They also allow for comprehension across an industry. [79]

4.1.1 Lens Standards

There are many standards that we could have considered regarding our lens design. Table 4.1.1 below lists important lens standards that were most relevant to our project.

Standard Name	Description

ANSI Z80.1	Ophthalmics - Prescription Ophthalmic Lenses - Recommendations
ANSI Z87.1	Current Standard for Safety Glasses
ISO 8578	Microscopes — Marking of objectives and eyepieces
ISO 9211	Optics and photonics — Optical coatings
ISO 10110	Optics and photonics — Preparation of drawings for optical elements and systems
ISO 11359-2	Plastics — Thermomechanical analysis (TMA) Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature
ISO 12312-1	Eye and face protection — Sunglasses and related eyewear Part 1: Sunglasses for general use
ISO 13666	Ophthalmic optics — Spectacle lenses — Vocabulary
ISO 14146	Radiological protection — Criteria and performance limits for the periodic evaluation of dosimetry services for external radiation
ISO 15004-2	Ophthalmic instruments — Fundamental requirements and test methods Part 2: Light hazard protection

Table 4.1.1 List of Important Lens Standards

Of the standards listed above, ISO 10110 is the most applicable in regard to our system's lens design. This standard consists of nineteen parts in total. It covers nearly every aspect regarding the drawing of optical elements such as lenses. The standard is designed to ensure the highest quality optical system that will produce accurate focusing for our auto-focusing system. The first part of the standard begins by addressing the general norm for how different optical elements should be represented in a drawing. [80]

The next few parts, two though four, had addressed how various material imperfections should be represented. The types of material imperfections addressed included stress birefringence, bubbles and inclusions, and inhomogeneity and striae. These parts have since been withdrawn and republished as part eighteen. Parts five through seven, then address how to indicate the acceptable tolerances of the following aspects: surface form, centering, and surface imperfections. These parts also clarify the acceptable tolerancing levels to ensure accuracy. [74, 80]

Part eight indicates how to represent the different surface textures on the drawing. The next part, nine, is only applicable if a thin film coating is applied. It informs the designer on how to label the various types of coatings for functional or protective purposes. Part ten is simply a table of the data of the lens. It serves primarily as a checklist of what has been completed on the drawing. Part eleven is another table that contains allowable deviations for the aspects that had not been toleranced up until this point. [80]

Part twelve deals with the labeling of on-axis aspherical surfaces including cylinders and toroids. Our system will utilize spherical lenses, and such this part will have no impact. The thirteenth part was on the topic of the damage threshold for laser irradiation but has been withdrawn. A later part, seventeen, addresses the same topic and is still published. [80]

Part fourteen pertains to the tolerance of wavefront deformation, in essence, it specifies the how much a wavefronts shapes may stray from the intended shape as it interacts with the optical element. Part fifteen was also related to the tolerance of wavefront deformation, but more specifically for systems containing elements. It has also been withdrawn. The next part, sixteen, focuses on the description of surfaces that add a diffractive optical function. While this aspect was not be utilized in our auto-focusing system, it was partially useful for our color identification. [74]

As mentioned previously, part seventeen pertains to the damage threshold of laser irradiation damage. More specifically, this part elaborates on how to properly indicate the levels at which laser irradiation will not result in damage to optical surfaces. Part eighteen pertains to the allowable tolerancing of the aspects previously described in the now withdrawn parts two through four. In addition to this, it also touches on the tolerancing of homogeneity. These parts also specify the amount of these material imperfections that are allowed to be present. Finally, part nineteen addresses how to present a general description of surfaces and components. [74]

4.1.2 Imaging Sensor Standards

Table 4.1.2 lists many important standards for CMOS sensors. These are all standards that we could have taken into consideration while designing our project. These standards address various subjects, including color, shading, noise, distortion, and more.

Standard Name	Description

ISO 12233	Photography and electronic still picture imaging, resolution, and spatial frequency
ISO 12232	ISO, speed rating, standard output sensitivity, and recommended exposure index
ISO 15739	Noise and dynamic range
ISO 14524	Methods for measuring opto-electronic conversion functions
ISO 17850	Geometric distortion
ISO 17957	Uniformity/shading measurements
CIE 15:2004	Defines colorimetry and evaluates color reproduction
ISO 19084	Chromatic displacement
ISO/IEC 14496-12	Storing multimedia content
ISO/TS 172321	Color characterization of digital still cameras (DSCs)

Table 4.1.2 List of Important Imaging Sensor Standards

Out of all these standards, CIE 15:2004 was the most applicable to our color identification system. It establishes a uniform method for measuring color and characterizing colorimetric systems as well as introducing color spaces.

The report establishes trichromatic color theory. The primary principle here is that human vision is dependent on the three cone photoreceptors that are known as the long, medium, and short cones that contribute to color discrimination. While their spectral ranges overlap, they are each sensitive to different groupings of wavelengths. The CIE in 1931 created the original standard to determine how the combinations of each of these colors could be used to produce the perceivable colors that abound around human vision, and how different functions of these cones and primary colors interacted with each other [81].

To perform this, three color functions known as the RGB (Red Green Blue) color matching functions were created so that a numerical representation of color could be used and manipulated to produce all possible color. Negative values for each function could be used to manipulate these values further [81].

However, these functions were placed inside of a three-dimensional coordinate space that included intensity as one of the dimensions. This became difficult to visualize, and thus the CIE opted to create a concept called chromaticity, which is essentially color minus intensity. The chromaticity coordinates were then plotted to create color gamuts that have informed the color spaces in standard use for virtually all color matching today [82]. An example of such a gamut is shown below in Figure 4.1.1.

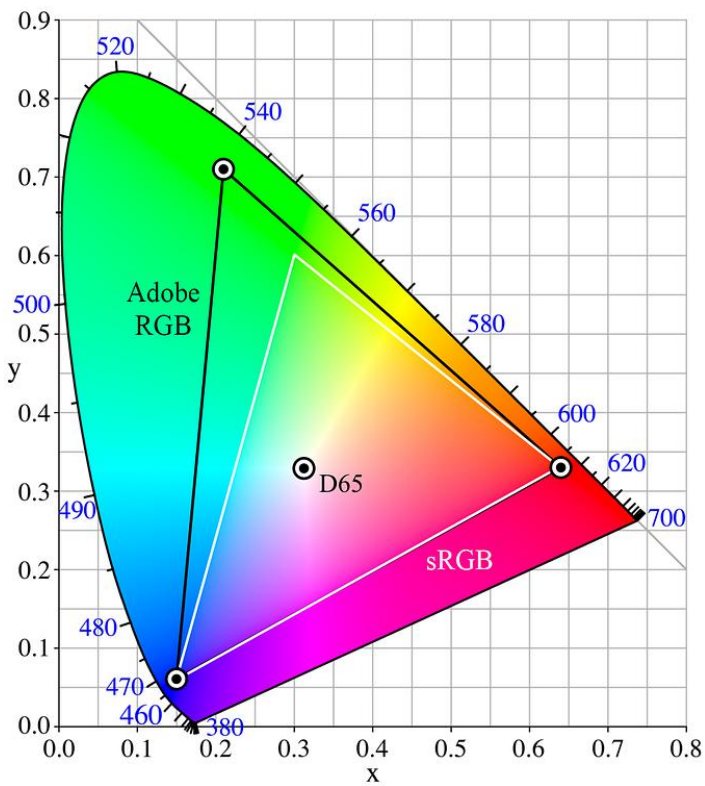

Figure 4.1.1 Color Gamut [82]

Another of these standards we took particular interest in was ISO 19084, as it is a standard created to evaluate the overall performance of image sensors. While it was created to evaluate both CCDs and CMOSs, for our purposes we only care about its evaluations towards CMOS sensors.

ISO 19084 does this primarily by evaluating three key parameters. The first is the sensitivity of the sensor, namely, evaluating its response to light and the determination of both its dynamic range and signal to noise ratio [83].

The second is the evaluation of spatial resolution. The standardization committee desired to evaluate the ability of sensors to resolve detail in the images produced by the sensors, thus informing the image quality of anything produced [83].

The final, and perhaps most important standard for us, was the color reproduction of an individual sensor. The standardization process for all three of these parameters ensures interoperability, that being the quality that ensures different sensors being able to function within various electronic systems while maintaining the same images they produce regardless of other components they may be integrated with [83].

4.1.3 Motor Standards

Regarding motors, there were many standards that we considered, such as the ones found in Table 4.1.3 below.

Standard Name	Description
ANSI/NEMA MW 1000	Magnet wire.
ANSI/NEMA 250	Enclosure Types
ANSI/NEMA MG 1	Motors and Generators
ANSI/NEMA BS 31007	Remote Inspection and Testing
ANSI/NEMA BI 50010	Enclosure FAQ - IP69 and IP69K

Table 4.1.3 List of Important Motor Standards

Of these, ANSI/NEMA MG 1 was the most relevant to our system as it provides guidelines for the designing, testing, and application of AC and DC motors and generators. While we are not utilizing any generators, our system will require several motors. This standard consists of thirty-four parts, broken down into four sections. The first section discusses general standards that apply to all machines, regardless of their size, electrical current, or the type of machine. It goes over naming conventions, ratings, performance, and tests. Section two covers small (fractional) and medium (integral) machines, such as small and medium sized AC and DC motors. It goes over their rating, testing, performance, and tolerancing. Moving on to section three where large machines are covered, the standard discusses induction, induction machines, synchronous motors, and DC motors larger than 1.25 horsepower per rpm. Finally, section four covers the performance standards that apply to all machines. [84]

4.2 Design Constraints

Much like any project, our system had many constraints that we had to conform to in order to successfully produce a working system. While we had the flexibility of imposing some of these constraints on ourselves, others, such as time, were set by existing deadlines. Each constraint was just as important as the others as they challenged us to complete the system within certain boundaries.

4.2.1 Budget Constraints

When it came to budget constraints, there was always a decision of weighing the importance of certain capabilities between the pricing of the product. This was a decision that significantly impacted our overall project as we prioritized cheaper priced items as long as they hit our main requirements within that category. This affected us as the products we picked had lower accuracy in measurements/data, more limitations to their functionalities which cost us more time and effort, lower quality photos, an overall decrease in performance speed, and bulkier items which for wearable glasses made things more difficult.

The autofocusing system relies on the ability of our technology to give us accurate readings and data. Because we are working with something as sensitive as the eyes and within a small distance, any adjustments we made to the lenses produced significant changes in vision for our user. One of our main technological components is an ultrasonic sensor. We used it to measure the distance from the lenses to their immediate surroundings to do an initial setup for the glasses. It is not the most accurate in distance reading compared to some more expensive options such as a LiDAR sensor and the range is much more limited given an ultrasonic sensor can only read up to a few meters and the LIDAR can read up to around three hundred meters. In addition to that, our choice of an MCU board had quite a large impact on how well our autofocusing system works. Because we wanted the autofocusing to complete in less than one minute, each adjustment we make to lenses either moving them closer or further away from the face must happen fairly quickly. Some MCUs come with higher processing power or more specific hardware peripherals like ADC converters or DMA controllers that can help it react to real-time events without a huge delay from processing overhead. Typically, boards with more hardware components or more efficient/quicker processing comes at a much higher cost. These are only a couple of components where their performance can greatly impact the accuracy of our lens system. There are various other parts that can have similar negative impacts but, when we took into consideration budget, we ultimately went with the option that fits the balance of performance and price.

Given we did not have any sort of sponsorship to help cover expenses, we decided to put in a certain amount of money per person. Taking into consideration our income as college students and how we budget our money into tuition, school supplies/textbooks, rent, gas to commute, food/groceries, etc. we agreed to put in a maximum of $250 per person for the overall project. This left us with a total of $1000 to carefully plan and use over two semesters. The money needed to cover all the costs of supplies and parts, and still leave spare money in case something was damaged, a part just was not working as intended in the system, or an overall system redesign.

4.2.2 Time Constraints

One of the clearest constraints in our design process were time constraints. The Senior Design course consists of only two semesters. During which most of our team members had jobs that required their time. That or they were enrolled in multiple courses each semester. This had to be worked around to find the time to really achieve all our goals and objectives by the deadlines. Using good techniques of planning and good use of our meeting times, this was achieved.

Becoming familiar with new concepts and new technology takes time and effort. As this is one of the main steps in a design process, research was mandatory. The advanced technology and information available today are beneficial, with most of the information we needed just one search away. This facilitated our research process yet having so many options of the same technology could at times become complicated and more difficult to pick just one. Having the tools to do research in a much more accurate and faster way was to our benefit.

There was always the possibility of running into obstacles like a delay in receiving the components we have selected. Various factors contributed to delays or not receiving the package: lost packages, delivered to the wrong address, out of stock, or delayed delivery date. To account for the probability of any of this occurring, we ordered our parts ahead of time, with enough time that if the situation mentioned above did happen, we would have had time to resolve it. In addition, we researched which sellers could be trusted and which could not.

The assembly and testing of our assistive lenses required a significant investment of time, as writing the report was only half of the design process and generally involved fewer potential problems than testing and assembling. To account for this, we conducted longer meetings dedicating a lot of time to the lab, experimenting and testing. We would initially verify if all components in our design were working properly. Then we sought guidance from our mentors if we found ourselves facing obstacles. The testing phase was critical, as it involved mechanical and electrical components and software code that could all face challenges that would impact our product's performance.

4.2.3 Size and Weight Constraints

Our assistive utility lenses are meant to improve the lives of visually impaired individuals by making a few tasks simpler to accomplish. In order for the lenses to assist an individual, the system must be worn. Due to this, it was absolutely crucial that the total size and weight was taken into consideration.

Since our lenses are meant to be worn, it was important that the entire system is comfortable. The idea is that the visually impaired individual is capable of wearing the assistive utility lenses at various points throughout their day as it gives them feedback and simplifies certain tasks that they may struggle with. Wearing anything additional is bound to cause some level of discomfort after a prolonged period of time. A bulky and heavy system will tire anyone out very quickly. Too much weight could also cause strain on an individual's muscles, which could potentially cause harm, especially if worn for extended periods of time. By designing the system to be as comfortable as possible, the system can accomplish its tasks of assisting the user as much as possible. We want the user to put the system on and leave it on as long as they need it. An ergonomically designed system is necessary for an individual to move around freely throughout their daily life. Our system was initially planned to be worn as a set of glasses, but as the project matured, it became clear that it must be a headset, this shift comes with the advantage of being able to rest on an individual's head more comfortably as opposed to applying all the weight onto their ears.

Our overall system relies on several individual optical systems to complete certain functions such as auto focusing. An instable system will result in lenses that are not properly aligned, leading to all kinds of aberrations. If the CMOS sensor's lenses are misaligned, then the auto-focusing function would not be capable of detecting a sharp image, leaving it inoperable and the user's vision will be locked into the wrong focal length. In the scenario that the CMOS sensor's lenses remain in alignment, but the user's lenses do not, then the individual will then be unable to see. The aberrations introduced by the misalignment will obscure the user's vision. By reducing the weight and size of the system, we can maintain a more stable alignment along the optical planes and ensure the auto-focusing feature can perform its duty properly. In addition to this, the system is worn on an individual's head. If it is heavy, then the user may have difficulty maintaining their own vertical stability which could lead to accidents and become a health concern. A lighter and smaller system certainly ensures more stability for the user as well.

The next consideration was the battery life of the system. This system has several moving parts that require motors. The heavier these parts are, the larger the motors that would have required, which would have in turn resulted in even more weight. The larger motors would also consume more power, draining our batteries at a quicker rate. While the system may not always be necessary and thus does not have to be powered on every minute of every hour, it should be powered on when the user requires assistance. In order to ensure the assistive utility lenses are available to assist whenever needed, a long battery life was necessary.

The final consideration was debatably either the most important or the least important. The aesthetics of the assistive utility lenses were taken into consideration. A large and bulky system would easily stand out and could garner unwanted attention. In a society where disabilities and assistive technologies are excessively stigmatized as they are, we do not wish to produce more social discomfort for the users of our system. While we may concede that the initial designs of the system are not the most aesthetically pleasing, we attempted to minimize the bulkiness of the design as much as we could without sacrificing the functionality of the system.

As a worn technology, the size and weight of our system could not be ignored for the reasons listed above. These constraints ensured our system became the beneficial, assistive technology it was meant to be.

4.2.4 Human Anatomy Constraints

Joining the topic of size and weight, human anatomy itself became an issue that had to be addressed and worked around. The power of the lenses we chose, the size of the system, and the weight of the instruments were important and were affected by the functions of the human body.

The standard human eye possesses optical power of about 60 diopters, with a focal length of 16.7 mm [85]. Given that we are appealing to users who suffer from myopia for our autofocusing system, we needed the lenses to provide at least -1.5 diopters to correct moderate nearsightedness. However, in doing so we also had to take care of accounting for excessive. Reducing the effects of magnification as we have our two-lens system move in and out in conjunction with input from the CMOS was crucial, as we want the user to experience the same benefits as normal corrective lenses when using the device.

We also considered the color identification system and how it is meant to appeal to the standard color gamut of a typical human eye. The cones and rods that humans use to produce vision are sorted into red, green, and blue color vision, and the interplay of these colors produce all of the possible combinations of color that a typical person perceives [5]. Therefore, we needed our CMOS sensor to be as accurate to the color gamut as possible. To do this, we compared the spectral sensitivity functions of the various sensors we were researching and observed how they overlap with human color vision. The more accurate they are, the more accurate our results would be when we inform the user of the color they are perceiving.

This same principle is applicable to the photodiodes and specifically the color filters we will attach to them, as we must take care to select color filters that will make our photodiodes sense colors that are as similar to those perceived by the cones of the human eye as possible.

The final consideration is of course the size of the human head itself. While this size can vary considerably, we will need to find a standard size that can either be adjustable or fit the greatest number of people possible. Research will need to be done to accommodate these measurements, or further design will be necessary to produce an adjustable product.

4.2.5 Accessibility Constraints

When it came to designing the structure and functions of our project, we had to take into consideration "ease-of-use" for the user. The glasses are meant to help people with impaired eyesight and make their lives a bit easier. If the glasses are too complicated or not straight-forward enough to the point, they could be confusing, it would not be beneficial to our target users. This forced us to be proactive and design with simplicity and accessibility in mind.

We added a helpful audio guidance system to notify the user as they progress through either the autofocus or color-identification system. Once either button has been pressed, a loud beep will be heard to signal that the process has started. If there is an error at any point, a voice message will be heard saying there was an error and to try to press the button again. At the end, another loud beep will be heard to notify you that the process has been completed. This audio is meant to help as there is no additional reading or visual queue that someone who is visually impaired might have trouble seeing.

While one of our stretch goals was to include app functionality, we also have had to consider the design of this app so as not to alienate anyone who might suffer from visual disabilities. Ensuring the use of different font sizes, text-to-speech features, and similar accessibility features would streamline the use of the app so that it could appeal broadly to as many users as possible.

5 Comparison of ChatGPT and other Similar Large Language Models

The large language model (LLM) or “AI” as it is popularly referred to as, has become a very trendy technology that everyone seems to be utilizing to some extant nowadays. It has certainly had a large impact on the workflow as people seem to go straight to it for answers. For better or for worse, LLMs are now being used in nearly every industry imaginable and they do not seem to be going anywhere anytime soon. When used properly, LLMs can be incredibly powerful tools for innovation. Considering the speed at which they can relay information, they are fantastic for cutting down the time it takes to research a topic. That is, assuming the information it provides is reliable.

5.1 Pros and Cons

Having utilized a few LLMs such as OpenAI’s ChatGPT, Google’s Gemini, and Microsoft’s Copilot, it is clear that each one has certain advantages and disadvantages. In general, LLMs are great for acquiring a summary of information on a topic quickly. Unfortunately, the information provided is not always accurate. Contrary to popular belief, LLMs are not actually intelligent, they parse through a lot of data, then relay that data in a pattern that, at best, gives you the information you were looking for and, at worst, confidently spits out a nonsensical statement that defies the laws of physics. They are also great for planning, though. They can often provide step by step instructions and help diagnose a multitude of IT problems. They can be incredibly beneficial as tools for productivity. However, they can also be utilized nefariously as some may choose to have a large language model write large sections of their papers or answer their assignments. The student who chooses to do this ultimately suffers as they do not gain any understanding of the subject matter when this is done. These ethical concerns are not limited to the educational sector and AI art has also grown in popularity, which can result in all sorts of concerning imagery.

ChatGPT is currently known as the best LLM out there and seems to live up to that name in most cases. It will provide an abundance of information for any question asked. It works great at debugging code and spotting potential mistakes. It will even suggest improvements to the code. Gemini and Copilot, while not as good, are still great at finding and relaying information. Copilot does a fantastic job of always providing sources on the subject matter in question.

As mentioned previously, the largest flaw of an LLM is that it will confidently relay false information and thus it is up to the researcher to validate the integrity of the information provided by the LLM. Copilot makes this easier by providing links to sources where the information can be validated, but it is still not perfect as there are situations in which the information provided cannot be found in the sources provided or is in fact contradictory to the information presented by the sources themselves. Ultimately, LLMs are great for brainstorming and getting a starting point, but they are not reliable enough to fully trust. That aside, it is unethical to take the information at face value without giving credit to those who deserve it. At least Copilot makes an attempt to give credit, even if it is not perfect at it.

5.2 A Prompt on Lenses

Prompt A-1 was presented to ChatGPT, Gemini, and Copilot. The prompt asked the LLMs to explain what Fresnel lenses are and they each provided unique responses with similarities throughout.

ChatGPT's response begins with a very brief history and a description that could be better in terms of describing the shape of the lens. It then continues with the following five sections: Structure of a Fresnel Lens, Purpose of a Fresnel Lens, Advantages, Disadvantages, and Sources. The 'structure' section is very helpful as the shape of a Fresnel lens is very unique and can be difficult to understand at first. This section also emphasis that some Fresnel lenses may be different based on whether they are to be used for imaging purposes or not. It fails to elaborate on what the differences in the structure are though. The 'purposes' section lists how Fresnel lenses are implemented across various industries from light houses to traffic lights. Next is the 'advantages' section which lists five advantages to using a Fresnel lens instead of a traditional lens. The fourth section lists four disadvantages of using a Fresnel lens, in which most are related to the optical performance of the lens. The final section lists the sources. There are only three sources listed, but they all appear legitimate at first glance. However, ChatGPT ends the response by clarifying that the sources provide further reading, implying that the information was not necessarily gathered from those sources. In addition to that, none of the information presented indicates where it was gathered from and thus it cannot be trusted without confirmation through independent research. Ultimately, ChatGPT was very useful at getting a decent understanding of what Fresnel lenses are and when they should be considered, but moving forward would require significantly more research.

Gemini's response contains a title and is also followed with a brief description of the lens. This description does a much better job of describing the shape of the lens than ChatGPT's brief description. That being said, it does not go into further detail regarding the shape and can leave the researcher imaging the incorrect structure. It should also be noted that Gemini does not bring up the history of the Fresnel lens, which ChatGPT did. The rest of the response is then split into three sections: Purpose and Applications, Pros and Cons of Fresnel Lenses, and Sources. The 'purposes' section here is significantly different than ChatGPT as Gemini lists various applications for Fresnel lenses instead of industries. Listing the applications instead of the industries is not necessarily better but it does allow the researcher to think more broadly about how to utilize a Fresnel lens instead of only considering the currently existing applications. The next section lists four advantages and three disadvantages to using Fresnel lenses. Several of the advantages listed by Gemini are nearly identical to the advantages listed by

ChatGPT. Gemini certainly could have listed more disadvantages, but the disadvantages it did list are surprisingly more informative than the ones listed by ChatGPT. Lastly, three sources are cited although there is no indication where any of the information was pulled from and thus can be concluded that the sources may not even contain the information provided. Gemini did manage to produce links to the sources which is convenient, but one of the sources is Wikipedia which is not a particularly reputable source. Although the sources within Wikipedia the Wikipedia article may be more reputable themselves.

Copilot's response begins with an incredibly concise statement on the history of the Fresnel lens and a brief description of the structure of the lens. Copilot's response is not very descriptive, which could leave the researcher confused regarding its structure. The response continues with the following four sections: Purpose, Pros, Cons, and Sources. The 'purpose' section lists four applications in which Fresnel lenses are utilized but remains vague in how the lenses are specifically involved. Copilot only lists three advantages, and they are very similar to the advantages listed by both ChatGPT and Gemini. There are three disadvantages listed, but two are nearly identical and the last one had not been listed by either ChatGPT or Gemini. Moving on to the last section, sources, this is where Gemini truly has the advantage. Gemini lists five sources with links to each one. In addition to this, Gemini cites the sources throughout the response, allowing the researcher to verify the information themselves directly. That being said, there have been some inconsistencies with the information presented and the information in the sources themselves.

Of the three LLMs, ChatGPT produced the most informative response, while Copilot's response was the least informative, yet it was the most concise. All three LLMs provided decent descriptions and purposes for Fresnel lenses, but Copilot's response was the easiest to verify due to the links provided. The links also made Copilot's response the easiest to transition into more research, because each link was tied to certain parts of the response. Allowing for a deeper dive on specific aspects of the response.

5.3 A Prompt on MCUs

Prompt A-2 was presented to ChatGPT, Gemini, and Copilot. The prompt was to explain what exactly an MCU is, what parts make it up, and the benefits it has over other logic devices.

ChatGPT's response begins with a short summary statement of what an MCU is followed by a simple list of what it typically consists of. It is very brief and not super descriptive, just stating it is a compact integrated circuit that operated within an embedded system, but that does answer the question on what an MCU is. It just does not go into depth on it as that was not part of the prompt I gave.

Next, it breaks the response into different segments for each question. The structure of the response makes it very easy to read and understand. It first breaks down the components of an MCU and gives a very detailed outline of all the potential parts and adds each of their functionalities. It not only talks about the overhead section, but it also dives into the smaller subsections. Like for example memory, ChatGPT breaks it down into flash memory, RAM, and EEPROM which shows how it goes a bit deeper into details as it could have excluded this. Then, it has a section on the functions of an MCU where it talks very basically about what it can be utilized to do. It is missing some basic functions, but it is just because it is trying to do broad categories and within those categories, the simpler functions are just not being stated directly. The last section is the benefits of using an MCU, it lists the major six reasons why it is convenient/easy-to-use and provides a little description on why. Finally, after that, it lists four sources, all of them being textbooks which makes it a bit vague as to where specifically it got the information it gave me. To confirm this information, I would have to do additional research to skim through the books and make sure that the response matches. Overall ChatGPT was pretty concise and broke down information to a readable and easy-to-understand state. It took a broad question and answered it well and provided additional information that was not directly asked in the prompt.

Gemini's response begins similarly to ChatGPT with an initial brief overview of what an MCU is and the segments that it integrates. It goes a bit more into detail about what an embedded system and integrated circuit is than ChatGPT did. It also created a sort of outline structured response that breaks the information down for easier reading. It first starts with the components of an MCU. It goes less in depth about capabilities of components and although it does also break down the sections into subsections, it does appear to be missing a couple listed by ChatGPT like EEPROM and basic input/output pin connections. Next is the segments on benefits of an MCU. It is a lot more brief and less descriptive than ChatGPT. It only lists four main benefits and leaves out less direct reasons why such as ease of development and real-time processing. Lastly it lists three sources, one of which says, "invalid URL removed". The sources do have direct links so I can click on them and access them more easily. They both are websites in comparison to textbooks with more summarized information, so it is a lot easier to fact check and confirm information given. Overall, Gemini still has fairly accurate and concise information. It does not seem to give additional information outside of the prompt like ChatGPT did and a search could benefit from a more detailed prompt.

Copilot's response begins with a very short statement saying that an MCU is an integrated circuit built for embedded systems. It does not give an initial listing of parts like the other LLMs did. In terms of structure, the response is given in a numbered list. It was simple to read and just like the other two, it was broken into different parts for the different questions. The first segment is on components of an MCU, CoPilot did not provide much information on any of the components, instead the short description was just of the subsections that were separated like before in ChatGPT and Gemini. For example, the memory description was just listing RAM and flash memory. It lacks any real substance on what their functions are. The next section is benefits of an MCU, it does have only five main benefits, but they are different than the ones ChatGPT and Gemini gave. It includes the benefit of a more compact size and easy-of-use not only from easy development, but it includes the fact that MCUs have pre-programmed libraries for certain tasks. Neither of these were brought up in the previous LLMs so that did impress me. Lastly, CoPilot listed five source links. It did not include a subject or author like Gemini or ChatGPT did but the information in the links seem to cover mostly what is seen in the resulting information. The only thing I did not like was that it used Wikipedia as a link which means the information was really from a different source than listed.

Overall, I think ChatGPT did the best job at replying to my prompt. It mostly gave more detailed responses with a nice breakdown of each category for ease of reading and understanding. It gave additional information as well that was not directly asked in the prompt. It is a nice source to use for initial research just to get an overview and figure out where to go next. The sources were not the best to fact-check, but the information matched what I previously researched. Although CoPilot had the shortest and least detailed response, the information it gave was new information that I did not see with ChatGPT and Gemini which is good to note.

5.4 A Prompt on Motors

Prompt A-3 was presented to ChatGPT, Gemini, and Copilot. The prompt was to explain the pros and cons of types of motors for our design.

ChatGPT's response was to suggest the stepper motor and the servo motor based on our requirements on small step size and can be programmable. The response started by listing the advantages of a stepper motor. Listing four main advantages, the first being Precision control. The stepper motor can move in discrete steps which is beneficial to our design. The second advantage mentioned was the open-loop control, the stepper motor is an open-loop system which means it does not require a feedback system to function therefore simplifying the design. The third advantage is cost-effective, generally they are less expensive than servo motors. The fourth advantage is that stepper motor has a good holding torque which can keep a position when power is applied to it. The disadvantages stated: resonance issues, torque drop-off and heat generation. In this case the heat generation is a complication in our design meanwhile the torque drop-off is not since we will need low speed and the stepper's torque decreases at higher speeds. Next, for the servo motor ChatGPT outlines the same number of advantages and disadvantages. The servo motor in contrast with stepper motor works in a closed-loop control, therefore, works using feedback systems that make the design more complex. Another advantage is that servo motors tend to have higher torque and smoother motion. Last advantage is it can achieve higher speed and acceleration but as mentioned before high speed is not favorable to our design. The servo disadvantages response: complexity, higher cost, and calibration needs. The servo motor requires calibration to ensure accurate performance.

Gemini's response starts by discussing the considerations involved in selecting the appropriate motor for our design. By highlighting the key factors to evaluate, including accuracy, torque, speed, and cost. Stepper motors were noted for their high precision and affordability, although they can be noisy and have limited speed capabilities. Servo motors offer smooth and quiet operation with higher speeds, but they tend to have higher costs and are less precise. Linear actuators were presented as another option, which allows for direction motion and high load capacity. But it has higher costs and with less accuracy. So just evaluate what our needs are and what motor will work best for our design.

Copilot's response starts by listing the advantages and disadvantages of a stepper motor. Stepper motors are known for their high accuracy and reliable repeatability in small step movements; however, they tend to operate at slower speeds and could require more complex control systems. The other motor, whose advantages and disadvantages were mentioned, was the DC motor. The DC motor will require an encoder to get accurate precision. The downside of the DC motor plus encoder is that it can be expensive.

Overall, all three responses were of great help. Although Copilot's response was short and not as much detail as when prompted to ChatGPT and Gemini. ChatGPT and Gemini provided good motor types and outlined the disadvantages and disadvantages of the motors concisely.

5.5 A Prompt on Sensors

Prompt A-4 was presented to the aforementioned AIs, asking them to explain the difference between CCDs and CMOSs and to describe which of the two is a better technology.

ChatGPT's Response starts off by summarizing CCDs, then moving onto CMOS sensors. They begin by describing the sensors as a type of image sensor that converts light into electrical signals. They then describe the process of how the sensors work, from light capture, charge transfer, and then signal processing. These descriptions are rather brief, choosing to give a quick summary of the topic than the level of detail that we had desired when submitting the query. Nevertheless, the AI then listed some uses for CCDs, ranging from professional photography and videography, astronomy, medical imaging, and other scientific applications like microscopy. It then repeated this process for CMOS sensors, contrasting it to the CCD sensors directly by mentioning that each pixel has its own charge-to-voltage conversion and readout circuitry. In further writing, it explains how unlike CCDs the light generates electrons at each pixel rather than being collimated into one source and mentions both the integrated processing and fast signal output. It mentions some uses, such as digital and security cameras. Following this, rather than performing a direct narrative comparison of the two technologies, the AI resorts to tabulating the two, directly comparing their overall strengths and weaknesses. It then ends by stating that there is no best option when choosing the particular sensor, as the CCD is preferred where image quality is critical while the CMOS is useful for its compactness and cheaper price. It gives a summary at the end where it advises to choose the CCD for image quality but to lean towards CMOS sensors for virtually every other application. The general summary of ChatGPT is that it gives a well-balanced comparison of the two technologies but fails to go into the depth of explaining more about how they work, from the charge transfers to the signal processing. However, for those who do not care about the physics behind these processes the comparison is sound.

Gemini's Response did not immediately jump into any one sensor, instead opting to explain how they both capture light and convert it into electrical signals, differing only in the methods by which they do so. It then dove into CCDs, explaining the principle of how the sensor operates and doing so at a desirable level of detail, explaining even that the sensors utilized a series of capacitors to store the charges, mentioning that their structure is more complex with multiple crystalline layers of various silicons and metals. It also opts to immediately list the pros and cons of the sensor, taking time to note that CCDs excel in capturing subtle details and colors. Then, Gemini performs the same process for CMOSs. While its explanation here is correct on how CMOSs integrate photodiodes directly onto each pixel, it would have been more desirable if they did more to explain that this approach is radically different compared to the CCD since the charge conversion happens directly at the photosite. Regardless, the AI proceeds to perform a fairly simple explanation of the structure of the sensor and its pros and cons, including a generally higher noise level but faster readout times. The AI then proceeds to list a few applications in two separate sentences before diving into answering which technology is best. Like ChatGPT, it opts to say that there is no clear winner and that the application is what matters. However, they do make it a point to mention that CMOS as a technology has had recent advances that put it up to par with many CCDs, decreasing the gap between them in terms of image quality that has allowed CCDs to remain relevant. It concludes by recommending again to consider the application of the sensor and proceed from there.

Copilot's Response was incredibly brief. It immediately describes CCDs, although it does so in little detail, possessing a section described as "how they work" but failing to describe how this integrated grid of semiconductor capacitors is actually arranged and functions. However, it does succinctly describe the function of the technology and then describes some uses for it. The same process is applied to CMOS sensors, where the AI again elects to ignore my request for details in favor of two small bullet points barely describing the technology and its function. It even uses one of those bullet points to compare the CMOS to the CCD rather than further describing the function of the technology. After mentioning some uses for CCDs, a table is formulated where a simple list of comparisons is made between the two, with each technology mostly being listed as “higher” or “slower” or other simple descriptors with no numbers to provide real comparison or in-depth analysis of the facets of each sensor. Copilot ends by stating that the choice on which to use depends on the application, and that generally CMOS sensors are becoming more popular due to cost and power factors but still lose out to CCD quality.

Overall, it is clear that Gemini generated the most useful response to the query. While ChatGPT was serviceable in providing an introduction to the topic, Copilot’s answer was abysmal and would have left the user asking the question entirely in the dark unless they asked for Copilot’s sources when answering. Gemini on the other hand managed to be both succinct and descriptive, efficiently explaining the merits of the two technologies while making it clear that CMOS sensors are beginning to match the strengths of their CCD counterparts.

6 Hardware Design

In this section, we provide an overview of the hardware architecture for our project. Examining how our components communicate between the various components and how they integrate to form a cohesive system. Additionally, we present the schematics of our subsystems, detailing their architecture and their connection with our MCUs.

6.1 Subsystem

For the design of our product, we considered the different subsystems: Motor, Colorimeter, CMOS, and Ultrasonic Sensor subsystem. Looking at their block diagrams, schematics, and architecture.

6.1.2 Motor Subsystem

The Motor Subsystem works as a dual motor system as shown in Figure 6.1.1. Motor #1 creates the linear motion of the moving Lense by using a lead screw mechanisms connected to a servo motor to autofocus the lenses in conjugation with the CMOS and Ultrasonic Sensor data. This motor had to be positioned to one side of the eyes of the user as this lens system is in front of the CMOS sensor. Motors #2 and #3 create the linear motion of the two non-stationary lenses that the user operates to observe the object or objects in view. The CMOS lens system has a support rod with a linear bearing on the opposite side of the motor, to support the weight of the lens and frames. Figure 6.1.2.1 shows the two lens systems from our hardware design.

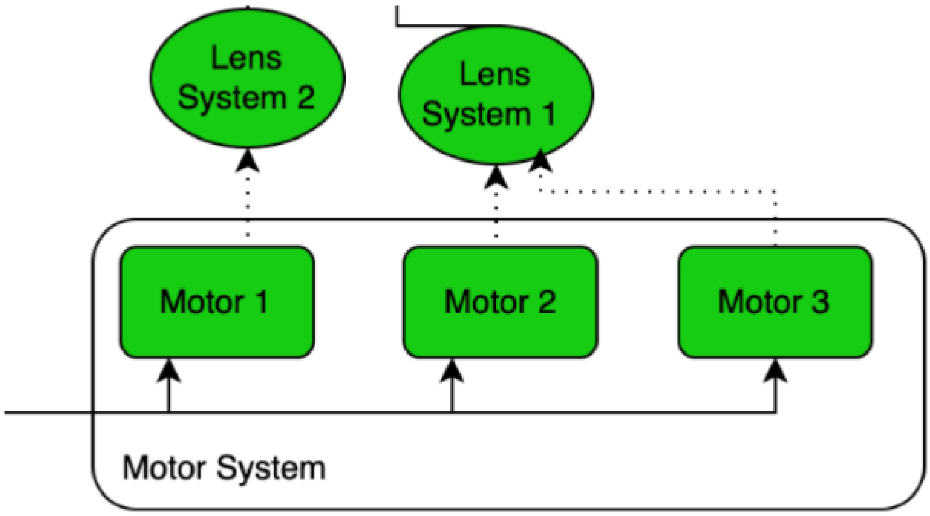

Figure 6.1.1 Motor Subsystem Block Diagram

6.1.2.2 Architecture of Motor Subsystem

The system features multiple motors positioned on either side of the user's head, with the same size lead screw that will control the linear movement of the dual two-lens system. Motor #1 lens system is placed in front of the CMOS camera. The lenses are housed in a 3D-printed frame, where the closest lens to the user is a stationary lens while the farther away is a moving lens. Motors #2 and #3 move the lens system which the user looks through. The motion of the second lens system is adjusted based on the data collected after the CMOS camera has been focused. To add support to the other side of the CMOS lens system, we added a rod with linear bearings. To have a better understanding of the structure in Figure 6.1.3 we can see a model of Motor #1 and Figure 6.1.4 is the model of Motor #2.

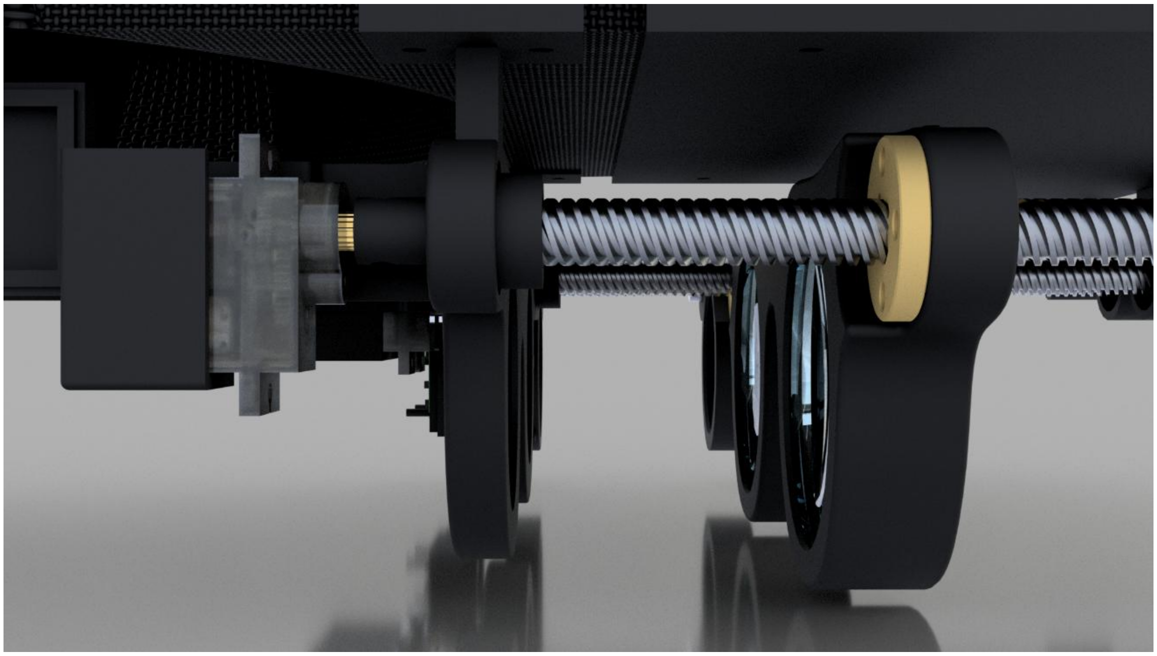

Figure 6.1.3 Motor #1 Structural Model

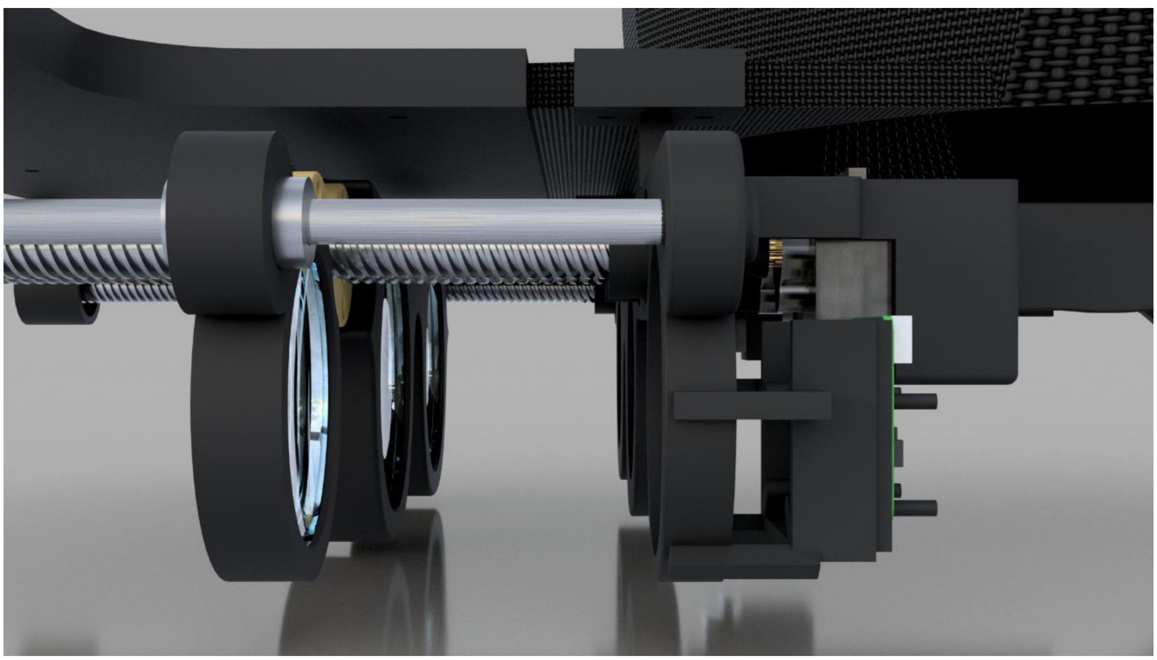

Figure 6.1.4 Motor #2 Structural Model

6.1.3 Colorimeter Subsystem

The Colorimeter Subsystem utilizes a TCS3200 sensor interfaced with the MCU. Figure 6.1.5 illustrates the necessary connections between the TCS3200 and the

MCU. The TCS3200 operates with an input voltage range of 2.7V to 5.5V, and since the ESP32 provides a 3.3V power pin, it is ideal for powering the sensor. Given that the TCS3200 draws minimal current (only 5μA), this setup is highly efficient. The subsystem generates data that is processed by the MCU for further analysis and user communication.

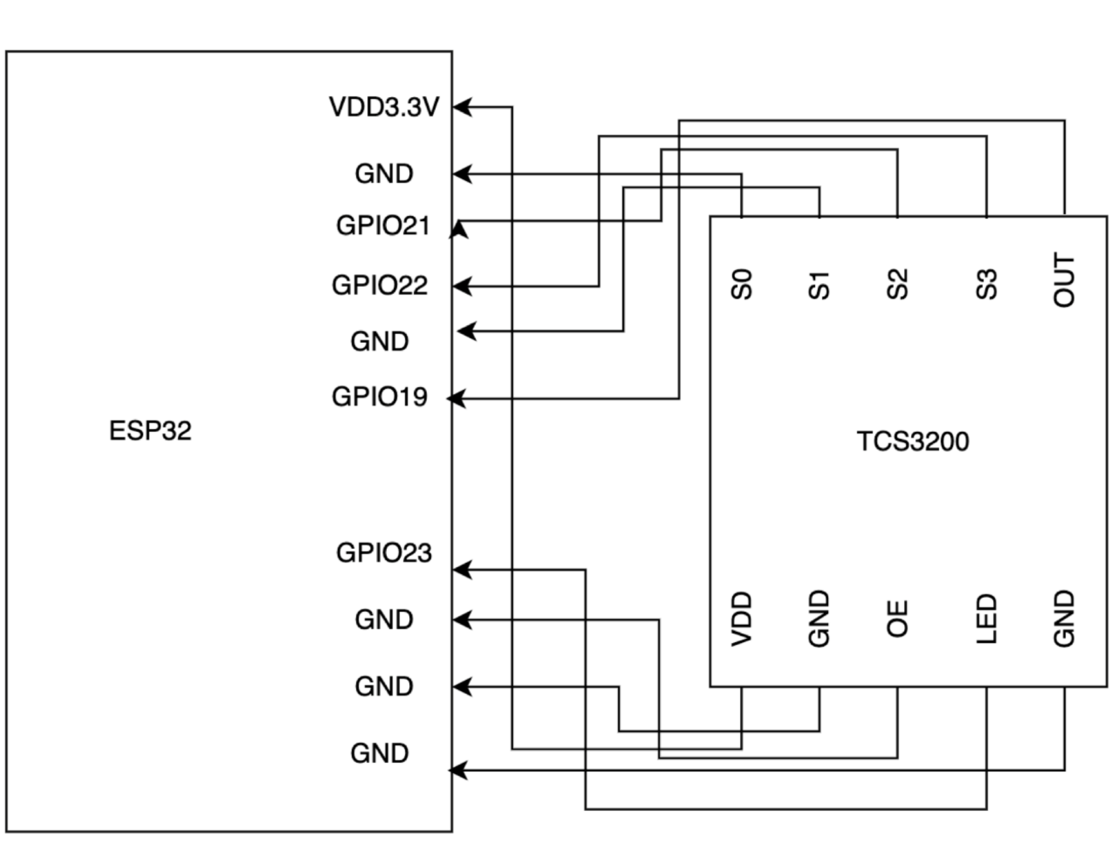

Figure 6.1.5 Colorimeter Subsystem Block Diagram

6.1.3.1 Schematic Diagram of Colorimeter Subsystem

The TCS3200, our chosen colorimeter, possesses white LEDs that shine light that is then reflected onto the photodiode collection area, which is comprised of 64 photodiodes split into 4 groups of red filtered, blue filtered, green filtered, and clear photodiodes. The schematic in Figure 6.1.6 has been sourced from theoryCIRCUIT's web page**.** It includes a current-to-frequency converter that takes light intensity and converts it into a square-wave output signal. That signal is communicated to the ESP32 to be enabling the color detection after referencing a color library and then informing the user.

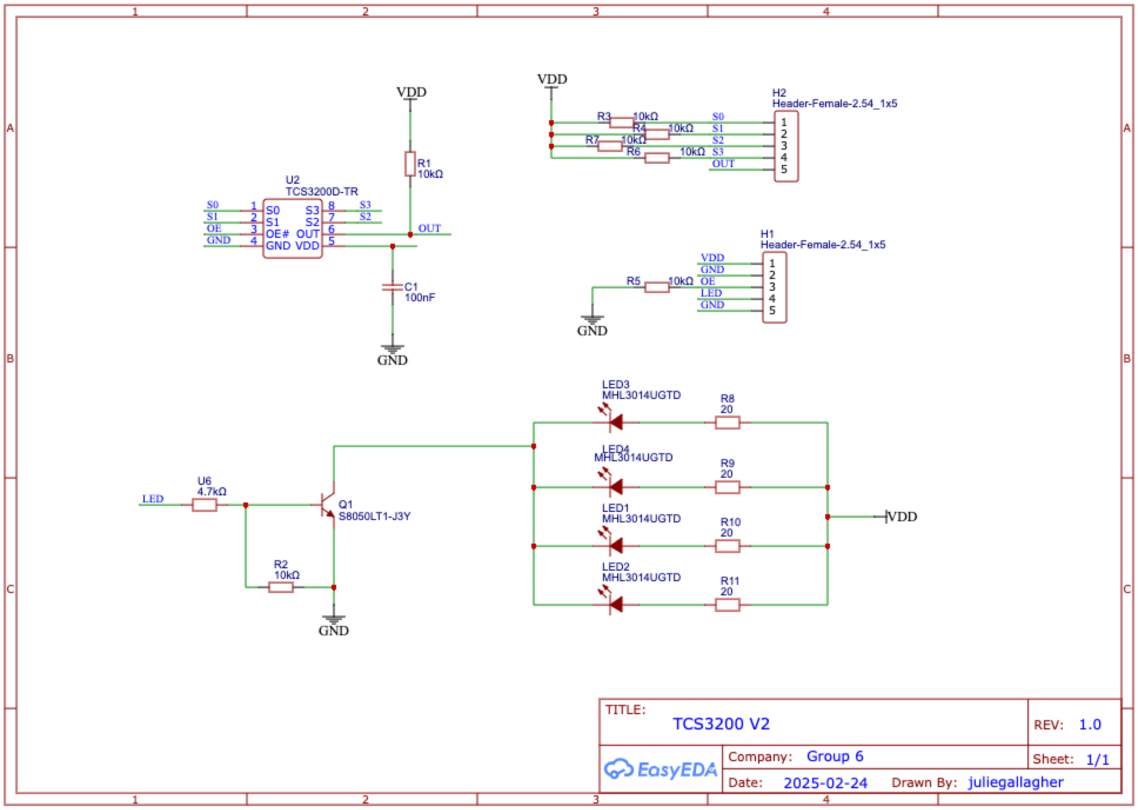

Figure 6.1.6 Colorimeter Subsystem Schematic

6.1.3.2 Architecture of Colorimeter Subsystem

The colorimeter subsystem involves the colorimeter paired with a lens system and is encased within a custom-built container that prevents any light from passing onto the colorimeter without traveling through the lens system. Shown before in Figure 6.1.6, the TCS3200, is a small board therefore to detect color we will place the sensor at the top of our visor on the front. This placement enables the sensor to directly face the object and detect its color.

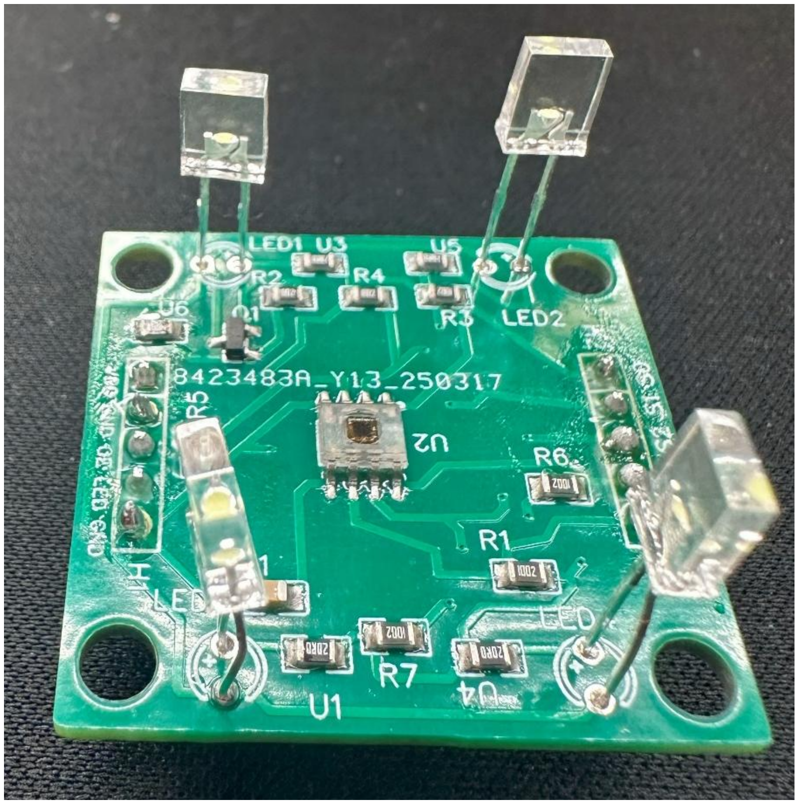

Figure 6.1.3 Colorimeter PCB

6.1.4 CMOS Subsystem

The CMOS subsystem involves the CMOS sensor communicating with the Raspberry Pi 4 via a ribbon cable. Figure 6.1.7 contains a representation of this connection. The CMOS sensor model is a Raspberry Pi Camera Module V2 that captures images looking through one of the lens systems. The image in Figure 6.1.8 has been sourced from the Raspberry Pi Foundation website [87] and is being used to reference what our CMOS subsystem looks like.

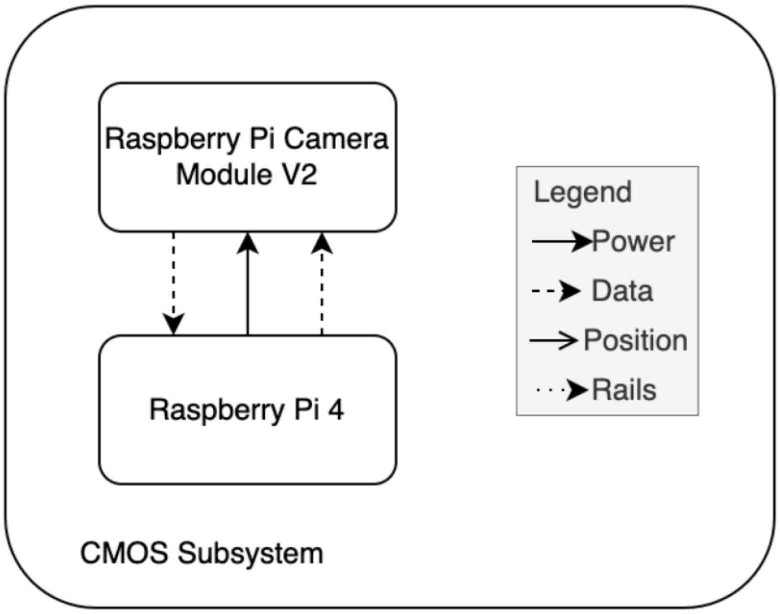

Figure 6.1.7 CMOS Subsystem

Figure 6.1.8 Raspberry Pi 4 and Raspberry Pi Camera Module V2 [87]

6.1.5 Ultrasonic Sensor Subsystem

The Ultrasonic Sensor Subsystem consists of the HC-SR04 Ultrasonic Sensor in connection with our MCU with a voltage divider that drops the 5 V signal from the sensor to a 3.3 V. Figure 6.1.9 below contains a representation of how the main PCB, the Raspberry Pi 4 and the ultrasonic sensor are all connected. The

Ultrasonic sensor is located near the user's vision path, so it can detect the distance between the user's eyes and the object in view. The voltage divider is a circuit consisting of simply two resistors in series as shown in Figure 6.1.10.

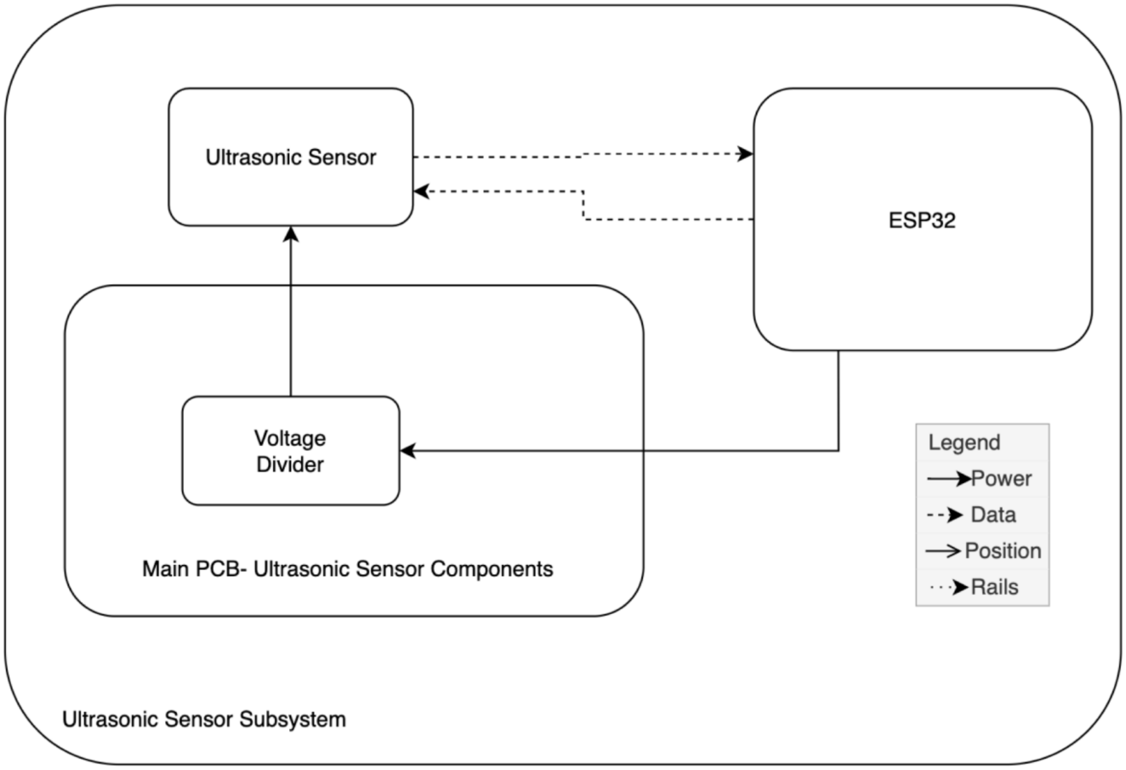

Figure 6.1.9 Ultrasonic Sensor Subsystem

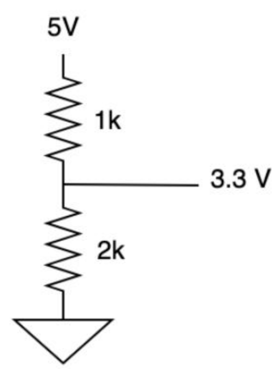

Figure 6.1.10 Voltage Divider

6.1.5.1 Ultrasonic Sensor Schematic

The schematic in Figure 6.1.11 was created by OSU (Oregon State University) and is used here to illustrate the Ultrasonic Sensor used in this project. No modifications were made to the original design. The schematic is a representation of the assembled component we utilized for our design.

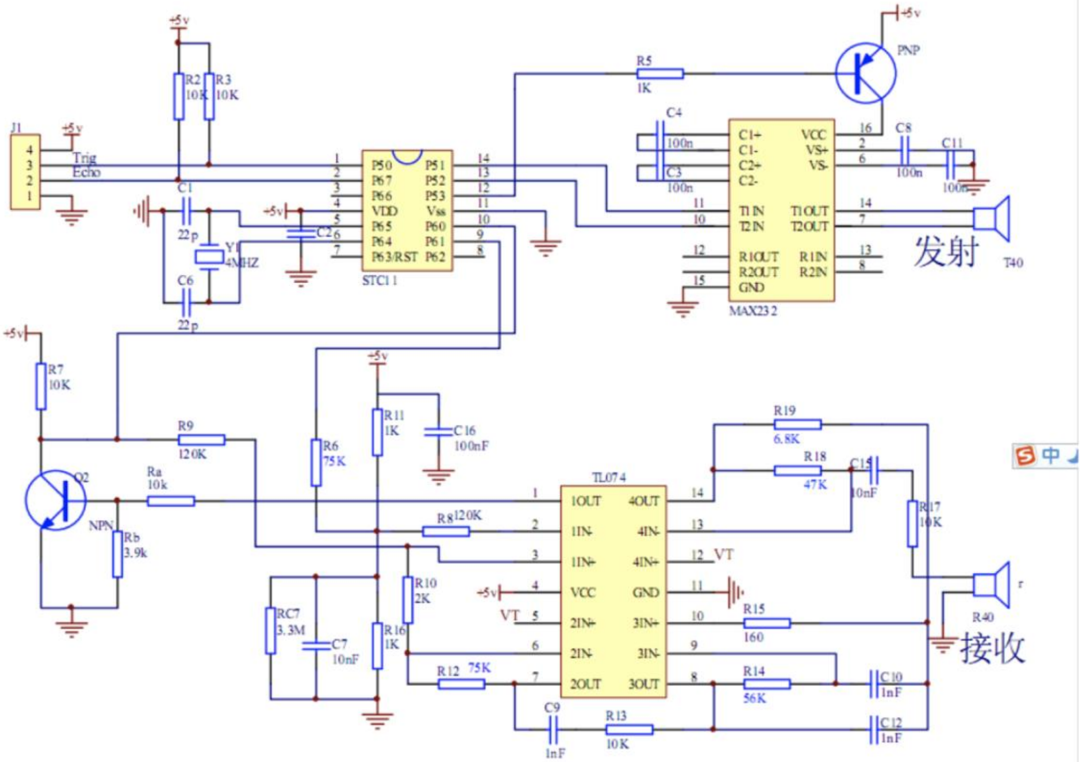

Figure 6.1.11 Ultrasonic Sensor HC-SR04 Schematic

6.1.6 Power Supply Subsystem

The Power Supply Subsystem incorporates a Li-Ion Battery pack that outputs 12V/ 3A into a jack connector found in our 5V regulator. Figure 6.1.12 presents the schematic of the LM2596 regulator in use. The power supply for our MCU requires a 3.3V operating voltage while peripherals such as the HC-SR04 require 5V operating voltage. To account for this, we designed a 3.3V regulator shown in Figure 6.1.12. A good power supply was essential for all our components to work properly and therefore prevent any problems with the system. To help with troubleshooting or any faulty component, among other reasons we designed the one regulator to be on their own board, the 5V regulator.

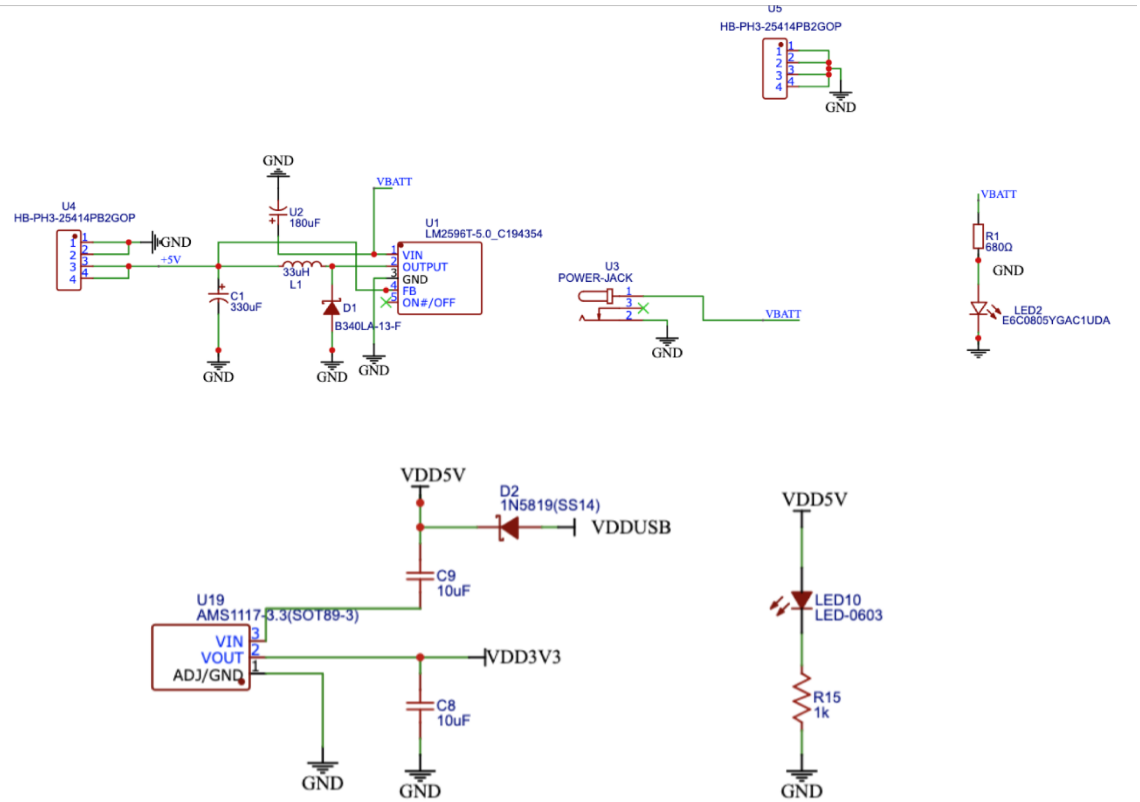

Figure 6.1.12 5V Regulator and 3.3V regulator (top schematic and bottom schematic accordingly)

7 Software Design

This section focuses on software planning and overall finalized software design. Its goal was to act as a roadmap and show how each software component interacts and its functionality. This gives a general overview of the development plan and aids in more efficient coding, testing, and troubleshooting. Below, we are focused on breaking down each system through detailed diagrams, discussing algorithm logic, explaining our part set-up, and how code was used to piece together the entire system and ensure reliable interaction.

7.1 Use Case Diagram

The Use Case diagram is a type of behavioral diagram in the Unified Modeling Language (UML) that can show how a system interacts with all the internal and external parts. It shows all the functional abilities of the system with roles (the actors) and the use cases or specific tasks/operations they can complete. The main goal of this type of diagram is to define the scope of a system by highlighting its interactions with external attributes, documenting the system's requirements, and giving a basic plan for the system design for when the developer begins to work on the software code.

Since our project is really split into two main segments: auto-focusing and color detection, our use case diagram follows the same structure. We have three main actors which represent people or mini systems that interact to complete the tasks: the user, the MCU or the Raspberry Pi 4, and our lens system with all the sensors and motors connected to it. We then can split up and give a more detailed description of each use case seen in the diagram within Figure 7.1.1.

Triggers: When a button is pressed, it initiates one of the functions either the auto-focus or color detection.
Measure distance: Uses the ultrasonic sensor to measure the distance of an object form the user.
Capture image: Takes a picture using the Raspberry Pi camera module to either use for the focusing or color analysis.
Adjust lens: Move the lens to properly focus the lens systems on whatever the object of interest is.
Focus verification: Utilizes an edge-detection algorithm to check if the image is in focus. If it is in focus then proceed to completion otherwise trigger the adjust lens.
Analyze color: Process the captured image and analyze it by pixels to identify the colors found.
Compare result: Compare the resulting colors with the data collected from the programmable color light-to-frequency converter to determine if both results are the same or not. In the case of the results not matching, retesting must be completed.
Speak results: For either system, a finalized audible message will play to inform the user if the system has been completed successfully. If not, it will audibly prompt the user that it was unsuccessful, and they must re-trigger the system by pressing the button again.

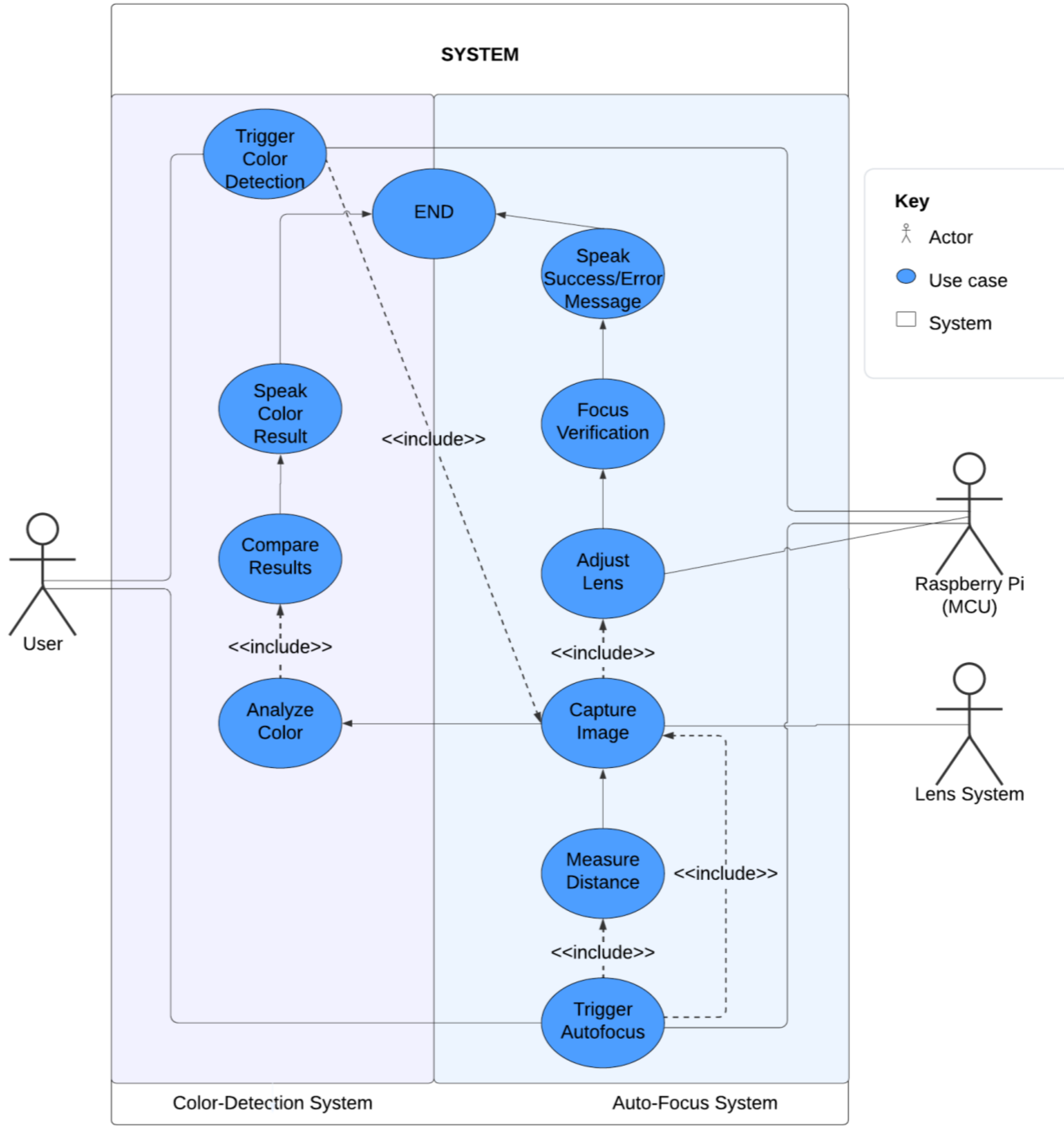

Figure 7.1.1 Use Case Diagram

7.2 Class Diagram

A class diagram is another UML or unified modeling language diagram that can help show the structure of a program. The class diagram shown in Figure 7.2.1 shows all the classes and how they are connected to one another. This helps to demonstrate the relationships between them as well as each one's individual attributes and methods.

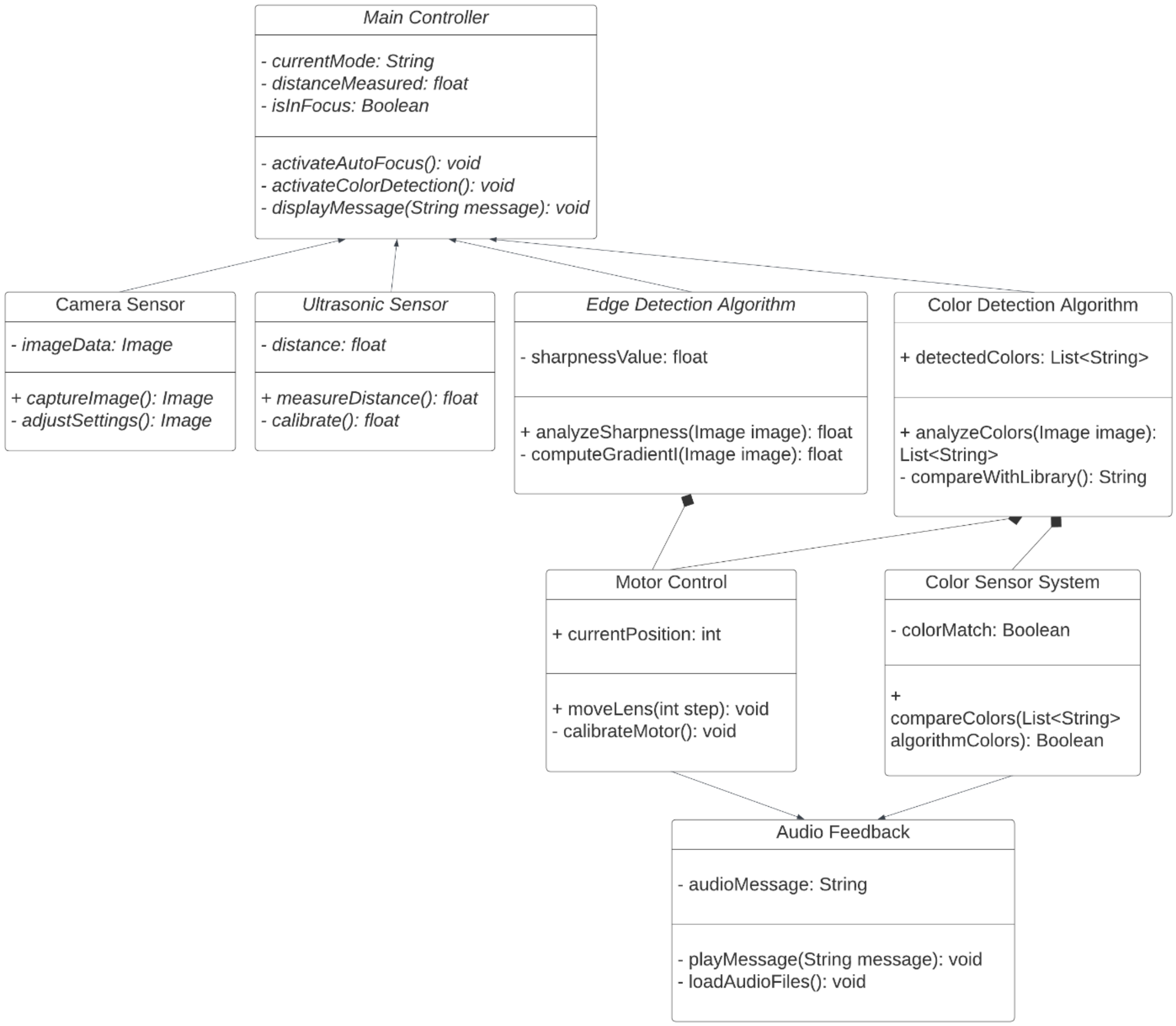

Figure 7.2.1 Class Diagram

7.3 User Interface

The user interface (UI) for this project is quite minimal given we focused on not having too complex of a setup or any sort of visual screens or cues. Since our system is meant to be a wearable and portable piece of equipment, the interface relied on four physical buttons and audio prompts for user interaction. This ensures that no external devices or visual displays are needed.

The four buttons were added to the side frame of the lens system. This allowed for easy access and when pressed, the button initiates the color detection or autofocusing systems, respectively. The more hands-free simple approach lets the user focus on their surroundings and not have to worry about what they are interacting with on their head. Since the buttons are interfaced with the Raspberry Pi's GPIO pins, it was extremely easy to add the handling of those user input presses. There are preset Python libraries where we could use RPi.GPIO or gpiozero that already have easy connection and interaction protocols to the GPIO pins. When the Raspberry Pi registers a button push with the change of the switch, it can trigger the appropriate system code to begin either color detection or autofocusing.

To aid in the effortless user experience, audio prompts are used through the process as the primary mode of communication. This makes our system especially accessible for visually impaired users. They are guided through the loading phase with updates given at the beginning of the process and the end. Since the Raspberry Pi 4 already comes with its own connected Bluetooth module, we did not have to worry about adding in external parts or servers to connect to. We chose to simply utilize a Bluetooth speaker either in the form of a small headset or just a regular speaker as a source of audio. Python has once again preset libraries for ease-of-use with pre-recorded audio files like pygame or sounddevice that were utilized to output our audio prompts. We could have also used pyttsx3 for text-to-speech if we wanted to have more customizable prompts and we could just type what we wanted spoken and the library would translate it to audio.

7.4 Color Analyzing Algorithm

In terms of our color analysis, it was a crucial part of our project. Especially given that our goal was to achieve at least 80% color identification accuracy while identifying one or more colors at the same time. To break down the algorithm, we implemented it in Python through the IDE Visual Studio Code. This was ideal given Python has a wide range of pre-made libraries that we utilized in terms of image processing and machine learning and its Visual Studio Code made adding extensions extremely convenient.

This algorithm was used for integrating the Raspberry Pi camera module with advanced image processing libraries that's goals are to focus on a specific region of interest (ROI), analyze the pixel data, and map the resulting colors to output strings given in a pre-set color library. To achieve this, we used the library OpenVS for the image processing given the photo output from the camera. Once the photo is received, the OpenVS cv2 module handles the loading of the image, the ROI isolation, and the color space conversion to HSV or the hue saturation value color model. Using HSV is necessary for better color detection as it separates the chromatic content (hue) from the intensity. An additional matplotlib library is then utilized to aid in debugging by plotting the ROI when coding to check for errors and displaying the image for review. Once converted and cropped to focus on the center portion of the image, the pixels are clustered together utilizing KMeans from the scikit-learn Python library. From there, the colors are then compared to the color library to identify the names of the colors. Those results are cross-checked with the color sensor's output to verify accuracy before being spoken as audio prompts to the user.

7.5 Edge Detection Algorithm

The edge detection algorithm is also a key component in the accuracy of our lens system. Not only did we have a restriction goal of the process finishing within one minute, but we also wanted the system to be accurately in focus by the end of the program. Same as the color analyzing algorithm, the edge detection was implemented in Python within Visual Studio Code.

The first step being getting a picture for analysis from the Raspberry Pi camera module. Once it has been loaded into the program, using the picamera2 library, the image is then preprocessed to convert it to grayscale as edge detection works best with single-channel images and color was an additional avoidable complication.

The algorithm then utilizes the Canny Edge Detection, which is a popular edge-detection available within the OpenCV library. It basically highlights certain portions of the image with significant changes in intensity. These are to be identified as the edges. There is a sensitivity threshold applied to filter out some of the background "noise" which helps a lot with accuracy especially given we are not using the highest quality camera. This threshold value needed to be determined, tested, and calibrated when putting together the lens, motor, and camera systems. After that, it calculates the variance of the Laplacian of the image which we use as a measure of sharpness. A higher variance means the edges are well-defined and overall, the image is more in focus and vice versa. Testing was necessary to determine this value, but a preset threshold was in place to determine if an image is within a reasonable range of focus. [88]

If that variance is below the threshold, the algorithm triggers the motor system to move utilizing libraries like RPI.GPIO to adjust the lens system to better focus. The lens moves in small increments in one direction, and another picture is taken, then the program repeats the edge detection process. If the image is clearer then the lens continues to repeat the same steps moving in the same direction, but if the image is blurrier then it moves in the opposite direction for double that initial increment before repeating. This continues until the lenses are sufficiently focused or if a timeout occurs after too much time to avoid an infinite loop. Once an end has been reached, the audio system either states that the process is finished, or it was unable to complete and prompts the user to press the button again.

8 System Fabrication / Prototype Construction

During the construction of our prototype, we began by identifying all the necessary components, then assigning them to their corresponding systems and subsystems. After confirming that the components were compatible and would perform the tasks necessary, we started to integrate all the subsystems together taking into consideration how the layout of the components would impact their performance. Certain aspects, such as optical alignment and interface compatibility took priority as we started to determine the placement of each component and subsystem. Whilst assembling the protype, the systems were tested to ensure they are properly functioning. This proactive procedure allowed us to identify any issues with the protype, so that we would not have to fully tear down the prototype whenever an issue was identified. Only the components functioning improperly would have to be replaced or reorganized.

By documenting every step of the construction process, we would avoid making the same mistake multiple times and streamline the process. Once all the components and subsystems were attached to the system, we were able to properly test each of the individual features and perform any minor adjustments as necessary until we had a finalized prototype.

8.1 PCB Layout

In this section we look at the PCB schematics and the PCB layout. To develop our schematic, we used the online platform EasyEDA [89] to design our PCB's. The initial step was to ensure proper voltage regulation for the motors, we incorporated the LM2596 voltage regulator on it's own board. To indicate when the battery is supplying power, an LED was added to the design. Meanwhile the ESP32 requires a 3.3V operating voltage for it we implemented the AMS1117 voltage regulator into the main PCB. In Figure

For the MCU in our main PCB we selected the ESP32 that communicates with peripherals: TCS3200, HC-SR04 and three MG90S servo motors. In Figure 8.1.1.1 and Figure 8.1.1.2 is the representation of our main PCB schematic diagram showing all necessary components that work with the ESP32 for the programming of the peripherals in our design. It involves the ESP32 modules, a power supply, USB- UART, two switches and the 38 pin connector among other components. While Figure 8.1.2 is the representation of the main PCB layout. The layout includes where all the traces and components were placed. This is one of the main steps for a working PCB, as it needs to follow design specifications for the traces, spacing, etc.

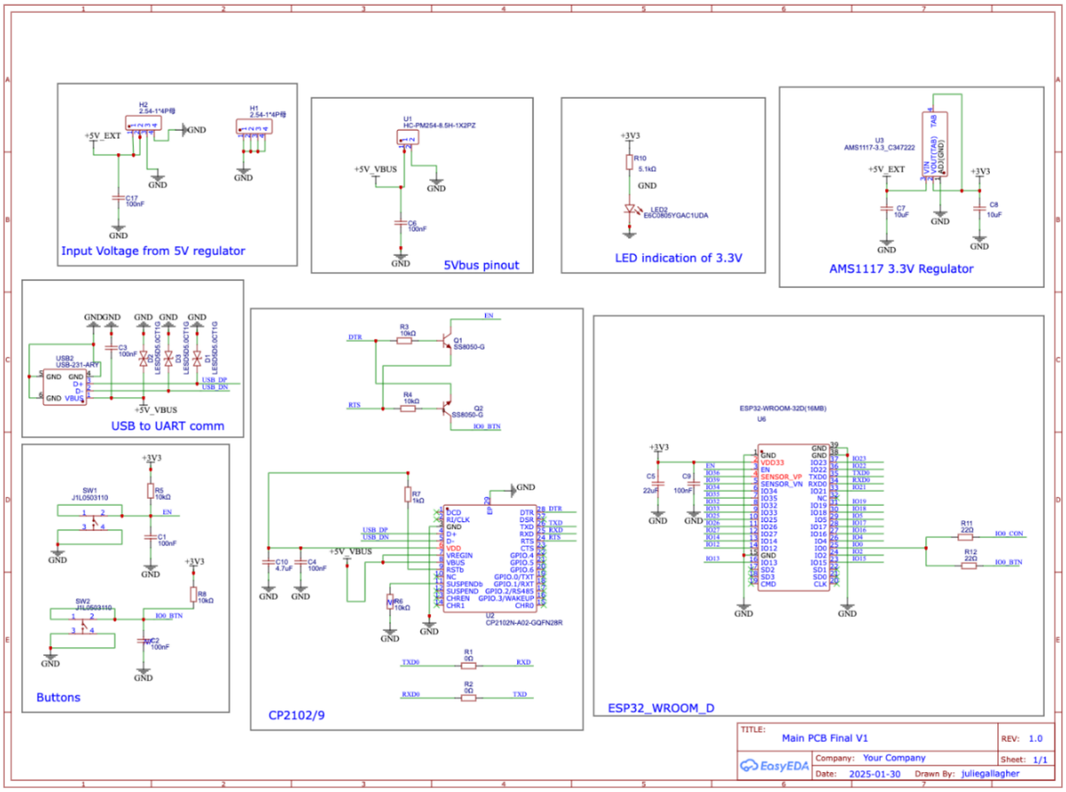

Figure 8.1.1.1 Main PCB Schematic

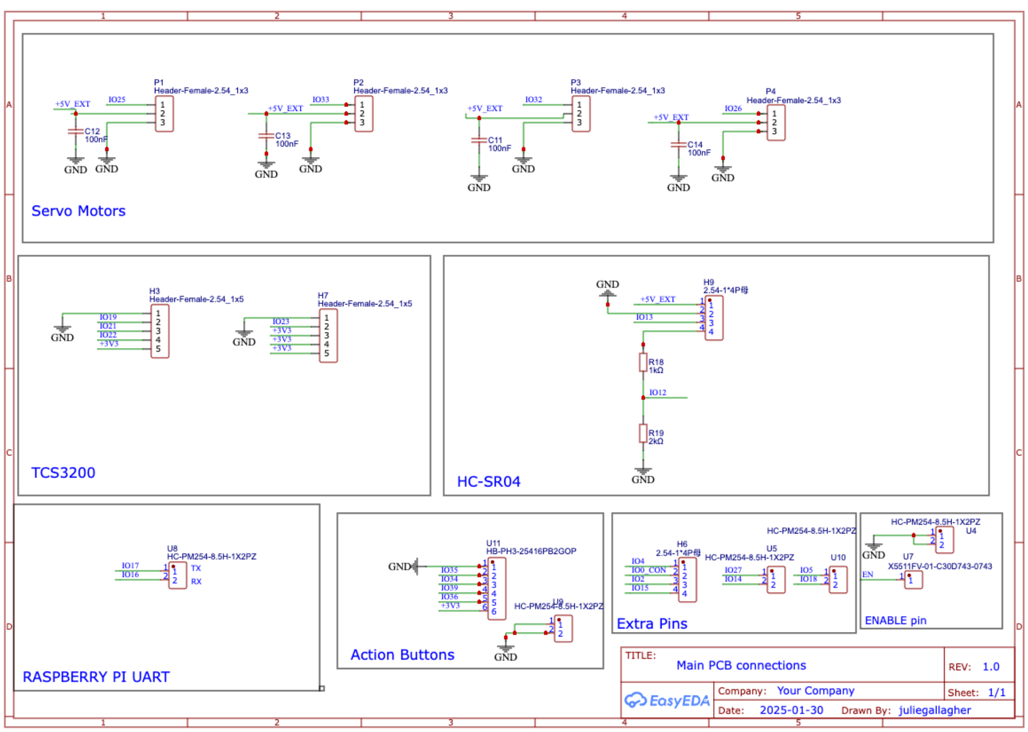

Figure 8.1.1.2 Main PCB Connection Schematic

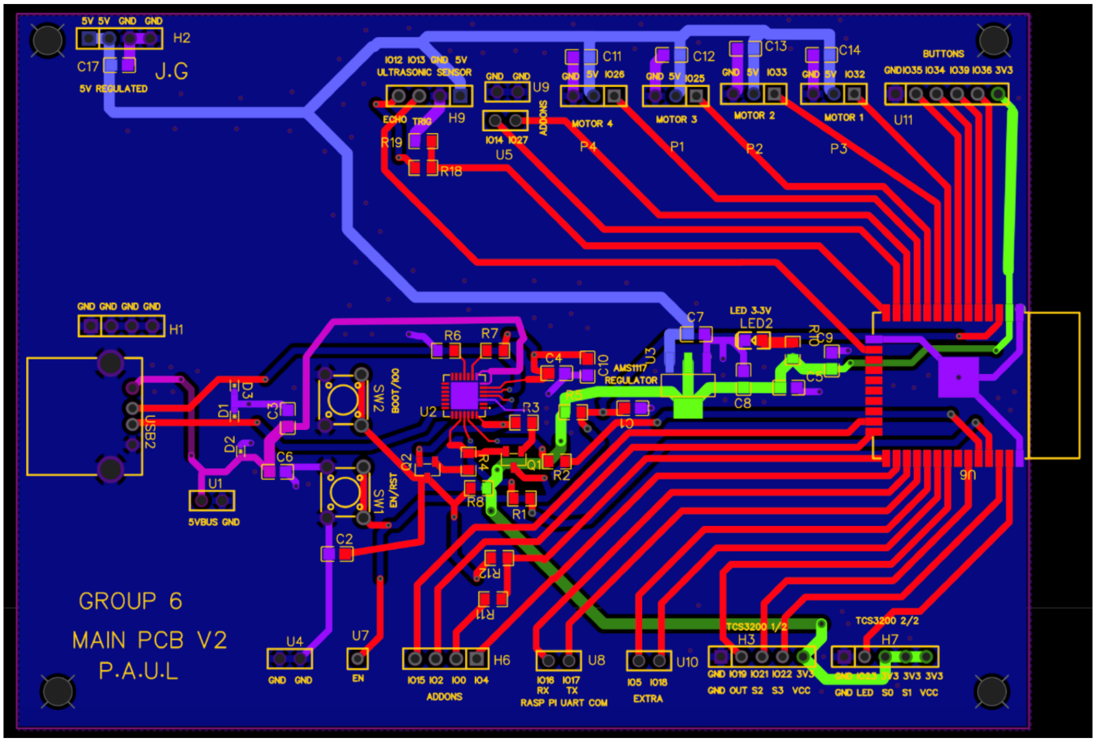

Figure 8.1.2 Main PCB Layout

Next PCB is our 5V regulator which includes the LM2596 at 5V 3A ratings. In Figure 8.1.3 shows the schematic of our regulator board. And Figure 8.1.4 shows the PCB layout of the board and how the board was ordered.

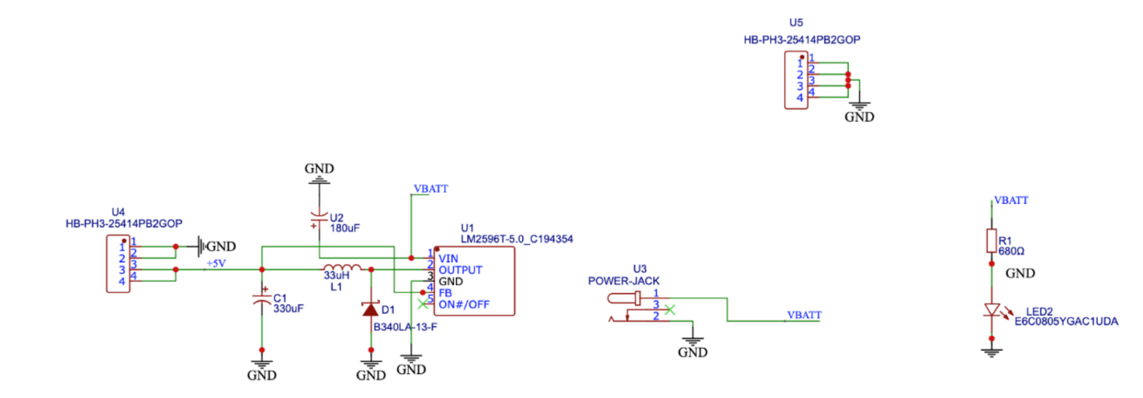

Figure 8.1.3 LM2596 5V Regulator Schematic

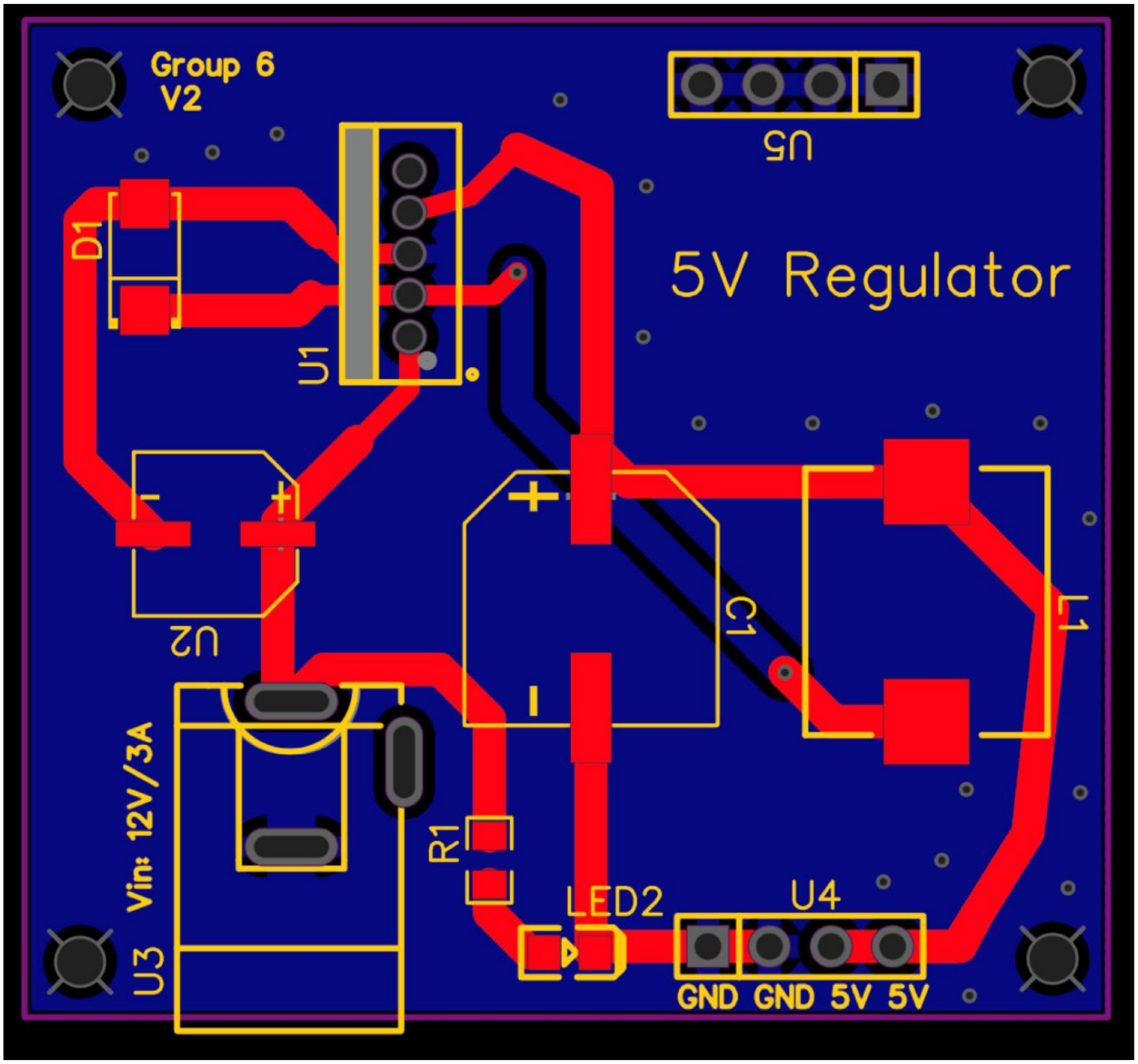

Figure 8.1.4 LM2596 5V Regulator PCB layout

The third board in our PCB design consists of the Colorimeter, in Figure 8.1.5 shows the schematic of it. This is the second iteration of this board as the first one resulted in us not being able to turn the white LED on and off by command. In Figure 8.1.6 shows the PCB layout of the board.

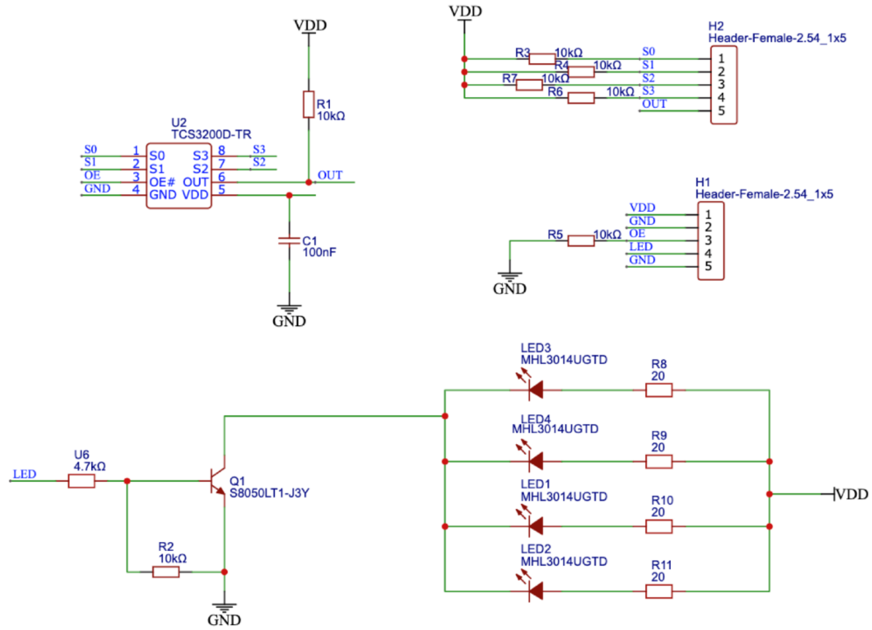

Figure 8.1.5 TCS3200 Board schematic

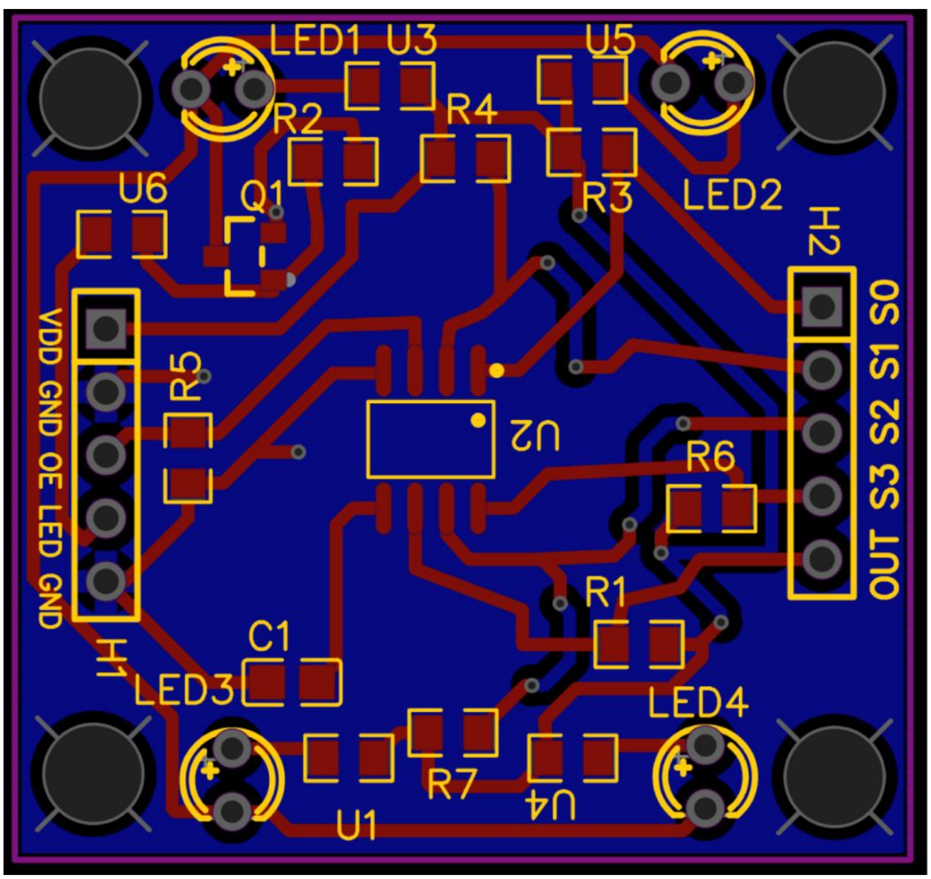

Figure 8.1.6 TCS3200 Board layout

The last PCB in our project was the action button board, this includes four buttons that set of the autofocusing, color identification, manual forward movement and manual backwards movement of the lens system. In Figure 8.1.7 shows the buttons boards schematic while Figure 8.1.8 shows the layout of the board.

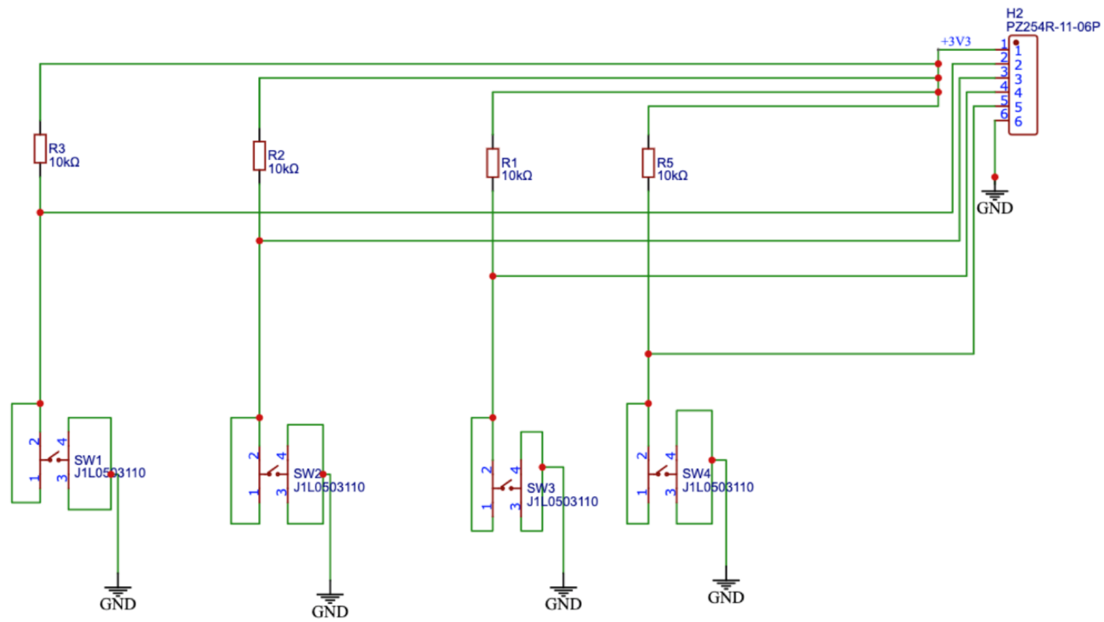

Figure 8.1.7 Buttons PCB schematic

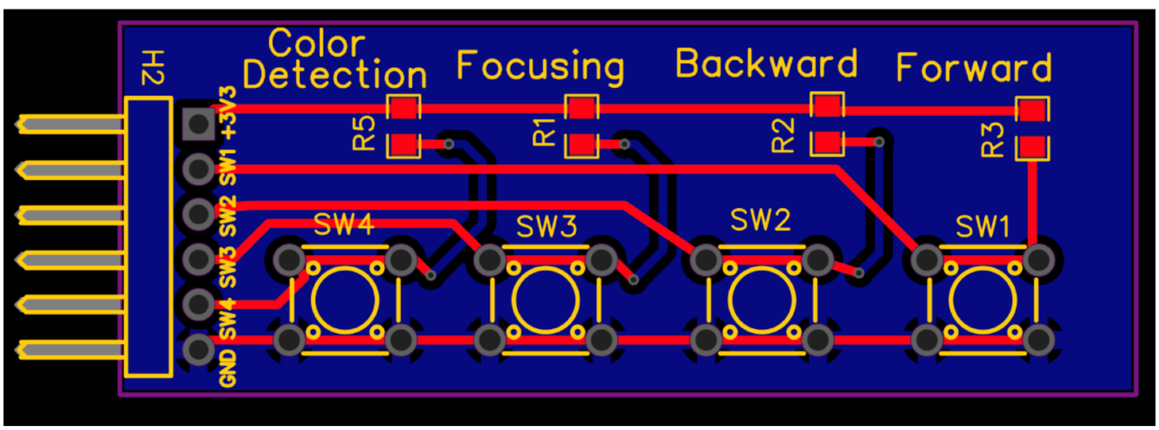

Figure 8.1.8 Buttons PCB layout

8.2 Prototype Design

The initial design for the system prototype was built around a visor as this headgear would allow the user to wear the system comfortably while maintaining optical alignment. Figure 8.2.1 below displays a rendering of that design. This digital rendering demonstrates how the various components were placed around the system. Each component seen was necessary for all the features to function properly. As can be seen, there is one lens system aligned with the user's eyes and another lens system aligned with a small CMOS sensor. These lens systems work in conjunction, but do not adjust simultaneously. This separation allows each lens system to be set to a different effective focal length, allowing the primary lens system to compensate for minor visual impairments such as nearsightedness or farsightedness. The time of flight sensor is placed at the edge of the brim so as to not be obstructed as the initial distance measurement is necessary to begin the auto-focusing system. The motors which adjust the distance between the lenses in both lens systems are placed at the sides, attached the temples of the frame. While this rendering currently lacks the majority of the electronics that are ultimately utilized, the Raspberry Pi 4 attached to the side of the visor demonstrates how various electronics are placed around the headwear. The positioning of the components necessary for the color identification system was not fully implemented at this point. That being said, since these components must remain unobstructed as well, we knew they had to be placed similarly to the time of flight sensor along the brim of the visor. Figures 8.2.2 and 8.2.3 below show renderings of the final design of the prototype with all the components attached. This final design was achieved after many iterations of individuals components were designed and 3D printed. Ultimately, the priorities of the design were to maintain optical alignment and minimize the bulkiness of the prototype.

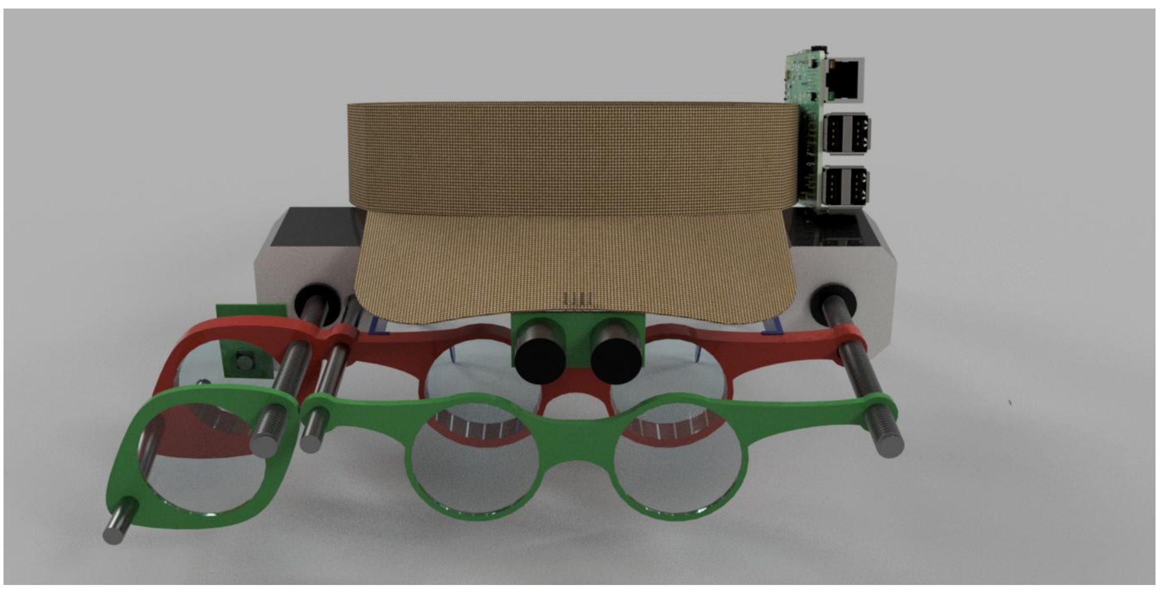

Figure 8.2.1 Full System Digital Rendering Version 1

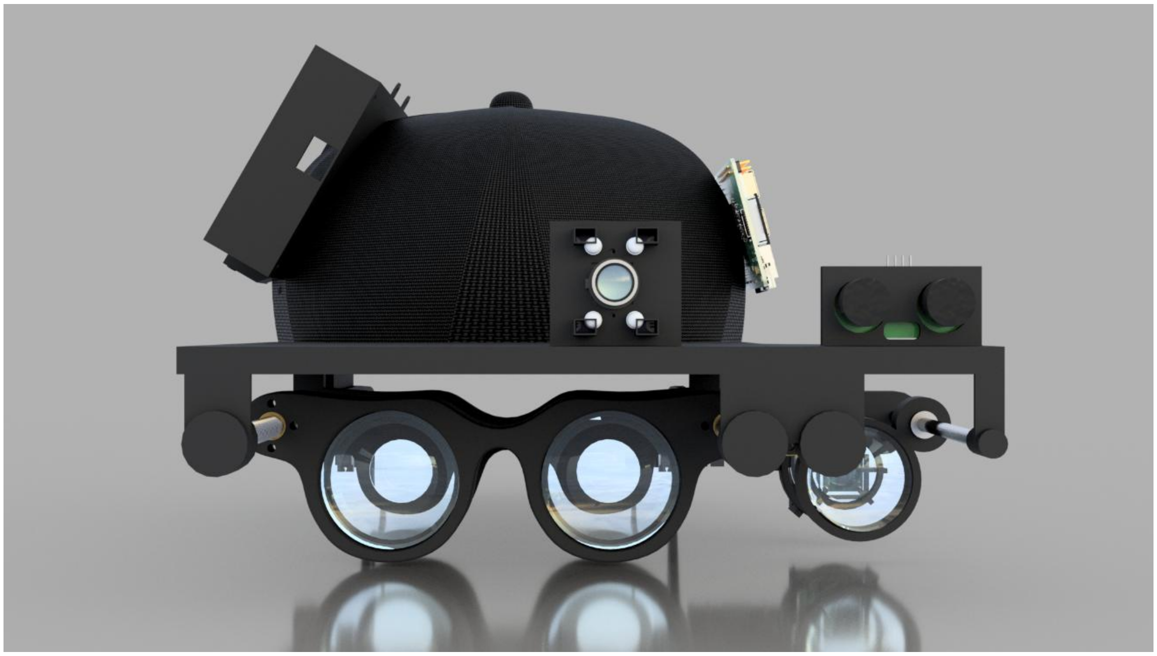

Figure 8.2.2 Full System Digital Rendering Final Version [Front View]

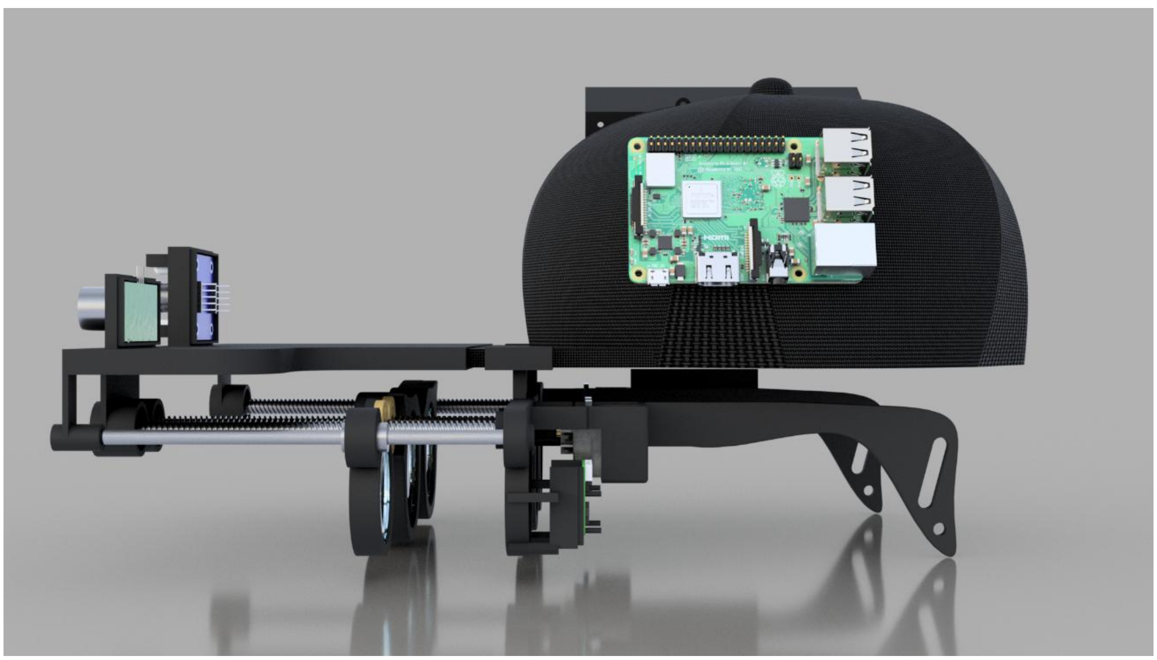

Figure 8.2.3 Full System Digital Rendering Final Version [Side View]

9 System Testing and Evaluation

During the development of any new system, testing and evaluation are invaluable. While calculations and subsequent simulations are important to the development process, testing is arguably more important. By testing the system, we were able to identify any unexpected issues or factors that were not initially accounted for. Upon testing and determining the failures within the system, it was then possible to make adjustments and corrections that ensured a properly functioning system. Ultimately, both system testing and evaluation were both crucial steps in the production of our system.

9.1 Hardware Testing

In this section, we focus on testing the overall effectiveness of our components while changing their environment. We had to ensure that the selected components could achieve the desired goals and specifications while maintaining the expected standards all within the given constraints. By testing the components, we would become aware if different components would ultimately be necessary for our system to function properly.

9.1.1 Photodiode Testing

To test our photodiodes, we used a BPW34S photodiode in series with a 1kΩ resistor as shown in Figure 9.1.1. We connected the cathode of our photodiode to a positive 5V DC voltage source while our ground was connected to a Multimeter probe. Next the other probe of our multimeter (non-grounded) probe was placed in the other side of the resistor, the side that is not sharing a node. We measured the current change when the light in the room was adjusted to higher and lower intensity. As expected, our current increased when the light intensity increased, while the current decreased when light intensity decreased. We tested the same circuit, but we placed a red filter in front of our photodiode and then flashed red light through it, resulting in a much higher current than when we tested with a green light shining through. In Table 9.1.1 we can see the results and the current drop when we flashed a green light through our photodiode. This test was the first step in the development of the color identification system as it confirmed that photodiodes in conjunction with filters would be utilized to detect unique colors.

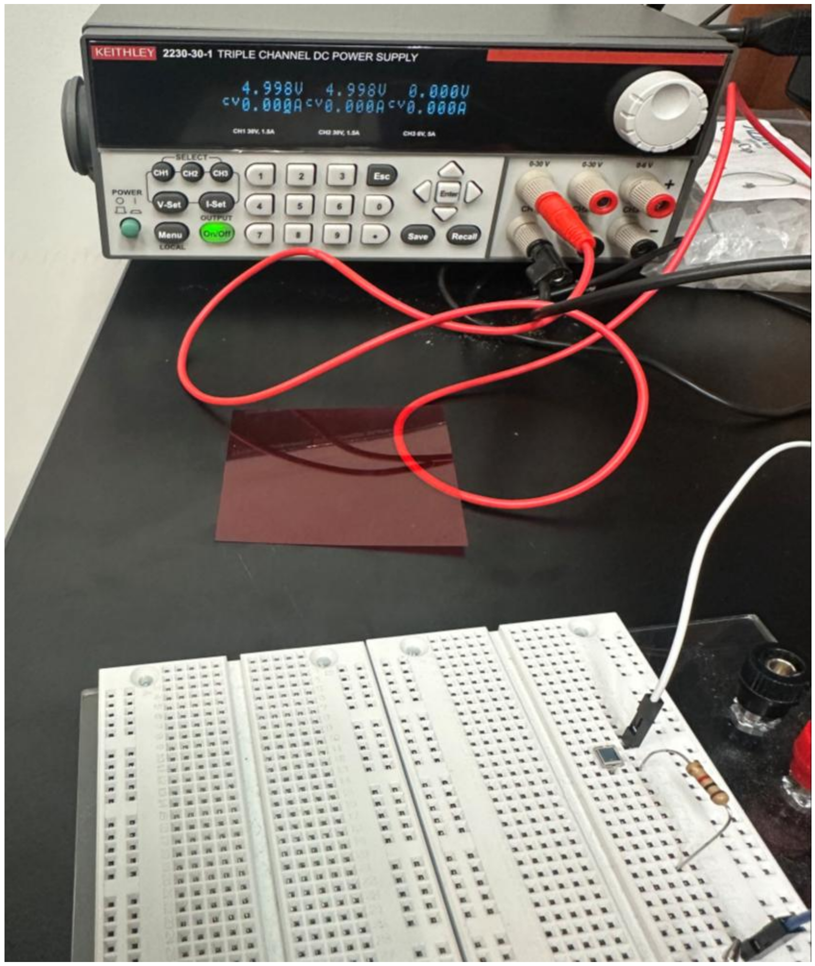

Figure 9.1.1 Photodiode Circuit for Testing

Current (mA) Flashlight off	Current (mA) Red Light	Current mA Green Light
0.1759	0.1230	0.0302

Table 9.1.1 Photodiode Testing Results

9.1.2 Motor Testing

Regarding our motors, we had initially selected the NEMA 17 motor in conjunction with the DRV8825 motor driver. To test them followed the setup from Figure 9.1.2. This allowed us to test different parameters, such as the motor rotating in both directions. The NEMA 17 motor requires voltage and current of 3.3V and 1.5A accordingly. Therefore, the DRV8825 current limit had to be adjusted. To do so we connected a multimeter probe to a small screwdriver and used it to turn the variable resistor to the required value for our motors. Then we had to measure the voltage until it reached our desired voltage. After properly limiting the current, we could test our motors.

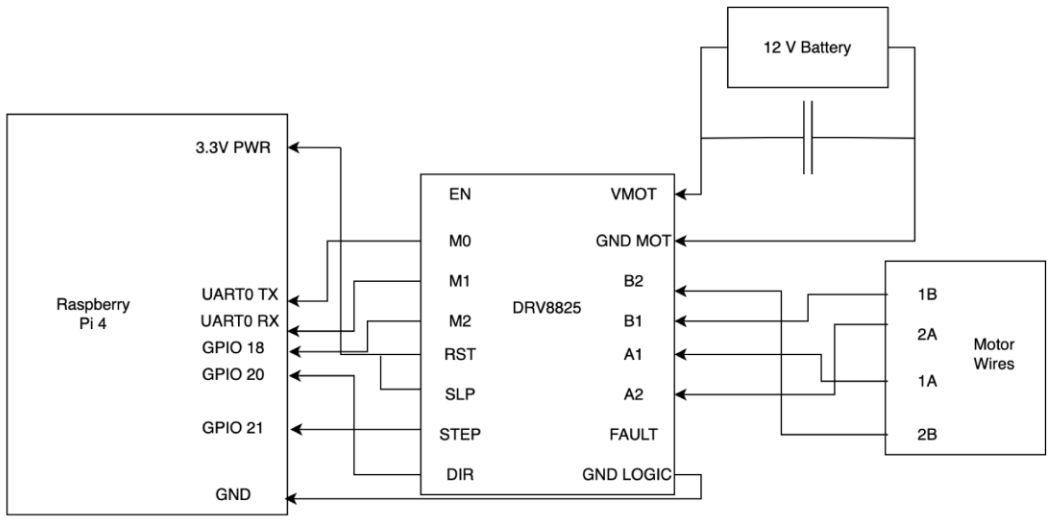

Figure 9.1.2 Motor Testing Setup

This initial test was based on our first decision of using stepper motors for our system. Later on we moved into servo motors as they are more lightweight than stepper motors. Testing on this motors consisted on visual analysis of which motor rotated faster than the others checking on both directions. For this we had acquired ten MG90S servo motors to test and calibrate on. From this we had two defective ones. Our focus was on having three motors that worked properly and that we could calibrate them to spin at the same speed. To do so we had to adjust the line of code that moved the motor clockwise and counterclockwise. As increasing the degrees in the code meant our motor will slow down counterclockwise and clockwise. An example code from Arduino IDE is: “servo1.write(1046); “, this line of code ran one of our motors in the clockwise direction. Adjusting the 1046 number accordingly to all three motors resulted in the three motors rotating at the same speed.

9.1.3 Focusing System Testing

Before we could accomplish our goal of a functioning auto-focusing system, we first started with a lens system that had a manually adjustable focal length. As an initial test, we utilized two lenses, one diverging and one converging, that were optically aligned. The two lenses were placed in a 3D-printed frame with rails to adjust the distance between the lenses and subsequently adjusting the effective focal length. This positive lens had a focal length of 78 mm, and the negative lens had a focal length of -69 mm. These focal lengths correspond to the optical powers of 12.82 D and -14.71 D, respectively. With a railing that can extend up to 25 mm, this gives a variable optical power that ranges from -1.5 D up to 2.5 D according to our calculations. These optical power ranges correspond to a variable effective focal length that ranges from -667 mm up to as close as 400 mm. Since these values were calculated under the assumption of thin lenses, they were not entirely accurate. Upon testing the actual range, it was clear that the effective focal length was indeed adjustable, but the range was not exactly as expected. Specifically, there seemed to be a larger optical power than calculated resulting in an actual range of approximately -0.5 D up to approximately 1.5 D. In addition to this, we noticed minor magnification as the distance between the lenses increased. This initial version of an adjustable focusing system can be seen in Figure 9.1.3 below.

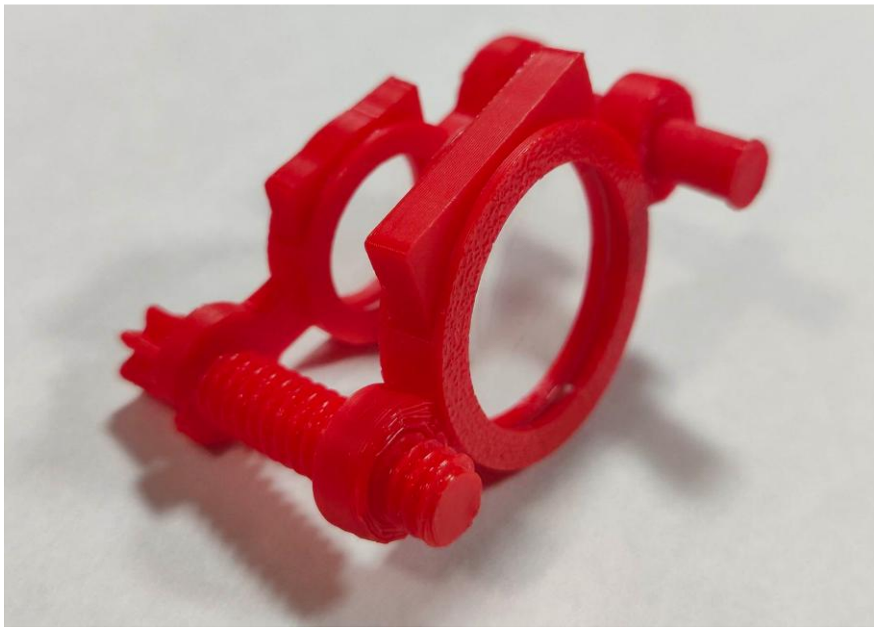

Figure 9.1.3 Adjustable Focusing System Version 1

After the success of the first version of this system, a larger, wearable version was designed. Version 2 as seen in Figure 9.1.4 was designed to more closely resemble eyeglasses. This version utilized a pair of lenses for each eye, resulting in a total of four lenses. Here the diverging lenses have a focal length of -50 mm, and the converging lenses have a focal length of 100 mm, corresponding the optical powers of -20 D and 10 D, respectively. With a variable distance between the lenses that can extend up to 100 mm, it was calculated that the variable optical power should, in theory, range from -10 D up to 10 D. These optical powers correspond to focal lengths of -100 mm and 100 mm, respectively. This is also assuming that we are utilizing thin lenses, which is certainly not the case. In reality, the optical power seemed to range from approximately -4 D up to approximately 12 D. The corresponding effective focal lengths are approximately -250 mm and 83.33 mm, respectively. With these powerful lenes, it was also clear that the magnification was noticeable as well. Due to this, the next version of the adjustable focusing system utilized less powerful converging and diverging lenses. This resulted in a smaller range of variable optical powers and thus a smaller range in variable effective focal lengths. The plan was to utilize a diverging lens with a focal length of -100 mm and a converging lens with a focal length of 150 mm. These lenses provided us the range of optical powers we desired while maintaining a maximum distance between the lenses of approximately 100 mm. However, upon testing the new lenses, we found that the maximum distance would have to be much larger, which we concluded would cause alignment issues as well as weight distribution issues. For these reasons, we chose to stick with the -50 mm diverging lenses and the 100 mm converging lenses.

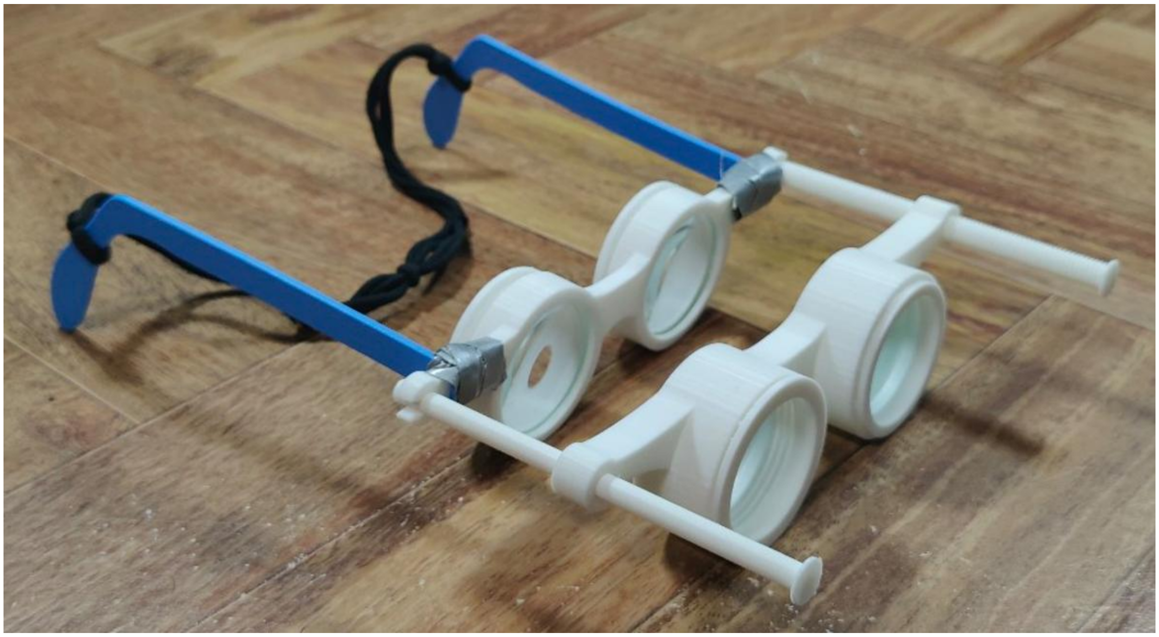

Figure 9.1.4 Adjustable Focusing System Version 2

For our final design as seen in Figure 9.1.5, we utilized the same lenses as the previous version. This time, however, we programmed in limitations on the maximum and minimum separation between the lenses. The maximum separation is set to 67.5 mm which corresponds to +3.5 D of optical power with a focal length of 286 mm. The minimum separation is set to 37.5 mm which corresponds to -2.5 D of optical power with a focal length of -400 mm. In order to test the negative optical power, an additional positive lens with an optical power of 5 D was attached to the existing positive lens. With the separation set to 25 mm, the total optical power of the system would then be +2.5 D with a focal length of 400 mm. Upon testing, we successfully achieved our desired optical powers.

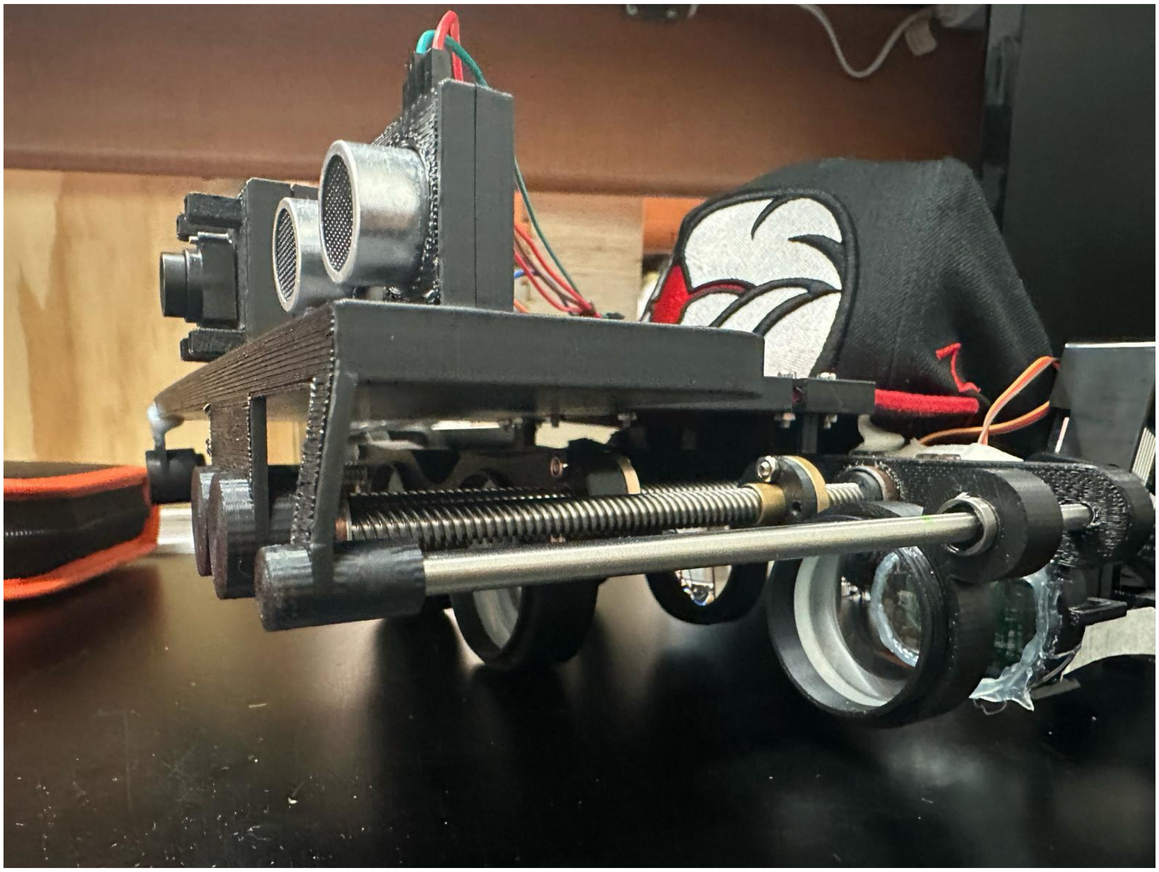

Figure 9.1.5 Adjustable Focusing System Final Version

To test the auto-focusing system, we placed a poster on a wall in front of our prototype at various distances, 400 mm, 666 mm, and 1000 mm. We then recorded the data from the tests onto Tables 9.1.2 and 9.1.3 below. On average, the acquired distance was approximately 37.12 mm above the actual distance. While not perfectly accurate, the acquired distance was suitable for a acquiring focus. During testing, the system could acquire focus in under 20 seconds consistently and typically found focus on its first attempt. This was incredibly promising. The actual optical power of the system was consistently within 0.1 D of the expected optical power. We had set a Sobel threshold focus value of 1000 as we found this to be an accurate indicator of an image in focus. Our tests managed to surpass this value significantly. This indicates that we potentially could have increased the threshold value even further to ensure a sharper focus.

Test #	Actual Distance (mm)	Acquired Distance (mm)	Expected Optical Power (D)	Actual Optical Power(D)	Expected Change in Separation of Lenses (mm)	Actual Change in Separation of Lenses (mm)
1	1000	1049.55	1	0.9	5	4.5

2	1000	1060.26	1	0.9	5	4.5
3	1000	1017.25	1	1	5	5
4	666	688.13	1.5	1.5	7.5	7.5
5	666	700.03	1.5	1.6	7.5	8
6	666	698	1.5	1.6	7.5	8
7	400	434.66	2.5	2.5	12.5	12.5
8	400	440.61	2.5	2.4	12.5	12
9	400	443.16	2.5	2.4	12.5	12
10	400	437.55	2.5	2.4	12.5	12

Table 9.1.2 Autofocus Test Results A

Test #	Autofocus Acquisition Time (s)	Sobel Threshold Focus Value	Initial Focus Value	Final Focus Value	# of Attempts
1	19.31	1000	464	1281	1
2	16.54	1000	463.1	1294	1
3	16.39	1000	466	1455	1
4	17.19	1000	476.3	1453	1
5	15.53	1000	471.65	1415	1
6	17.63	1000	482	1420	1
7	18.88	1000	521	1283	2
8	17.53	1000	517	1276	1
9	17.16	1000	528	1307	1
10	17.38	1000	520.07	1270	1

Table 9.1.3 Autofocus Test Results B

9.2 Software Testing

In this section, we focus on some general testing done to verify how certain components worked and interacted with one another during the software design testing period. Some sections utilized pre-made code found online which is cited in the references and shown in the appendix for ease of testing.

9.2.1 Colorimeter

The TCS3200 was connected to our ESP32 PCB and run on it. Unfortunately, there was a small mistake on the PCB that we did not have time to fix, that being the lack of two additional ports that we needed to control two of the pins on the TCS3200 (S0 and S1). This prevented us from being able to control the Output-Enable (OE) and thus the sensor itself. However, we found a workaround by connecting OE to ground and thus still ultimately being able to control the sensor; we just cannot stop its output without ending the program.

The colorimeter is programmed in Arduino, utilizing a calibration and a detection cycle. After calibrating to a black surface and a white surface, the three RGB values are averaged out to their lowest and highest values, which defines the bounds of the calibration. This cycle is performed upon button activation and must be repeated whenever detection is desired by the user because of the possibility of changing light conditions. The program then reads the RGB values, and if it determines that two of them are within a predefined threshold it assigns them to a secondary color (cyan, magenta, or yellow), or if the threshold is exceeded it assigns the detected color to a primary color (red, green, or blue). If the system detects near-maximum or minimum values, it assigns black or white.

9.2.2 Raspberry Pi Camera Module

For the Raspberry Pi Camera Module it is necessary to make sure that it is working properly and can be integrated easily with OpenCV libraries within Python for image analysis. Our biggest concern is with the quality of the photo. Although it does not have to be the highest quality, it needed to be clear enough the pixels were differentiable from one another they could be sorted into separate colors. Overall, not much software was necessary to test the implementation of it. Using some basic line commands within the Raspberry Pi 4 desktop terminal, we were able to enable all the proper camera settings once the camera module was attached to the board. From there we were able to use a command to take a simple picture with the camera and output it with whatever name is defined. Figure 9.2.1 below contains the picture taken during our video demo that proves that the camera is working as intended.

Figure 9.2.1 Camera Testing
(Camera Module v2 in the bottom left and its live feed displayed on the screen)

Our testing with the color detection portions of the camera module v2 involved running the color detection algorithm. This entailed capturing a cropped image with the camera and then using the cv2 library to then scan through the pixel values within this image to calculate the RGB values within. Afterwards, the sum of the intensities is compared, and the system then determines the color detected based on the highest value. We ran a number of trials to test this functionality and found that it was consistent at a range of up to 2 feet, with the results tabulated below.

Test #	Object Color	Detected Color (Module v2)
1	red	red
2	red	red
3	red	red
4	red	red
5	green	green
6	green	green
7	green	green
8	green	green
9	blue	blue
10	blue	blue
11	blue	blue
12	blue	blue

Table 9.2.1 Color Detection Test Trials

9.2.3 Audio Feedback

Audio is a crucial part of our system. Especially given we are focused on visually impaired individuals who do not want to rely on any sort of additional visual feedback. To do some simple testing, we implemented the basic message library called pygame in Python which plays a predefined audio message; the code is shown below in the appendix (B-1). We utilized a simple if statement checks if the proper state is found. In this case there is an error and color detected state. When we connected a Bluetooth speaker to my laptop, it played a simple message "Process completed" and if there was an error of any sort, it would state that the process was incomplete. Overall, a remarkably simple conceptual check, but audio was successfully implemented.

9.2.4 Ultrasonic Sensor

For the testing of the ultrasonic sensor, it was necessary to make sure it could connect properly to the Raspberry Pi and read out accurate measurements for the algorithms to use later. Given I used an ultrasonic sensor for my junior design project, we just recycled and reused the code we made to measure and print out the distance on an LCD display. The image can be seen below in Figure 9.2.2 where the output from the ultrasonic sensor is shown.

Figure 9.2.2 LCD Display of Ultrasonic Sensor distance measurement

The code was uploaded using an MSP board and a premade PCB/breadboard to power and connect the display to the ultrasonic sensor. You can see here the measured distance was only 37mm or about 1.4 inches. It all worked accurately up to about a couple meters and as close as 1 mm.

The ultrasonic sensor sent the information directly from the ESP32 to the Raspberry Pi so all distance measurements were exactly the same for every test we did.

9.2.5 Edge-detection

To test the conceptual plan for implementing an edge-detection code, we were able to find a pre-coded GitHub where a Sobel filter was implemented to measure contrast of an image and from there, we were able to identify which sides of the pixels were the edges of the photo. The code is referenced and shown below in the appendix (B-2). Here, Figure 9.2.3, shows the initial photo loaded into the program.

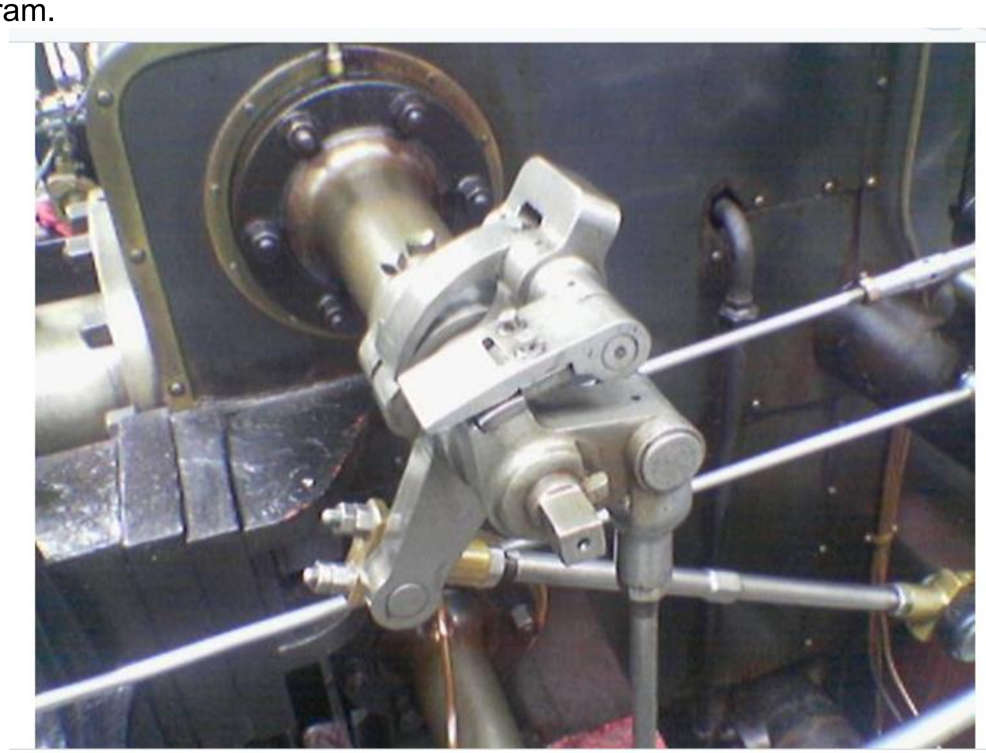

Figure 9.2.3 Edge-Detection testing (initial input)

A simple picture of this mechanical part is then grey scaled and then run through matrixes to separate the pixels into a three-by-three patch. The resulting image is seen below in Figure 9.2.4.

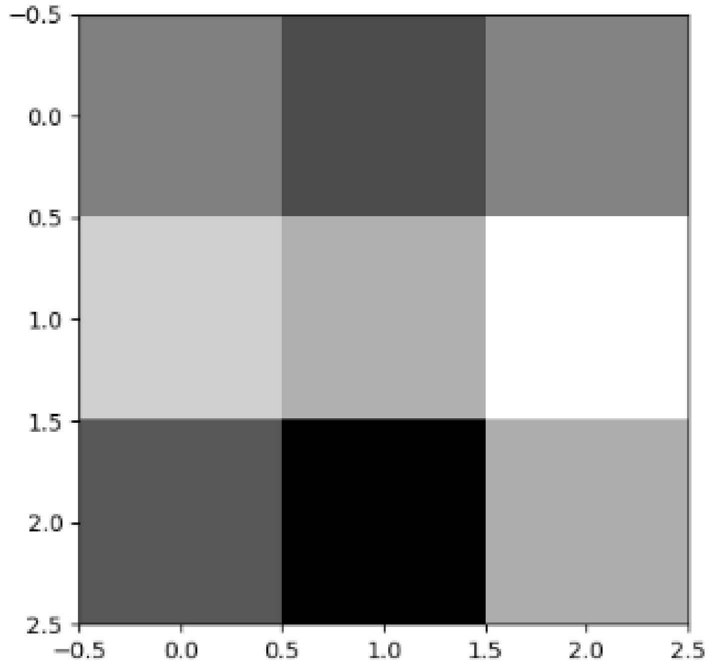

Figure 9.2.4 Edge-Detection testing (greyscale matrixes output)

From here, the matrixes are run, and those values are used to calculate a few simple operations seen in Formula 9.2.1. This will measure out which values are within a certain range for each individual pixel area.

$$\sqrt{[G_x(A)]^2 + \left[G_y(A)\right]^2} \tag{9.2.1}$$

After which, the resulting value will tell the number of pixels contained in the output image and use those values to create a new image. This image will highlight which sides are edges and which ones are not. This is just one implementation of edge-detection. There are many approaches and given our needs for adjustment based on picture quality next semester, there may need to be a different approach used. [90]

The following table showcases our autofocusing tests and highlights the value for the sobel filter that we ultimately went with, which was 1000.

Test #	Distance from wall (mm)	Autofocus time (s)	Sobel Thresh Value	Final Sobel Value	# of attempts
1	1000	19.31	1000	1281	1
2	1000	16.54	1000	1294	1
3	1000	16.39	1000	1455	1
4	666	17.19	1000	1453	1
5	666	15.53	1000	1415	1
6	666	17.63	1000	1420	1
7	400	18.88	1000	1283	2
8	400	17.53	1000	1276	1
9	400	17.16	1000	1307	1
10	400	17.38	1000	1270	1

Table 9.2.2

Our program ran for an average of 17.35 seconds until autofocus was achieved, and the program ultimately took an average of 1 attempt to focus. We deem this a major success for our system.

9.3 Integration of Systems

After careful testing of each individual subsystem, we began the process of integrating them together. The following section is a record of how our various components interplay with each other in the final design.

9.3.1 Raspberry Pi 4

The Raspberry Pi 4 is serving as the central processing unit for our project in charge of organizing the functionality of all the connected parts. This MCU gives the computational power necessary to process all incoming data and redirect it to the proper system analysis (color detection or edge detection) to give out the proper audio feedback. Here, we are focused on how the four main components are connected with the MCU: Raspberry Pi camera, ultrasonic sensor, motor, and audio.

Given that the camera module we are utilizing is the Raspberry Pi camera module, a direct add on meant for the Pi MCU boards, integration is very straight forward. The camera module is connected through the dedicated Camera Serial Interface (CSI) port and is controlled through pre-set Python libraries like OpenCV and picamera.

The ultrasonic sensor is set up with the sensor connecting to an ESP32, which then communicates with the Raspberry Pi. Python libraries like RPi.GPIO and/or gpiozero were utilized to interact to receive and send communication signals. When the Pi needs a measured distance, it will trigger a signal to be sent to the sensor which will emit an ultrasonic pulse. That received signal will represent the time taken for that pulse to return which can then be transmitted to the Pi and calculated into a distance measurement.

The motors are connected similarly to the ultrasonic sensor with a motor driver being attached to the Pi on the GPIO pins and interacted with through the libraries such as RPi.GPIO and gpiozero. The autofocus algorithm will trigger the motor through the Pi if a lens adjustment is needed and the Pi will instruct the motor to move in incremental steps until either the goal focus is achieved, or the program terminates from a timeout.

Audio did not require much of a setup given we chose to utilize a Bluetooth connection. The Raspberry Pi 4 already comes with a built in Bluetooth and Wi-Fi module which made connectivity extremely simple. The only thing necessary was a setting change to allow the Pi to make its connection. For a backup plan, the Pi also came with a built-in audio jack in case we decided not to use Bluetooth for whatever reason. In which case, we could just connect earphones as our way of audio output.

9.3.2 Auto-Focusing System

The auto-focusing system utilizes the ultrasonic sensor, both motors, both lens systems, and the CMOS sensor. All of these components are guided by the Raspberry Pi 4 and the ESP32 to perform the individual tasks necessary for the auto-focusing feature to function properly. Most of these components are physically attached to a 3D-printed frame that is attached to the hat.

All the lenses are placed within custom-made lens holders. The lenses used in the primary lens system are set in optical alignment with the user's eyes. This is achieved through a design that resembles the frames for eyeglasses. The front and back pairs of lenses for this system are capable of mechanically separating through the use of motors with threaded rods. As for the CMOS sensor's lens system, the setup is nearly identical aside from the use of a guide rod and a linear bearing. The optical alignment here is aligned with the CMOS sensor. This lens system utilizes a separate motor allowing each lens system to adjust independently as necessary.

9.3.3 Color Identification System

The color identification system utilizes the CMOS sensor, the colorimeter, the lens system for the CMOS, and a lens to guide light to the colorimeter. These components are guided by the ESP32 and the Raspberry Pi 4, which compares the output of the CMOS and colorimeter to determine the detected color. These components are all attached to the front of the headset, with the CMOS at the side of the headset and the colorimeter attached to the top of the visor, in front of the forehead.

As stated with the auto-focusing system, the CMOS sensor's lens system is aligned with the CMOS sensor and possesses its own motor to adjust as necessary. The lens for the colorimeter is static and directly in front of the colorimeter. The colorimeter is enclosed within a custom-made container that blocks ambient light, ensuring that the only light that can pass through the lens will reach the photodiodes that determine the wavelengths of light present.

9.4 Plan for Senior Design 2

Considering the limited time left once Senior Design 2 began, we started our final semester by ensuring any unacquired components were immediately ordered to arrive in a timely manner. Whilst waiting for the items to arrive, we continued to test and assemble what we could based on the components that we had already acquired.

As the components arrive, we tested them individually to ensure that they'd function properly with our system. If we found certain components to be unsuitable for our purposes, we had to order the proper replacement components. The proper components would then be determined by analyzing where the originally acquired components fell short and by performing simulations to verify improved performance. As we confirmed the components were suitable for our needs, we progressively assembled and tested each system of the protype until the full prototype was functional. We believed that this would align with the submission of a midterm demonstration of our prototype. Unfortunately, this wasn't quite the case. The majority of our systems were functioning decently well, but certain components had to be replaced with better parts and the prototype could not be fully assembled yet.

As the prototype developed into its finalized iteration, we started testing for unexpected errors. Once the anticipated concerns were all resolved, we started to prepare the system to function under less ideal environments and identify when the system may face obstacles. Essentially, at this point the system was functioning, and we were testing its limits, so as to push those limits further. Once finalized, we presented our final video demonstration and moved on to the revision of this report to include any adjustments we made to the system. After this, we prepared the finalized prototype for its final demonstration.

10 Administrative Content

As the backbone of an organized plan, the administrative content below served to keep us on track to accomplish our goals by the end of Senior Design 2. By addressing our budget and anticipated costs, we minimized our expenses and avoided unnecessary spending. The milestones were projections of our progress and how far along we anticipated being on a weekly basis. By properly and evenly distributing our workload, we ensured that each member of the team was contributing equally. We wanted to do the best we could to ensure no aspect of the project went overlooked.

10.1 Budget and Financing

As a team, we agreed to spend up to $250 each for a maximum cost of $1000. Since we had not secured a sponsor for our project, we had to fully finance the project ourselves. This was a key reason we had set the budget to $250 each. The cost was expected to be just below half of our budget, at approximately $470. The key to keeping our costs down was proper research to reduce unnecessary purchases. In addition to this, by choosing to 3D-print the majority of our frame, we managed to reduce costs as well.

Ultimately, the cost of the components used in the final design was approximately $470. However, when taking into consideration all the components that were tested, even if they were not used in the final design, the total cost was closer to $910.

10.2 Bill of Materials

Table 10.2.1 below contains expenses. As we progressed through the development of this prototype, we updated this finance table to accurately reflect out total expenses.

Component	Name	Price	Quantity	Total Price
CMOS Sensor	Raspberry Pi Camera Module v2	$13	1	$13
Primary Lenses	Eisco Biconvex Lens (+100 mm Focal Length)	$12	3	$36
Secondary Lenses	Eisco Biconcave Lens (–50 mm Focal Length)	$14	3	$42

Lead Screws	150mm T8 Tr8x8 Lead Screw and Brass nut	$7.89	3	$23.67
Buttons	Adafruit mini	$0.50	5	$2.50
Frame	3D Printed	-	1	N/A
Motor	MG90S- Servo Motor [8-Pack]	$16.99	1	$16.99
Colorimeter	TCS3200	$20	1	$20
Raspberry Pi 4	Raspberry Pi 4 4GB Starter PRO Kit – 4GB RAM	$139.99	1	$139.99
PCBs	ESP32-WROOM-32D, 5V Regulator, TCS3200	$70	3	$70
PCB components	SMT,SMD, LEDS, etc.	$45	N/A	$45
Power Supply	Talentcell Rechargeable 12V 6000mAh/5V 12000mAh DC Output Lithium ion Battery Pack	$32.99	1	$32.99
3D-Printer Filament	Elegoo PETG (1) & PLA (1)	$14.99	2	$29.98
Total Cost		~$472.12		

Table 10.2.1 Finance Table

10.3 Milestones

To achieve the goals and objectives set for this project, we had laid out milestones that had to be accomplished on a weekly basis for both Senior Design 1 and Senior Design 2 as can be seen in Table 10.3.1 and Table 10.3.2 respectively. While we could predict exactly how the project would progress, we attempted to plan and prepare so that we could make adjustments as necessary. Ultimately, the milestone tables had to be relatively flexible as we were certain that we would face unexpected obstacles. As it turns out, we did in fact face unexpected obstacles.

Senior Design 1	
Week	Goal
1 – 2	Form groups and finalize project concepts.
3	Divide and Conquer 10-page draft due.
4	Divide and Conquer review meeting w/ Dr. Chan and Dr. Kar.
5 – 6	Post Divide and Conquer Revision on website.
7	Create Gantt chart. Begin research.
8	Research standards and identify constraints for 60-Page draft.

9	Finish 30-pages of the 60-page draft.
10	Complete and submit the 60-page draft.
11	60-Page review meeting w/ Dr. Chan and Dr. Kar.
12	Post 60-Page Revision on website.
13	Begin work on 120-page report.
14	Complete 120-page report.
15	Post 120-page report and demo video on website.

Table 10.3.1 SD1 Milestone Table

Senior Design 2	
Week	Goal
1	Purchase parts that have not yet been acquired
2 – 6	Begin assembly of the prototype
7 – 10	Test prototype and adjust as necessary
11 – 12	Finalize prototype
13	Peer presentation
14	Submit Final Report
15	Final Presentation

Table 10.3.2 SD2 Milestone Table

10.4 Work Distribution

Table 10.4.1 below lists the tasks that needed to be accomplished for our system to function as well as how those responsibilities were assigned with a primary and secondary team member assigned to each task.

	Task	Primary Responsibility	Secondary Responsibility
Auto-Focusing Feature	Set up a lens system for variable optical powers	Genaro Morales	Midkhat Satdanov
	Set up a secondary lens system for the CMOS sensor	Genaro Morales	Midkhat Satdanov
	Adjustable movement between lenses	Genaro Morales	Julie Gallagher
	Programming to detect focus and adjust lens separation as necessary	Kayla Stanley	Genaro Morales
	Setup up colorimeter to accurately detect colors	Midkhat Satdanov	Julie Gallagher

Color Identification Feature	Design lens system to improve color detection	Midkhat Satdanov	Genaro Morales
	Correlate colors detected by CMOS and colorimeter to accurately identify the color present	Kayla Stanley	Midkhat Satdanov
Software	Set up Raspberry Pi to communicate with hardware	Kayla Stanley	Julie Gallagher
	Program buttons to initiate appropriate features	Kayla Stanley	Everyone
	Set up ESP32 to communicate with peripherals	Julie Gallagher	Genaro Morales & Midkhat Satdanov
	Program audio response system to give appropriate responses	Kayla Stanley	Everyone
Hardware	Design a PCB for our system	Julie Gallagher	Kayla Stanley
	Design an appropriate power supply system	Julie Gallagher	Kayla Stanley
	Ensure interconnectivity of components	Julie Gallagher	Kayla Stanley
	Design frames for multiple systems	Genaro Morales	Everyone

Table 10.4.1 Work Distribution Table

10.5 Declaration

We hereby declare that we have not copied more than seven pages from the Large Language Model (LLM). We have utilized LLM for drafting, outlining, comparing, summarizing, and proofreading purposes.

11 Conclusion

The Poly-Assistive Auto-Focusing and Color-Identifying Utility Lenses for Mild Visual Impairments project represents the latest iteration in assistive technology that was designed with humanity as its primary focus. Our objective was to create technology that helps those with mild visual impairments navigate the world more easily with a single packaged solution, without the need to go out and acquire several different sets of glasses and other assistive devices that must be swapped out to achieve different aims. To do so, the solution that this team has produced involves an interlaced, complimentary network of lenses and optomechanical devices that work in tandem to provide the user with the tools they need to overcome their visual obstacles.

The primary methods by which these aims are achieved are separated into two subsystems, the autofocusing system, and the color identification system. Both systems overlap both by necessity but also by intention to reduce the bloat of physical components the user must wear. The autofocusing system involves a sophisticated set of lenses that are guided by motorized rails, changing the position and therefore optical power of the lenses the user looks through. The color identification system utilizes both a colorimeter and a CMOS sensor to ensure the highest degree of accuracy possible when informing the wearer of the color of the object they are perceiving. The CMOS especially ties both systems together, as it is required to set the parameters by which we determine whether the image the user sees is in focus as well as sorting through the colors of the environment and relaying that information to the user.

Both of these systems rely on this interplay of components to ensure proper recognition and optical power and are guided by the powerful Raspberry Pi 4 and the less powerful ESP32. The choice of components to maximize the accuracy and efficiency of each subsystem was highly intentional and meant to produce the best possible outcomes, and we had made such choices sometimes in spite of higher prices as we understood the needs of the project.

Our design process was not necessarily always straightforward, however. Several changes were made along the way as we narrowed the focus and refined the specific details of what P.A.U.L. was meant to be capable of. Originally, our specifications for optical power were meant to place the capabilities of the system at producing between -1.5 to +1.5 diopters. As we conducted further research, we realized that it would be beneficial to increase this range to -1.5 to +2.5 D. Furthermore, while the color detection system was originally meant to be comprised of a complicated series of photodiodes in a housing with a diffraction grating, we realized that it would be simpler to design a colorimeter as a pcb and add optics to the system to enhance its function. Additionally, the presence of a diffraction grating would have required us to ensure that all of the incoming light onto the system would be angled in a specific direction and thus we opted to remove the diffraction grating. We also had to seek out components that were as compact as possible, something that had posed a particular struggle when it came to the selection of our motors.

There were some pitfalls we managed to avoid, though. Project I.R.A.S. from a previous UCF senior design group incorporated a less powerful computer for its design, only for that team to realize that their chosen ESP32S did not have the processing power to employ all of their desired features. Therefore, we immediately chose to go with the Raspberry Pi 4 despite a higher and more prohibitive cost due to the lessons we gleaned from past endeavors. Additionally, our comparison with existing technology that is being produced by large corporations such as Meta revealed the market niches that we could fill with our own project, namely by prioritizing more accessibility in our system.

P.A.U.L.'s design enables a high degree of flexibility and wide applicability to the greatest number of consumers possible. By simply setting the system to their optical prescription, the user's experience with P.A.U.L. becomes highly personalized. With its lower cost and greater set of assistive features compared to market competitors, the headset puts a pioneering foot forward across multiple fronts in the realm of eyewear. P.A.U.L.'s design marks a step forward in improving the quality of life for anyone who requires its assistive features.

This document contains a comprehensive record of P.A.U.L.'s design process, covering the design philosophy, motivations, theories, technologies, part selection, implementation, limitations, and administrative procedures that composed its overall design. The careful research executed by the University of Central Florida's students at the College of Engineering and Computer Sciences and the College of Optics and Photonics demonstrates our capabilities and our aptitude for overcoming the challenges faced during the implementation of P.A.U.L.'s design. It is our sincere hope and intention with this project that it becomes one of many technologies that enhances the lives of those inconvenienced by any form of physical impairment, and we move forward with its design hoping to contribute to the future of assistive technologies.

Appendix

A. Large Language Model Prompts

A-1 Prompt on Fresnel Lenses

Explain, in detail, what a Fresnel Lens is. What purpose does it serve? What are its pros and cons? Provide sources for your information.

ChatGPT's Response:

A **Fresnel lens** is a type of lens originally developed by French physicist Augustin-Jean Fresnel for use in lighthouses. It consists of a series of concentric, annular sections, each representing a portion of a simple lens but flattened to reduce material thickness. This design significantly decreases the weight and volume of the lens while maintaining its ability to focus light efficiently.

Structure of a Fresnel Lens
A typical lens is thick at the center and thinner at the edges, focusing light to a single point. The Fresnel lens replicates this behavior but in a much more compact form. By dividing a standard convex or plano-convex lens into thin, concentric rings called "prisms" or "steps", each section focuses light much like a part of a standard lens. These prisms reduce the amount of material used while keeping the lens' optical properties.
There are different types of Fresnel lenses based on their design and purpose:

- **Imaging Fresnel Lenses:** Used in optical systems like magnifiers or solar concentrators.
- **Non-imaging Fresnel Lenses:** Often used for light collection or distribution, such as in lighthouse optics or solar panels.

Purpose of a Fresnel Lens
The primary purpose of a Fresnel lens is to focus light efficiently while using much less material compared to conventional lenses. This makes it ideal for applications where large aperture lenses are needed but size, weight, or cost constraints exist. Fresnel lenses serve various functions across different industries:

1. **Lighthouses:** To focus light into a narrow beam that can be seen over long distances.
2. **Solar Energy:** Used to concentrate sunlight onto a small solar cell or thermal receiver, increasing efficiency.

3. **Lighting and Projection Systems:** For stage lighting, overhead projectors, and photography lighting to focus or disperse light evenly.
4. **Magnifiers:** Handheld magnifiers, headlamps, and reading aids often use Fresnel lenses due to their thinness and lightweight design.
5. **Automotive and Traffic Lights:** Fresnel lenses are sometimes used in taillights or indicators to control light direction.

Advantages of Fresnel Lenses

1. **Lightweight and Thin:** The lens uses less material, making it significantly lighter and thinner than traditional lenses, especially for large apertures.
2. **Cost-Effective:** Less glass or plastic material is required, reducing production costs, especially for large lenses.
3. **Compactness:** Fresnel lenses are ideal for applications where space is limited.
4. **High Efficiency for Large Apertures:** They are excellent for large optical systems, as they can focus light without the bulk of a conventional lens.
5. **Flexibility in Materials:** Fresnel lenses can be made from glass or plastic, offering versatility depending on the application (e.g., lightweight plastic for consumer products or durable glass for industrial use).

Disadvantages of Fresnel Lenses

1. **Reduced Image Quality:** Fresnel lenses are not as precise as traditional lenses, often leading to image distortion, chromatic aberration, and a loss of sharpness. The segmented surface creates diffraction effects that can degrade image quality.
2. **Optical Efficiency Loss:** Although they are good at focusing light, they do not focus it as accurately as traditional lenses due to surface discontinuities and the stepped design, leading to some loss in optical efficiency.
3. **Durability Concerns:** Plastic Fresnel lenses are lightweight and cheap but may not be as durable as glass lenses. They can scratch easily and are more prone to wear and tear.
4. **Limited Applications for Imaging:** While suitable for applications that do not require high-resolution focusing (like solar concentrators or lighthouses), they are less suited for precision optical applications (e.g., high-end cameras).

Sources

1. Smithsonian Institution. **The Fresnel Lens: Revolutionizing Lighthouse Optics** - Provides an overview of the development of the Fresnel lens for lighthouses and its historical significance.
2. GRI Renewable Industries. **Fresnel Lenses in Solar Energy Applications** - Discusses the use of Fresnel lenses in concentrating solar power systems for improved energy collection.

3. Optics Express Journal. **Analysis of Fresnel Lens Design** - Detailed technical paper on the optical properties, efficiency, and drawbacks of Fresnel lenses.

These sources provide further reading on Fresnel lenses, covering both their historical context and modern engineering applications.

Gemini's Response:

Fresnel Lens: A Thin, Lightweight Optical Device
A Fresnel lens is a special type of optical lens designed to focus or disperse light while significantly reducing its thickness compared to traditional lenses. It achieves this by dividing the lens surface into concentric rings or grooves, each with a different curvature. These rings or grooves are essentially small sections of a traditional lens, stacked together to form a much thinner overall structure.
Purpose and Applications
Fresnel lenses are widely used in various applications due to their unique properties:

- **Light Focusing:** They are excellent at focusing light to a specific point, making them ideal for applications like lighthouses, searchlights, and projectors.
- **Light Dispersion:** Fresnel lenses can also be used to disperse light, as in the case of solar panels, where they concentrate sunlight onto a smaller area to increase efficiency.
- **Optics:** They are employed in optical instruments like telescopes, microscopes, and cameras to improve image quality and reduce weight.
- **Automotive Industry:** Fresnel lenses are used in headlights and taillights to enhance visibility and reduce glare.
- **Architectural Lighting:** They are employed in architectural lighting designs to create unique and dramatic effects.

Pros and Cons of Fresnel Lenses
Pros:

- **Lightweight:** Fresnel lenses are significantly thinner and lighter than traditional lenses, making them easier to transport and install.
- **Cost-Effective:** Due to their simpler manufacturing process, Fresnel lenses are often more affordable than traditional lenses.
- **Efficient:** They are highly efficient in focusing or dispersing light, making them ideal for applications where maximum light output is required.
- **Versatility:** Fresnel lenses can be designed to meet a wide range of optical needs, making them versatile in various applications.

Cons:

- **Image Quality:** While Fresnel lenses are effective for many applications, they may not always produce the same level of image quality as traditional lenses, especially for high-resolution imaging.
- **Aberrations:** Fresnel lenses can introduce aberrations, such as chromatic aberration and spherical aberration, which can affect image quality.
- **Limited Aperture:** The design of a Fresnel lens can limit its aperture, which can affect the amount of light it can collect.

Sources:

- **Encyclopædia Britannica:** https://www.britannica.com/technology/Fresnel-lens
- **Wikipedia:** https://en.wikipedia.org/wiki/Fresnel_lens
- **Optics and Photonics News:** https://spie.org/conferences-and-exhibitions/optics-and-photonics

In conclusion, Fresnel lenses offer a unique and efficient solution for various optical applications, combining lightweight design, cost-effectiveness, and high optical performance. While they may have certain limitations, their advantages make them a valuable tool in many fields.

Copilot's Response:

A **Fresnel lens** is a type of compact lens originally developed by French physicis Jean Fresnel for use in lighthouses1. It's designed to capture more light than a co nventional lens of the same size by using a series of concentric grooves, each ac ting as an individual refracting surface2.

Purpose

Fresnel lenses are used in a variety of applications where a large aperture and s hort focal length are required2. They are commonly found in:

- **Lighthouses**: To focus light into a powerful beam visible from far distance s3.
- **Theater and Film**: As spotlights and projectors4.
- **Solar Power**: To concentrate sunlight onto a small area for heating or pow er generation1.
- **Projectors and Magnifiers**: For illumination and image projection2.

Pros

- **Lightweight and Thin**: Despite their large aperture, Fresnel lenses are m uch lighter and thinner than conventional lenses2.
- **Cost-Effective**: They are cheaper to produce due to less material usage5.
- **Versatile**: Can be used in various applications, from lighthouses to project ors4.

Cons

- **Image Quality**: They can suffer from chromatic aberration and distortion, affecting image quality5.
- **Heat Generation**: In high-intensity applications, they can get very hot4.

- **Limited Use in Imaging Systems**: Not suitable for all optical systems due to image quality issues6.

Sources

- [Wikipedia: Fresnel Lens]
- [PetaPixel: How a Fresnel Lens Works]
- [Britannica: Fresnel Lens]
- [Edmund Optics: Advantages of Fresnel Lenses]
- [Artlist: Fresnel Light: Pros and Cons]

Does this cover what you were looking for, or is there something more specific you'd like to know?

A-2 Prompt on MCUs

Tell me about an MCU. What does it do and what parts make it up? What are the benefits of using it over other logic devices? Please list the sources.

ChatGPT's Response:

A **Microcontroller Unit (MCU)** is a compact integrated circuit designed to govern a specific operation in an embedded system. An MCU typically includes a processor core, memory, and programmable input/output peripherals. Here's a breakdown of its components, functions, and benefits:

Components of an MCU

1. **Central Processing Unit (CPU)**:
   - The brain of the MCU, responsible for executing instructions and processing data. It performs calculations and controls the timing of operations.
2. **Memory**:
   - **Flash Memory**: Non-volatile storage for the program code and firmware. It retains data even when the power is off.
   - **RAM (Random Access Memory)**: Volatile memory used for temporary data storage while the MCU is running.
   - **EEPROM (Electrically Erasable Programmable Read-Only Memory)**: Non-volatile memory used for storing small amounts of data that must be preserved across power cycles.
3. **Input/Output Ports**:
   - Digital and analog I/O pins allow the MCU to interact with external devices, sensors, and actuators.
4. **Timers and Counters**:
   - Hardware modules that allow for time-based operations, such as generating PWM signals, measuring time intervals, and creating delays.
5. **Communication Interfaces**:
   - Protocols such as UART, SPI, I2C, and CAN for serial communication with other devices.

6. **Analog-to-Digital Converter (ADC)**:
    - Converts analog signals from sensors into digital data for processing by the CPU.
7. **Digital-to-Analog Converter (DAC)** (optional):
    - Converts digital signals back into analog for output purposes.

Functions of an MCU

- **Control Systems**: Automating tasks in devices like home appliances, automotive systems, and industrial machinery.
- **Data Processing**: Collecting and processing data from sensors to make decisions and control outputs.
- **User Interface**: Managing user input from buttons, displays, and other human-machine interfaces.
- **Communication**: Sending and receiving data to/from other devices, enabling networking capabilities.

Benefits of Using an MCU Over Other Logic Devices

1. **Integration**: MCUs combine multiple functionalities (CPU, memory, I/O) into a single chip, reducing board space and component count.
2. **Cost-Effectiveness**: Because of their integration and mass production, MCUs can be more cost-effective than using separate discrete components for control, memory, and I/O.
3. **Power Efficiency**: MCUs are designed for low-power applications, making them ideal for battery-operated devices.
4. **Flexibility**: Programmability allows for easy updates and modifications in functionality without hardware changes.
5. **Real-Time Processing**: Many MCUs can handle real-time applications, providing timely responses to inputs.
6. **Ease of Development**: Abundant development tools, libraries, and community support facilitate rapid development and prototyping.

Sources

1. **Microcontrollers in Practice** by Martin P. Bates, Pearson Education, 2016.
2. **Introduction to Embedded Systems: Using ANSI C and Arduino** by David Russell, McGraw-Hill, 2018.
3. **Designing Embedded Systems with Arduino** by J. D. K. W. Lee, Springer, 2020.
4. **Microcontrollers: From Assembly Language to C Using the PIC18F** by David W. Smith, Cengage Learning, 2014.

Gemini’s Response:

What is an MCU?

An MCU, or Microcontroller Unit, is a small, single-chip computer system that integrates a processor, memory (both ROM and RAM), and input/output peripherals on a single chip. It's designed to perform specific tasks within embedded systems, which are devices that have a computer embedded within them.

Components of an MCU

1. **Central Processing Unit (CPU):** The brain of the MCU, responsible for executing instructions.
2. **Memory:**
   - **ROM (Read-Only Memory):** Stores instructions and data that cannot be changed during operation.
   - **RAM (Random Access Memory):** Used for temporary storage of data and program instructions.
3. **Input/Output (I/O) Peripherals:** These include:
   - **Analog-to-Digital Converters (ADCs):** Convert analog signals (like temperature or voltage) into digital values.
   - **Digital-to-Analog Converters (DACs):** Convert digital signals into analog signals (for controlling motors or LEDs).
   - **Serial Communication Interfaces:** For communicating with other devices (e.g., UART, I²C, SPI).
   - **Timers:** For generating precise time intervals or delays.
   - **Pulse-Width Modulation (PWM) Generators:** For controlling the duty cycle of a signal (e.g., controlling motor speed).

Benefits of MCUs over Other Logic Devices

1. **Integration:** MCUs combine multiple components into a single chip, reducing the need for external components and simplifying design.
2. **Flexibility:** They can be programmed to perform a wide range of tasks, making them versatile for various applications.
3. **Low Power Consumption:** MCUs are designed for low-power operation, making them suitable for battery-powered devices.
4. **Cost-Effective:** Due to their mass production and integration, MCUs are generally more cost-effective than discrete logic components.

Sources:

- **Microcontrollers: A Comprehensive Guide:** [invalid URL removed]
- **Microcontroller Basics:** https://www.tutorialspoint.com/microcontroller-basics
- **What is a Microcontroller?** https://www.techtarget.com/iotagenda/definition/microcontroller

Note: The Marvel Cinematic Universe (MCU) is a separate concept, a fictional universe created by Marvel Studios. It is not related to Microcontroller Units.

CoPilot's Response:

Sure! An MCU, or **Microcontroller Unit**, is a compact integrated circuit (IC) desi gned to govern specific operations in embedded systems1. Here's a breakdown of its components and benefits:

Components of an MCU:

1. **Processor Unit (CPU)**: Acts as the brain, executing instructions and perfo rming calculations2.
2. **Memory Modules**: Includes **Flash Memory** for storing programs and **RA M** for temporary data storage1.

3. **Communication Interfaces**: Allow the MCU to communicate with other d evices, such as UART, SPI, and I2C3.
4. **Input/Output (I/O) Ports**: Enable interaction with external devices like sen sors and actuators2.
5. **Peripherals**: Additional components like timers, analog-to-digital converters (ADCs), and digital-to-analog converters (DACs) that extend the MCU's functionality3.

Benefits of Using an MCU:

1. **Cost-Effective**: MCUs are generally cheaper than other logic devices like FPG As4.
2. **Power Efficiency**: Designed for low power consumption, making them ide al for battery-operated devices1.
3. **Ease of Use**: Pre-programmed for specific tasks, simplifying development and deployment5.
4. **Compact Size**: Integrates all necessary components on a single chip, savi ng space1.
5. **Versatility**: Can be used in a wide range of applications, from home applia nces to automotive systems1.

Sources:

1. Cadence PCB Solutions
2. Wikipedia - Microcontroller
3. Arrow Electronics
4. IBM Blog
5. Techwalla

A-3 Prompt on Motors

For a motorized Lense system that moves in small step size and can be programmable, which is the best motor to use and what are their pros and cons.

ChatGPT’s Response:

“When choosing a motor for a motorized lens system that requires small step sizes and programmability, the most common options are **stepper motors** and **servo motors**. Here’s a breakdown of both:

Stepper Motors

Pros:

1. **Precision Control**: Stepper motors move in discrete steps, allowing for precise control of position.
2. **Open-Loop Control**: They can be controlled without feedback systems, simplifying the design.
3. **Cost-Effective**: Generally less expensive than servo motors.
4. **Good Holding Torque**: Can maintain position when power is applied.

Cons:

1. **Resonance Issues**: Can experience vibrations at certain speeds, which may affect image stability.
2. **Torque Drop-Off**: Torque decreases at higher speeds, which can limit performance.
3. **Heat Generation**: Can run hot under continuous use, potentially affecting nearby components.

Servo Motors

Pros:

1. **Closed-Loop Control**: They use feedback systems, allowing for more accurate positioning and speed control.
2. **Higher Torque**: Typically provide more torque and can maintain it over a wider range of speeds.
3. **Smooth Motion**: Generally offer smoother operation compared to stepper motors, reducing vibrations.
4. **Speed and Acceleration Control**: Can achieve higher speeds and faster accelerations.

Cons:

1. **Complexity**: Require a more complex control system with feedback loops, increasing design complexity.
2. **Cost**: Typically more expensive than stepper motors.
3. **Calibration Needs**: Require calibration and tuning to ensure accurate performance.

Conclusion

For a motorized lens system focusing on small step sizes and programmability:

- **Stepper Motors** are often preferred for their simplicity and cost-effectiveness, especially for applications where precise positioning is critical and feedback is not necessary.
- **Servo Motors** are better suited for applications needing high torque, speed control, and smoother operation but at a higher cost and complexity.

The choice depends on your specific application requirements, such as budget, precision needs, and system complexity."

In conclusion, the information gathered from ChatGPT helped narrow down and what type of motor will fit better in our design. Taking into consideration the pros and cons we are leaning more into a stepper motor. As it fulfills our budget and weight constraints."

Gemini's Response:

The best motor for a motorized lens system that moves in small step sizes and can be programmable depends on several factors, including the required accuracy, speed, torque, and cost. Here are some of the most common options, along with their pros and cons:

Stepper motors:

Pros:
High accuracy and precision
Can be easily programmed and controlled
Relatively low cost
High torque at low speeds
Cons:
Can be noisy and prone to vibrations
May require additional circuitry for smooth operation
Limited speed range

Servo motors:

Pros:
Smooth and quiet operation
High speed and acceleration
Can be easily controlled with a PWM signal
Wide range of torque and speed options
Cons:
May be more expensive than stepper motors
Lower accuracy and precision
May require additional circuitry for position feedback

Linear actuators:

Pros:
Simple and direct motion
High load capacity
Can be easily controlled with a voltage signal
Wide range of stroke lengths and speeds
Cons:
May be more expensive than rotary motors
Lower accuracy and precision
Limited speed range

Choosing the right motor:
The best motor for your application will depend on your specific requirements. If you need high accuracy and precision, a stepper motor may be the best option. If you need smooth and quiet operation, a servo motor may be a better choice. If you need high load capacity and direct motion, a linear actuator may be the best option. Here are some additional factors to consider when choosing a motor:

Required accuracy and precision: Stepper motors are generally more accurate than servo motors or linear actuators.
Required speed and acceleration: Servo motors and linear actuators can achieve higher speeds and accelerations than stepper motors.

Required torque: Stepper motors and linear actuators can handle higher loads than servo motors.
Cost: Stepper motors are generally more affordable than servo motors or linear actuators.
Size and weight: The size and weight of the motor will also be important factors to consider.

By carefully considering these factors, you can choose the best motor for your motorized lens system.

Copilot's Response:

For precise movement in a motorized lens system, consider **stepper motors** or **DC motors with encoders**.
Stepper Motors:
Pros:

- **Precision**: High accuracy in small step movements.
- **Repeatability**: Reliable positioning.

Cons:

- **Speed**: Generally slower.
- **Complexity**: May require more complex control systems.

DC Motors with Encoders:
Pros:

- **Speed**: Faster than stepper motors.
- **Control**: Precise with the use of encoders.

Cons:

- **Cost**: Can be more expensive.
- **Complexity**: Requires closed-loop control systems.

Your choice depends on whether you prioritize speed or precision. What are you leaning toward?

A-4 Prompt on Sensors

In detail, describe CCD and CMOS sensors. What are they used for? Compare them and tell me which one is best.

ChatGPT's Response:

CCD Sensors
Definition:
Charge-Coupled Device (CCD) sensors are a type of image sensor that convert

light into electrical signals. They consist of an array of capacitors that transfer charge across the chip to produce an image.

How They Work:

1. **Light Capture:** When light hits the sensor, it generates electrons in each pixel.
2. **Charge Transfer:** The accumulated charge in each pixel is transferred across the sensor in a sequential manner to an output node.
3. **Signal Processing:** The charges are converted into a voltage, which is then processed to create an image.

Uses:

- Professional photography and videography (due to high image quality)
- Astronomy (for capturing faint celestial bodies)
- Medical imaging (e.g., in endoscopes)
- Scientific applications (such as microscopy)

CMOS Sensors

Definition:

Complementary Metal-Oxide-Semiconductor (CMOS) sensors are another type of image sensor that also converts light into electrical signals, but they do this differently than CCDs. Each pixel has its own charge-to-voltage conversion and readout circuitry.

How They Work:

1. **Light Capture:** Similar to CCDs, light generates electrons in each pixel.
2. **Integrated Processing:** Each pixel has its own amplifier and circuitry, allowing for simultaneous readout of the pixels.
3. **Signal Output:** The voltage generated is processed on-chip, leading to faster readout times.

Uses:

- Consumer electronics (like smartphones and webcams)
- Digital cameras
- Automotive applications (e.g., backup cameras)
- Security cameras

Comparison

Feature	CCD	CMOS
Image Quality	Generally higher; better low-light performance	Good, but varies by model; can be lower in low-light conditions
Power Consumption	Higher; typically requires more power	Lower; more efficient, allowing for battery-powered devices
Speed	Slower; sequential readout can introduce delays	Faster; can read all pixels simultaneously
Cost	Generally more expensive to manufacture	Usually cheaper; can be produced in larger quantities

Integration	Less integration; requires external components	Highly integrated; more features on-chip (like noise reduction)
Size	Generally larger; bulkier for the same resolution	Smaller; can be miniaturized for compact devices

Which One is Best?

The "best" sensor depends on the specific application:

- **CCD Sensors** are often preferred in applications where image quality is critical, such as professional photography, scientific imaging, and high-end video production. Their superior low-light performance and image quality make them ideal for these scenarios.
- **CMOS Sensors** have become increasingly popular for consumer electronics due to their lower power consumption, smaller size, and cost-effectiveness. They are well-suited for devices like smartphones, where compactness and battery life are essential.

In summary, if ultimate image quality is paramount and budget allows, CCD is often the choice. For most everyday applications, especially where cost and power efficiency matter, CMOS sensors are typically preferred.

Gemini's Response:

CCD vs. CMOS Sensors: A Detailed Comparison

CCD (Charge-Coupled Device) and **CMOS (Complementary Metal-Oxide-Semiconductor)** sensors are two primary technologies used in digital imaging. Both capture light and convert it into electrical signals, but they operate on different principles.

CCD Sensors

- **Principle:** CCDs utilize a series of capacitors to store and transfer electrical charges generated by light. As light strikes the sensor, it creates electron-hole pairs. These charges are then shifted along the sensor's surface to a readout circuit where they are converted into digital signals.
- **Structure:** CCDs typically have a more complex structure, requiring multiple layers of polysilicon and metal for the capacitor arrays.
- **Pros:** Known for their high image quality, low noise, and wide dynamic range. They excel in capturing subtle details and colors.
- **Cons:** Higher power consumption, slower readout speeds, and a more expensive manufacturing process.

CMOS Sensors

- **Principle:** CMOS sensors integrate photodiodes directly onto each pixel. When light strikes a photodiode, it generates a current that is amplified by a transistor on the same pixel. This amplified signal is then converted into a digital value.
- **Structure:** CMOS sensors have a simpler structure, with fewer layers and smaller pixel sizes, making them easier to manufacture.

- **Pros:** Lower power consumption, faster readout speeds, and lower manufacturing costs. They are well-suited for applications requiring high frame rates, such as video recording and fast-moving subjects.
- **Cons:** Generally have higher noise levels and may exhibit a slight color shift compared to CCDs.

Applications

- **CCD Sensors:** Primarily used in professional photography, astronomy, and medical imaging due to their superior image quality.
- **CMOS Sensors:** Widely used in consumer cameras, smartphones, and video cameras due to their lower cost, faster performance, and lower power consumption.

Which One is Best?

The "best" sensor depends on the specific application and priorities. For applications requiring the highest image quality and low noise, CCD sensors are often preferred. However, for applications that prioritize speed, low power consumption, and affordability, CMOS sensors are a more suitable choice.

In recent years, advancements in CMOS technology have significantly improved their image quality, narrowing the gap between CCD and CMOS sensors. As a result, CMOS sensors have become the dominant choice in many consumer and professional applications.

In summary, while CCD sensors offer superior image quality, CMOS sensors have become more versatile and widely adopted due to their advantages in speed, power consumption, and cost. The choice between CCD and CMOS ultimately depends on the specific requirements of the application.

Copilot's Response:

CCD (Charge-Coupled Device) Sensors

How They Work:

- Made up of an integrated grid of semiconductor capacitors that hold an electrical charge.
- Converts light into an electrical charge, which is then transferred through the capacitors to be read out.

Uses:

- High-end photography, astronomy, and scientific applications where image quality is paramount.
- Known for producing high-quality images with low noise and excellent light sensitivity.

CMOS (Complementary Metal-Oxide-Semiconductor) Sensors

How They Work:

- Contains an array of photodiodes, each with its own amplifier, converting light into electrical signals directly at the pixel level.
- Allows for faster data processing and lower power consumption compared to CCD sensors.

Uses:

- Widely used in consumer electronics, such as smartphones, digital cameras, and video cameras.
- Used in industrial applications where speed and power efficiency are important.

Comparison

Feature	CCD Sensors	CMOS Sensors
Image Quality	High (low noise, excellent light sensitivity)	Good (improving with technology)
Power Consumption	Higher	Lower
Speed	Slower	Faster
Cost	Higher	Lower
Complexity	More Complex	Less complex
Applications	High-end photography, astronomy, scientific research	Consumer electronics, industrial applications

Which One is Best?

The choice depends on the specific application:

- **CCD sensors**: Best for high-end photography and scientific research where image quality is critical.
- **CMOS sensors**: Ideal for consumer electronics and industrial applications where speed, power efficiency, and cost are more important.

In general, CMOS sensors are becoming more popular due to their lower cost and power consumption, but CCD sensors still hold their ground in high-end imaging applications.

Does this work for you?

B. Software Code

B-1 Audio Files

```
import pygame

# Initialize pygame mixer
 pygame.mixer.init()

# Load audio files
 audio_files = { "process_completed": "audio_files/process_completed.mp3",
"error": "audio_files/error.mp3", "color_detected":
"audio_files/color_detected.mp3" }

def play_audio(state):

"""Play audio based on the current state."""
 if state in audio_files:
        pygame.mixer.music.load(audio_files[state])
        pygame.mixer.music.play()
        while pygame.mixer.music.get_busy():
            continue  # Wait for the audio to finish
else:
        print(f"Unknown state: {state}")

# Test function
 if __name__ == "__main__":
        print("Testing audio feedback...")
        play_audio("process_completed") play_audio("error")
        play_audio("color_detected")
```

B-2 Edge-Detection

```
from matplotlib.image import imread
import matplotlib.pyplot as plt
import numpy as np
```

```
# #----------------------------------------------------------------------------------------------------
-------------
# PART I - Transforming an image from color to grayscale
# #----------------------------------------------------------------------------------------------------
-------------

# Here we import the image file as an array of shape (nx, ny, nz)
image_file = 'Images/original_image.PNG'
input_image = imread(image_file)  # this is the array representation of the input
image
[nx, ny, nz] = np.shape(input_image)  # nx: height, ny: width, nz: colors (RGB)

# Extracting each one of the RGB components
r_img, g_img, b_img = input_image[:, :, 0], input_image[:, :, 1], input_image[:, :, 2]

# The following operation will take weights and parameters to convert the color
image to grayscale
gamma = 1.400  # a parameter
r_const, g_const, b_const = 0.2126, 0.7152, 0.0722  # weights for the RGB
components respectively
grayscale_image = r_const * r_img ** gamma + g_const * g_img ** gamma +
b_const * b_img ** gamma

# This command will display the grayscale image alongside the original image
fig1 = plt.figure(1)
ax1, ax2 = fig1.add_subplot(121), fig1.add_subplot(122)
ax1.imshow(input_image)
ax2.imshow(grayscale_image, cmap=plt.get_cmap('gray'))
fig1.show()

# #----------------------------------------------------------------------------------------------------
-------------
# PART II - Applying the Sobel operator
# #----------------------------------------------------------------------------------------------------
-------------

"""
The kernels Gx and Gy can be thought of as a differential operation in the
"input_image" array in the directions x and y
respectively. These kernels are represented by the following matrices:
      _               _                 _               _
     |                 |               |                 |
     | 1.0   0.0  -1.0 |               |  1.0   2.0   1.0 |
Gx = | 2.0   0.0  -2.0 |    and     Gy = |  0.0   0.0   0.0 |
     | 1.0   0.0  -1.0 |               | -1.0  -2.0  -1.0 |
     |_               _|               |_               _|
```

```
"""

# Here we define the matrices associated with the Sobel filter
Gx = np.array([[1.0, 0.0, -1.0], [2.0, 0.0, -2.0], [1.0, 0.0, -1.0]])
Gy = np.array([[1.0, 2.0, 1.0], [0.0, 0.0, 0.0], [-1.0, -2.0, -1.0]])
[rows, columns] = np.shape(grayscale_image)  # we need to know the shape of the input grayscale image
sobel_filtered_image = np.zeros(shape=(rows, columns))  # initialization of the output image array (all elements are 0)

# Now we "sweep" the image in both x and y directions and compute the output
for i in range(rows - 2):
    for j in range(columns - 2):
        gx = np.sum(np.multiply(Gx, grayscale_image[i:i + 3, j:j + 3]))  # x direction
        gy = np.sum(np.multiply(Gy, grayscale_image[i:i + 3, j:j + 3]))  # y direction
        sobel_filtered_image[i + 1, j + 1] = np.sqrt(gx ** 2 + gy ** 2)  # calculate the "hypotenuse"

# Display the original image and the Sobel filtered image
fig2 = plt.figure(2)
ax1, ax2 = fig2.add_subplot(121), fig2.add_subplot(122)
ax1.imshow(input_image)
ax2.imshow(sobel_filtered_image, cmap=plt.get_cmap('gray'))
fig2.show()

# Show both images
# plt.show()

# Save the filtered image in destination path
# plt.imsave('sobel_filtered_image.png', sobel_filtered_image, cmap=plt.get_cmap('gray'))
```

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