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

(P.A.U.L.)

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2 Project Description

The P.A.U.L headset is 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 act as reading glasses with automated variable optical powers.

The color-identification system is 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 is designed to be around existing forms of headwear. By utilizing an existing form of headwear such as the common ball cap of 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. While the exact form of headwear has not been selected, headwear with some form of brim will be prioritized as it will provide stability and maintain the alignment of the optical axes.

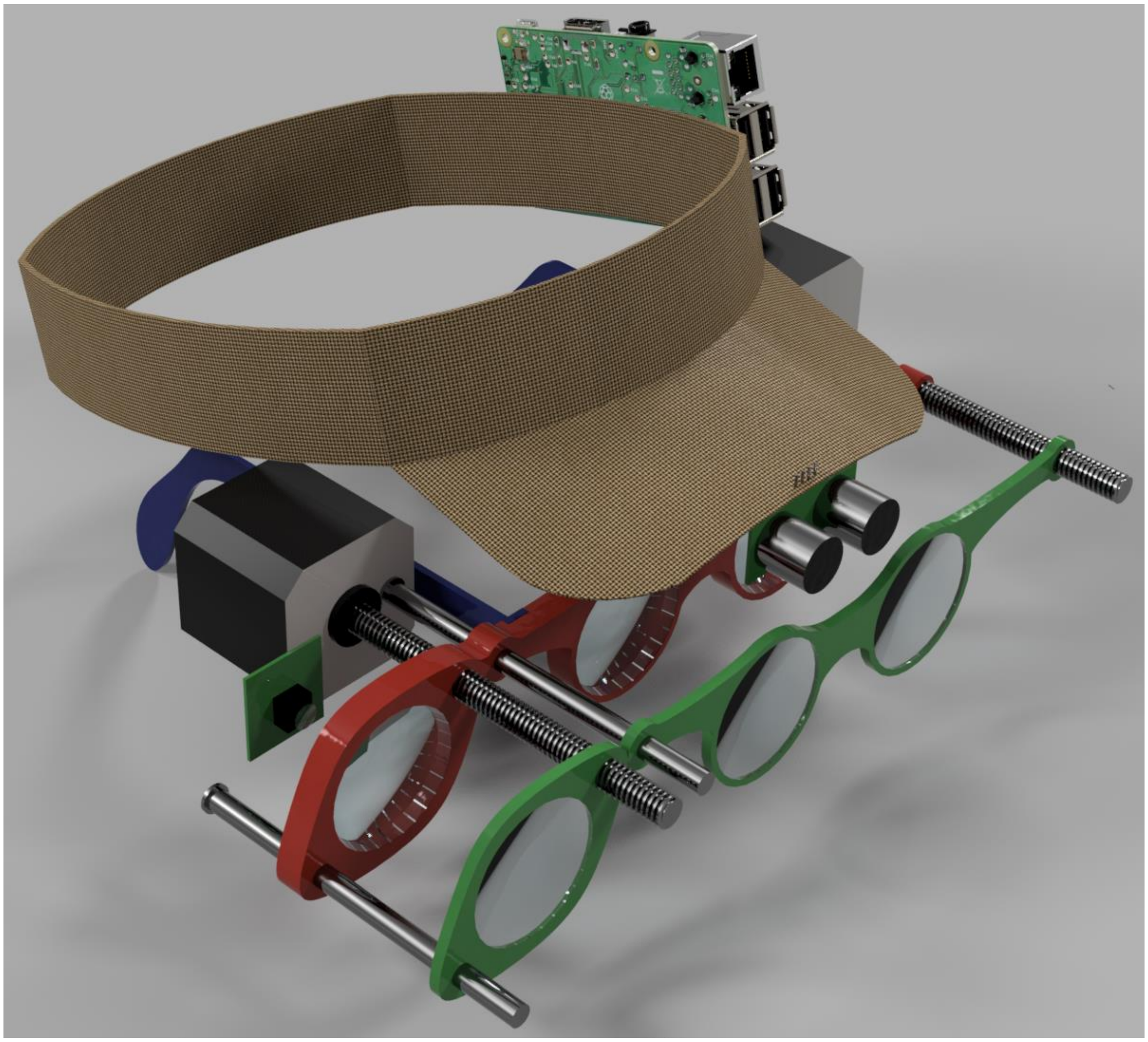

Figure 2.0.1 Digital Rendering of Assembled System

2.1 Motivation and background

The development of assistive lenses stems 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[1]. 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 will 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 [2]. 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 would be 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 [3]. 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 would help 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 will be 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 will be 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 come up with a device that can support individuals with various visual disabilities, we've come across several existing products that also support visually impaired individuals through various methods. While the majority of these existing products are designed with the purpose of supporting visually impaired individuals, not all of them are. 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[4]. 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 will still be 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[5]. 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 will be capable of. This feature will 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 will benefit 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 will 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. [6]

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 are developing 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, we aim to 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, can be 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 aim to develop 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 will assist individuals with tasks such as color coordinating their outfits or selecting the correct apple while out grocery shopping.

2.3.1 Basic Goals

- Successfully adjust the effective focal length of the lens systems to the approximated focal length acquired by the time-of-flight sensor.
- Identify when an image is in focus using an edge-detecting program.
- 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

- Correct refractive error of mild myopia and mild hyperopia to correlate the lens system to a power of 0 D for unique individuals.
- Improve the auto-focusing system to provide between -1.5 D and +2.5 D of optical power in under five seconds.
- Improve color identification to ensure accuracy above 80%.

2.3.3 Stretch Goals

- Miniaturization of system for increased portability and comfort.
- Increase the number of accurately identifiable colors to six.
- 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 an infrared 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 that captures images, then applies a Laplacian filter to enhance the edges. Improve program to calculate the Laplacian variance to determine if an image is in focus. An image is determined to be in focus if it is above the predetermined threshold.
- Design a color identification system utilizing three photodiodes. Place a red, blue, or green color filter in front of each photodiode to isolate the colors identifiable by each photodiode,
- 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 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 be set the optical power of the total system, including the user's eyes to 0 D.
- Improve the lens design to minimize aberrations and increase depth of focus. Program incremental movement to adjust separation between lenses as necessary to improve the effective focal length of the lens system until focus is acquired.
- 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

2.4.1 Auto-focus

To support individuals with vision loss such as near-sightedness and far-sightedness, we want to include a system that provides artificial accommodation. To support this, we plan to use a two-lens system that can be ordered 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 will arise as we try to focus the system. Optical aberrations are errors caused by uneven spreading of light across a system. While these can be corrected with lens design, our system requires 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 60 diopters.

To solve this issue, we will implement 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.”

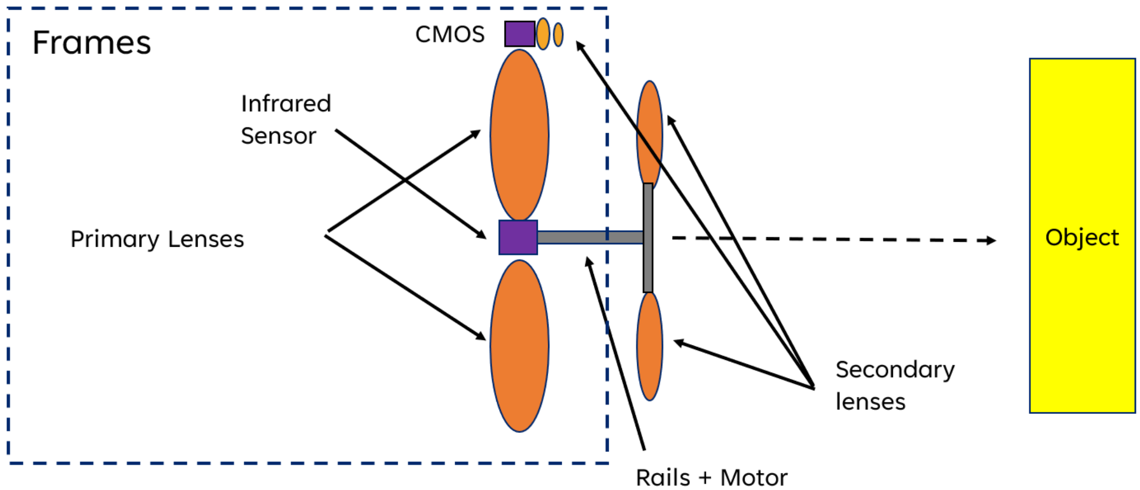

Figure 2.3.1 Auto-Focusing Feature Diagram

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 would provide audio information on the primary color of an object in central view. This system would work 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 would pass or reflect off the filters. If it passes, the respective photodiode records the signal and matches it with a corresponding color or shade. This system allows for combinations of up to 8 different colors or shades, namely red, green, blue, cyan, magenta, yellow, white, and black. However, the main drawback of this system is its low sensitivity. To offset this, a strobe light would illuminate the central area immediately in front of the user to provide more reflection and color feedback. This reflected light would likely need collimation and to pass through a diffraction grating before passing into the photodiodes. This photo-diode setup is still supplementary however and would require an additional system.

This other system would involve 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 are 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.

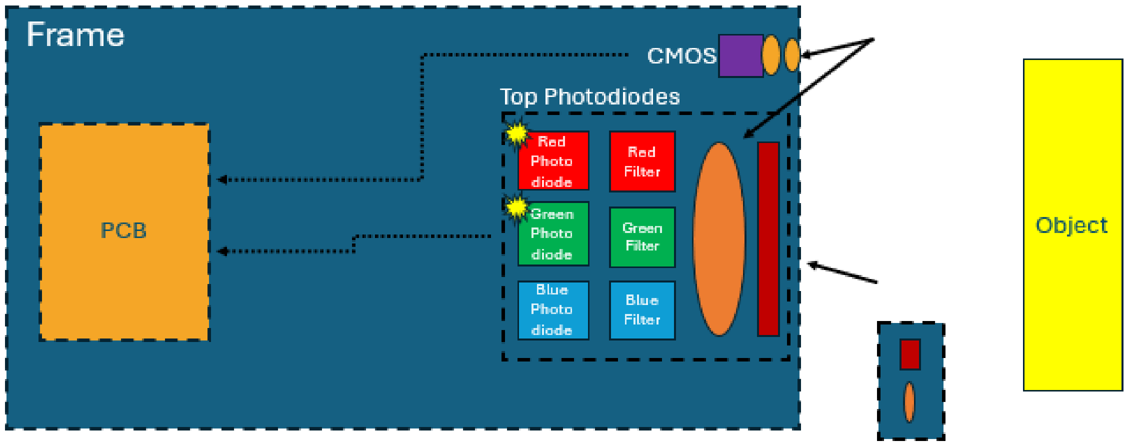

Figure 2.3.2 Color-Identifying Feature Diagram

2.5 Specifications

System Engineering Requirements	
Parameter	Requirements
Time to Focus	≤ 30 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 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

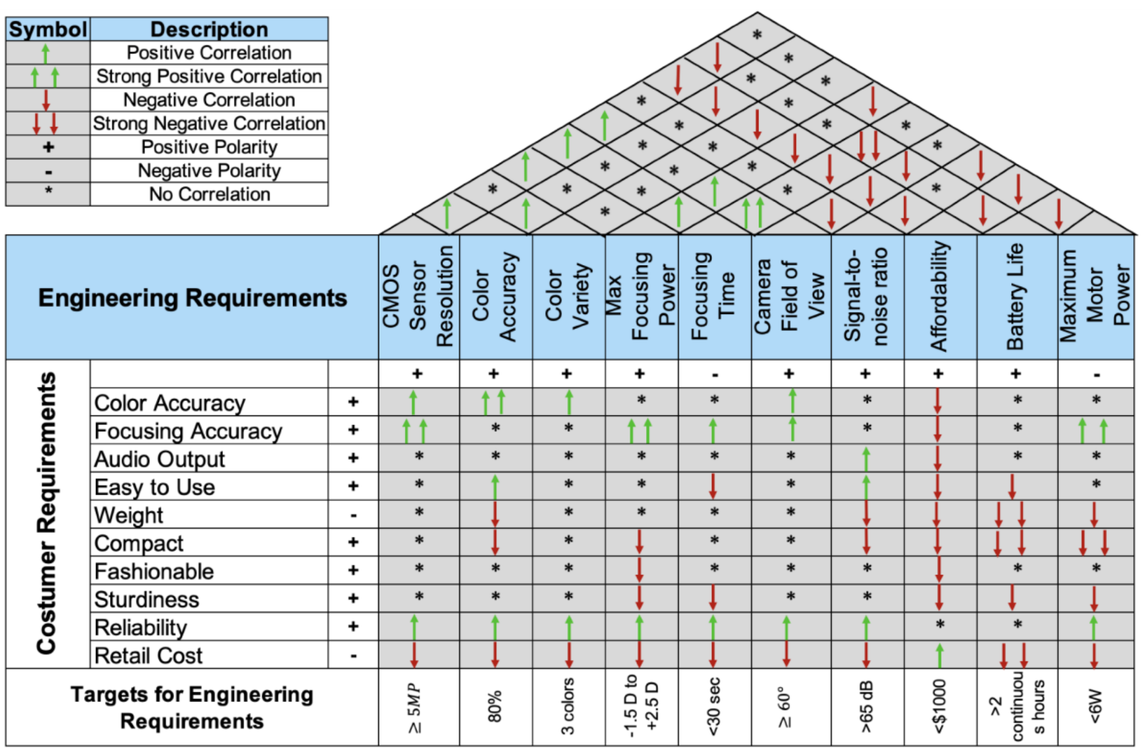

Figure 2.6.1 House of Quality

2.7 Block Diagrams

2.7.1 Hardware Block Diagram

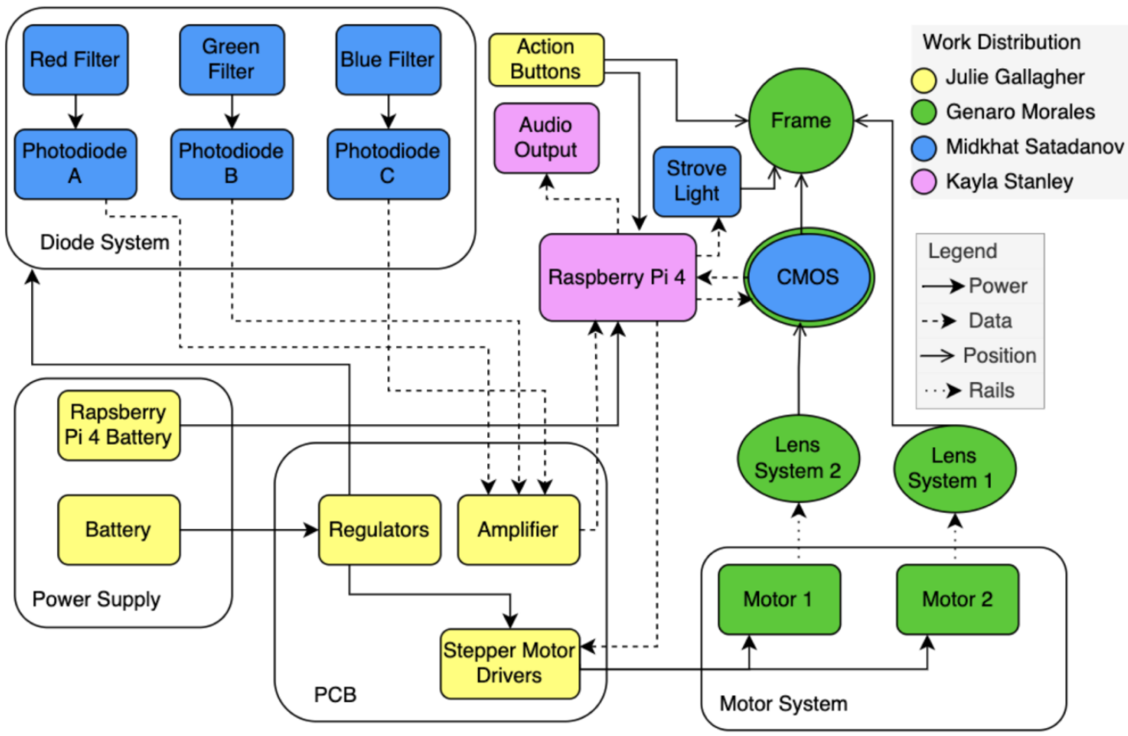

Figure 2.7.1 Hardware Block Diagram

2.7.2 Software Flow Charts

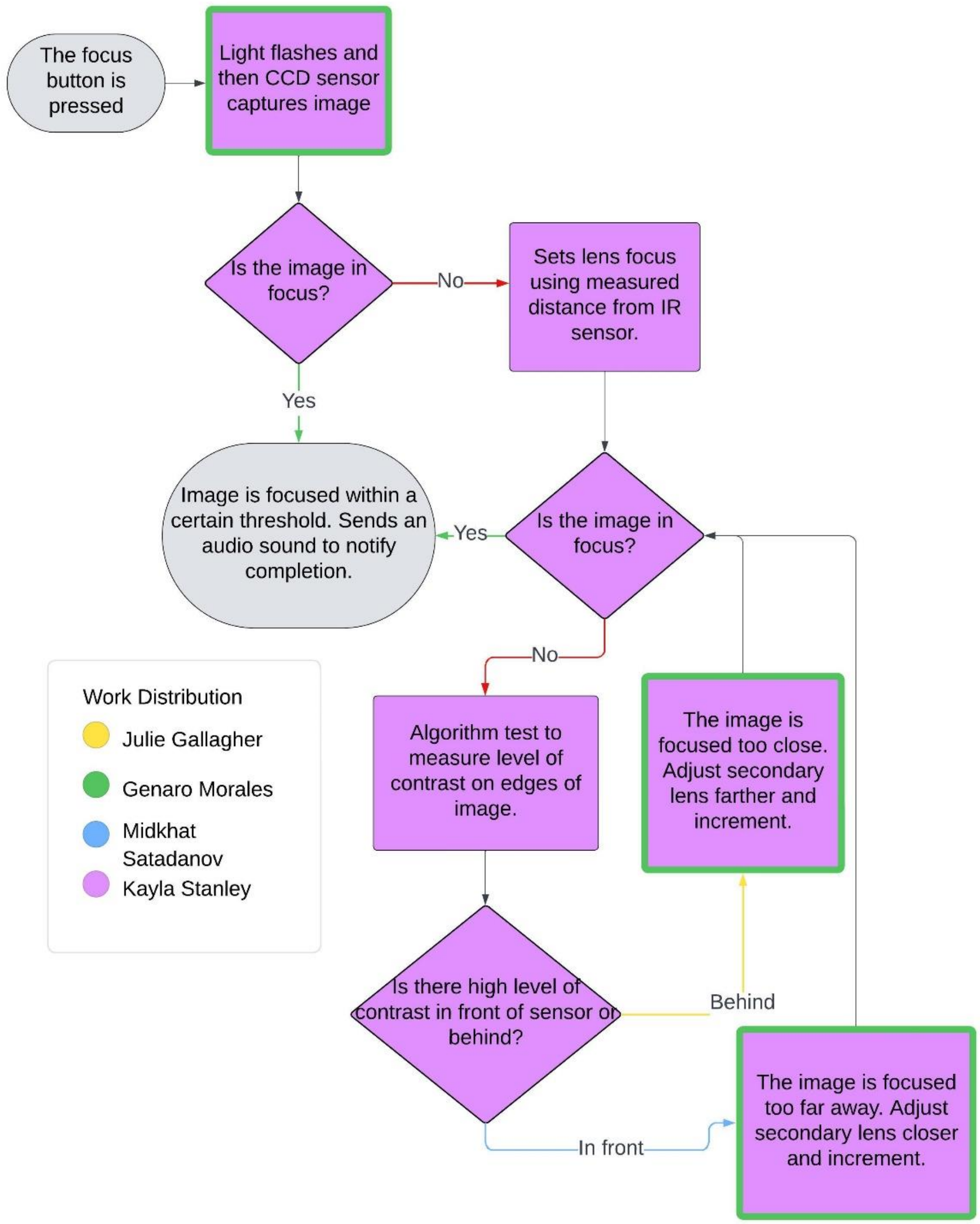

Figure 2.7.2 Auto-Focusing System Flow Chart

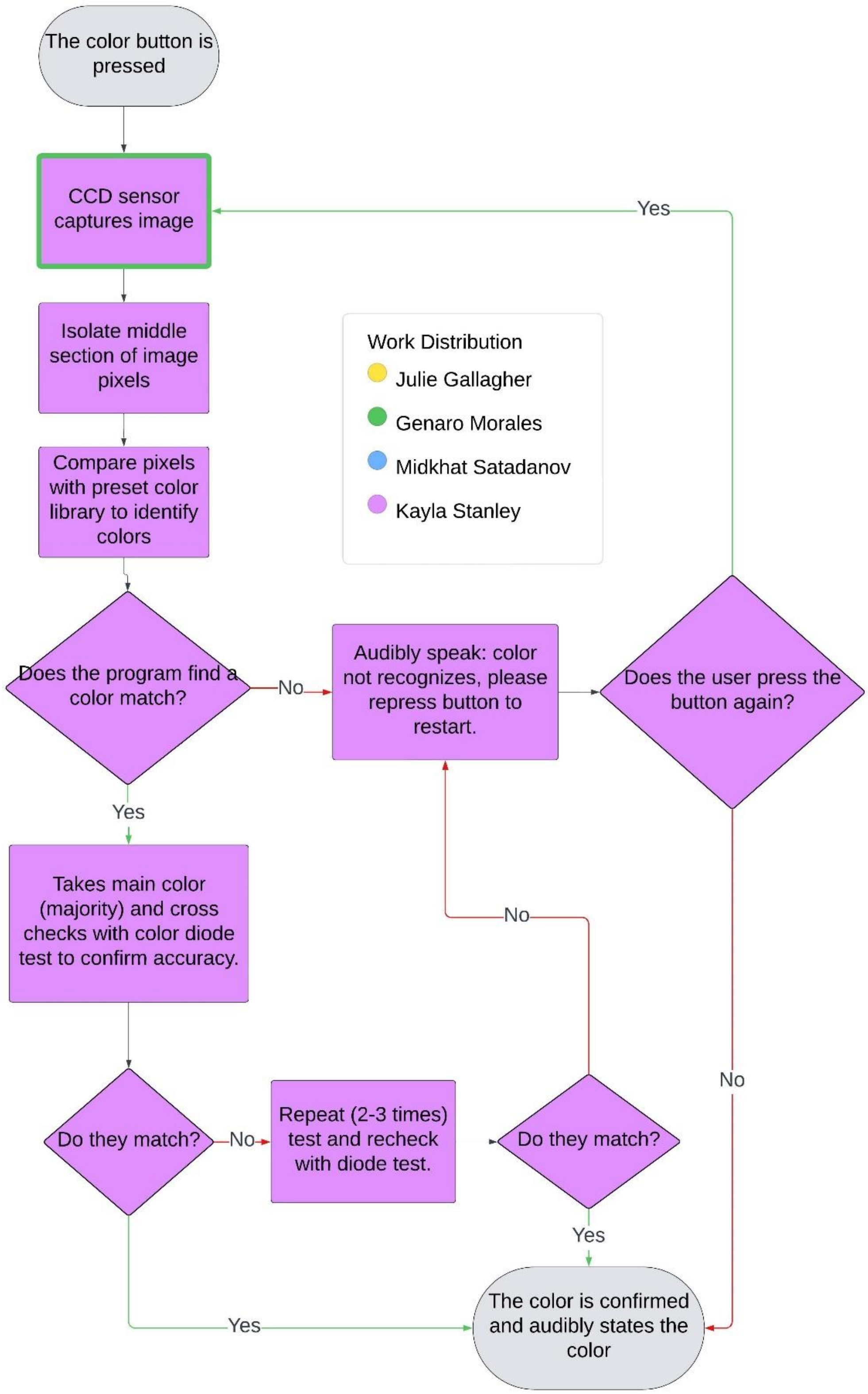

Figure 2.7.3 Color Identification System Flow Chart

3 Research and Part Selection

The primary concerns for the part selection of this project were related to the selection of the lenses and sensors. The final decisions regarding motors, frames, and all other subsequent components are contingent on the decisions we make regarding the parameters of those parts.

3.1 Imaging Sensors

There are two primary imaging sensors that are currently utilized. 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 [7].

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 [7].

For the color recognition system, we have a choice on whether we wanted to proceed with a CMOS or CCD sensor. Our requirements for the system need us to be able to differentiate the colors of the image taken to a degree that is as accurate to the colors seen by a typical human eye as possible. To match this correctly, we use the Commission Internationale de l'Eclairage's definition of an ideal spectral sensitivity function (SSF) [8].

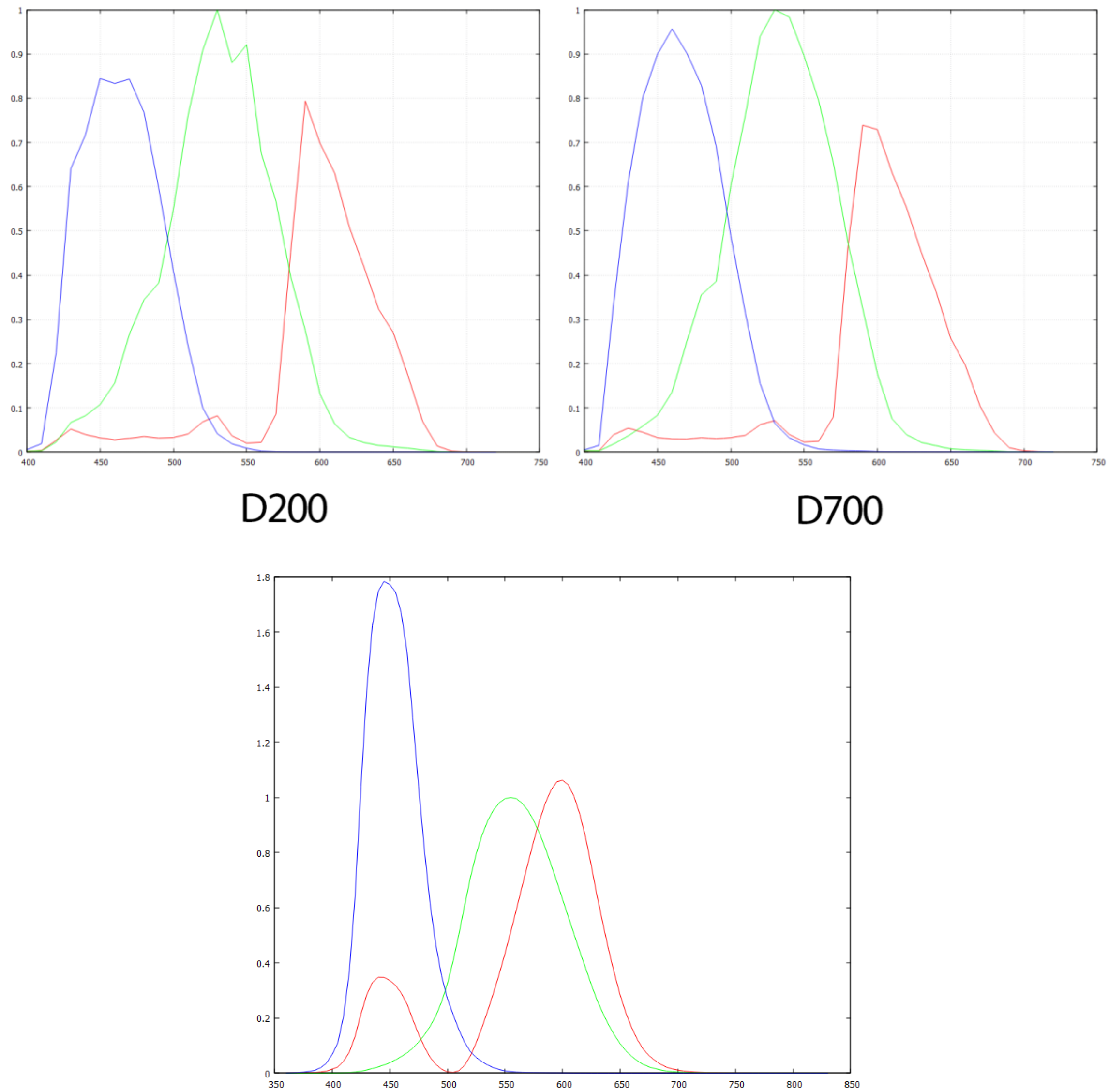

Figure 3.1.1 SSF of CMOS (left) vs CCD (right) compared with human SSF (bottom) [9]

Due to these requirements, the first and foremost 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 must be determined by both image quality and economic concerns. In terms of image quality, the primary concern regarding CMOS sensors is 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 [7], this difference in noise ratio has been eliminated in newer CMOS models. Our design may incorporate older CMOS sensors, 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 [7].

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 has 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.

Full-frame sensors by physical necessity are therefore the largest standard type of sensor and thus pose a potential constraint on our design if we were to use them. This can impose both financial and design limitations on us and will be considered as we begin 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 we need to observe larger landscapes, which in our case is not what our camera system is intended on doing. However, one very important aspect of full frame cameras to consider that would truly be 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 be crucial in outdoor applications, something our team has been investigating as we pursue the application of the color identification photodiode system in light-saturated conditions. If we can manipulate our sensor's ISO settings, its sensitivity to light, then we can further this application.

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 3 main ways as 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.

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.

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 only consideration that may prevent us from using this particular sensor is the fact that it still may be too cumbersome to attach to our system.

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 have decided to write about them in a general sense because the limitations that they come with can be applied to virtually all sensors at these size ranges.

Primarily, the main concern with such small form factor lenses would be 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 any noise to our system would be detrimental to the legibility of this system. For this reason, if we are to use a small form factor lens, we would likely want to focus on nothing smaller than a half inch frame.

3.1.3 Imaging Sensor Selection

When selecting an appropriate camera, we will need one that has both a field of view smaller than 120 degrees as that is within the range of our lens experiment requirements, a decent resolution of at least several megapixels or an equivalent measurement to ensure correct color recognition and autofocusing assistance, and one that will connect seamlessly with the computer we purchase.

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. This aspect of the sensor means that, without its own digital converter attached, we would need 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 make 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.

An issue may arise 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 could potentially interfere with or obscure some of the incoming data. Ideally, we are desiring an FOV of less than 120.

Perhaps the main advantage of this sensor is the fact that we already own 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 a diagonal image that is 7.9mm 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 call for it, we can (irreversibly) remove this filter.
The most important aspect 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.

The use of the telephoto lens would produce an image format of 1 inch, which as stated previously would produce higher quality photos under most normal conditions. Additionally, it is unlikely that at the sensor sizes we are investigating, we could find an image space much larger than this. The field of view of the telephoto lens would be 22.3 degrees, well within the desired range. Adding the telephoto lens changes the resolution to 10 megapixels (MP). The final consideration is that the back focal length produced by this lens would be 17.53mm, although this facet would likely not be critical given that our desired range for the color identification and autofocusing systems would lie within 2 meters.

The 6mm wide angle would produce images in the half inch space with an FOV of 56 degrees. The resulting resolution would equal 3 MP. Additionally, the wider angles would distort the image, reducing the resolution by a significant margin. As a final aside, the back focal length would be 7.53mm.

The final choice then would likely depend on our desired field of view. While the telephoto lens would produce higher quality images, the wide-angle lens’s field of view could be 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 produce a greater depth of field, which could be very 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 assist in ensuring that the autofocusing system produces sharper and clearer images for the user. We are choosing to err on the side of caution, so the wide angles would be preferable.

Overall, given that we are likely to move forward with a raspberry pi, a camera that integrates seamlessly into that system would be 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 will likely be distorted to fit into the frame, but this is not as important given that our intent is to only consider the object(s) in the center of the image when we use 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 be 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 30.4g as opposed to 34g (41g with adaptor and dust cap). Given that the system will need to be as comfortable to wear as possible, even tiny differences such as this start becoming non-negligible.

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 enable us to use 8mm, 25mm, and fisheye lenses. The 8mm in particular could be enticing, as it changes the image space to a 1/1.7”, which would let us capture more of the object we’re imaging while increasing the resolution to 12 MP. The resulting FOV of this lens would produce 62 degrees, perfect for our needs.

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 are 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 interesting to us specifically because of its wider FOV and, unlike the HQ and the GS, the camera comes pre-equipped with a lens and itself is only $35, significantly cheaper than the base $50 for the HQ and GS.

The camera 3 wide which we will abbreviate to the C3W is smaller than the previous two models by a significant margin, with dimensions of 25 by 24 by 12.4mm, 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.

3.1.3.5 Raspberry Pi Camera Module v2

The final consideration for the raspberry pi camera modules comes in the form of 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, and the same price as the module 3.

There is only one reason therefore as to why we are considering the module v2 at all, and that is due to its *lack* of an autofocusing feature. 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 want to discard due to our need to calibrate the autofocusing ourselves. After scouring online forums, it does seem that the newer modules can be programmed to not perform this feature, but the code to do so seems finicky at best. Thus, there is a chance we may move forward with the v2 for this reason alone.

3.1.3.6 Camera Comparison Table

Conveniently, the Raspberry Pi website already contains a list that compares the cameras considered above (and others), listing their general attributes. These will be mentioned, along with the attributes of the BETAFPV sensor as we consider the drawbacks and strengths of the different modules. For the HQ and GS Raspberry Pi cameras, assume that attributes are listed 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.

	Camera Module v2	Camera Module 3 Wide	HQ Camera	GS Camera	BETAFPV C02
Net Price	$25	$35	$75	$75	Free
Size	25 x24 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 will scan for color is a crucial component in our system, we felt that it would not be enough to ensure our color detection was accurate. Rather than simply scanning through an image, the project needs to incorporate optics to measure the wavelength of incoming light that our system attempts to detect, ensuring a sort of two-factor authentication 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 is important to investigate the merits of each method and any variations therein to decide which component would serve 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. For our purposes, we want to investigate photodiodes, phototransistors, and photoresistors to discover which would be most suitable for our applications.

However, this alone will likely not be enough. The light that comes onto our sensors, whether it passes through color filters or not, will still need to be aligned with the detectors themselves. While some incoming light will hit the detector properly, a lack of collimation will prevent maximum efficiency with the amplifier. Ideally, we would want the reflected light to first be collimated and then pass into a diffraction grating to best separate the wavelengths before passing into the photoconductors. For economic reasons, our team will try to build the system without using collimating lenses or a diffraction grating, but as senior design 2 comes we will try to quickly identify whether the system is 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.

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

Perhaps the most important disadvantage to the photodiode is its dark current. When powered in a reverse-biased fashion, dark current is noise being 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 isn't 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.

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 do not need precise timing in the range of nanoseconds as that will be imperceptible to human conceptions of time.

The main benefit that would come from using a phototransistor over a photodiode would be the fact that it would be easier to physically space it within our design. The lack of necessity for an amplifier would mean that we can fit more onto the detector system without needing to worry about 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 factor at play.

The main benefit of photoresistors is that they do not require a bias to operate.

3.2.4.1 TEMT6200FX01

The TEMT6200FX01 is an ambient light sensor that is a silicon NPN phototransistor. Its main draw is that it is sensitive to wavelength similar to those of the human eye and has peak sensitivity at 550 nm. Its tiny size, at a length, width, and height of 2 by 1.25 by 0.85

3.3 Time-of-Flight (ToF)

For our auto-focusing feature to function properly, we'll need to measure distance. This can be accomplished by utilizing the principle of time-of-flight. The measured distance will be 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[10]. 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[11]. 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. The distance (d) can then be calculated using Equation 3.3.1[10] 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.

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

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. Equation 3.3.2[12] 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.

$$d = \frac{v \times \theta}{2\pi f} \tag{3.3.2}$$

We are utilizing direct ToF, because this will provide 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[13]. 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[13]. 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 very 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 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'll 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 sensor. 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. The drawbacks 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 do not require the incredible range and precision that lasers provide, thus we’re not planning on utilizing this kind of sensor. The prohibitive cost further solidified our decision not to use a laser diode ToF sensor.

3.4 Lenses

Our system requires an adjustable lens system capable of focusing on various ranges. To accomplish this, the focusing power of the system must be able to vary between -1.5 D and +2.5 D. There are a variety of systems and types of lenses that can be utilized to accomplish this. Liquid lenses, flexible lenses, and traditional glass or plastic lenses can be used in the system. Each of these lenses can be used to 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, we can significantly reduce the intensity of the aberrations that may be present.

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[14].

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

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

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[15].

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[16]. 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[16].

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[16]. 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[17].

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[17]. 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[16].

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[17]. 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[18].

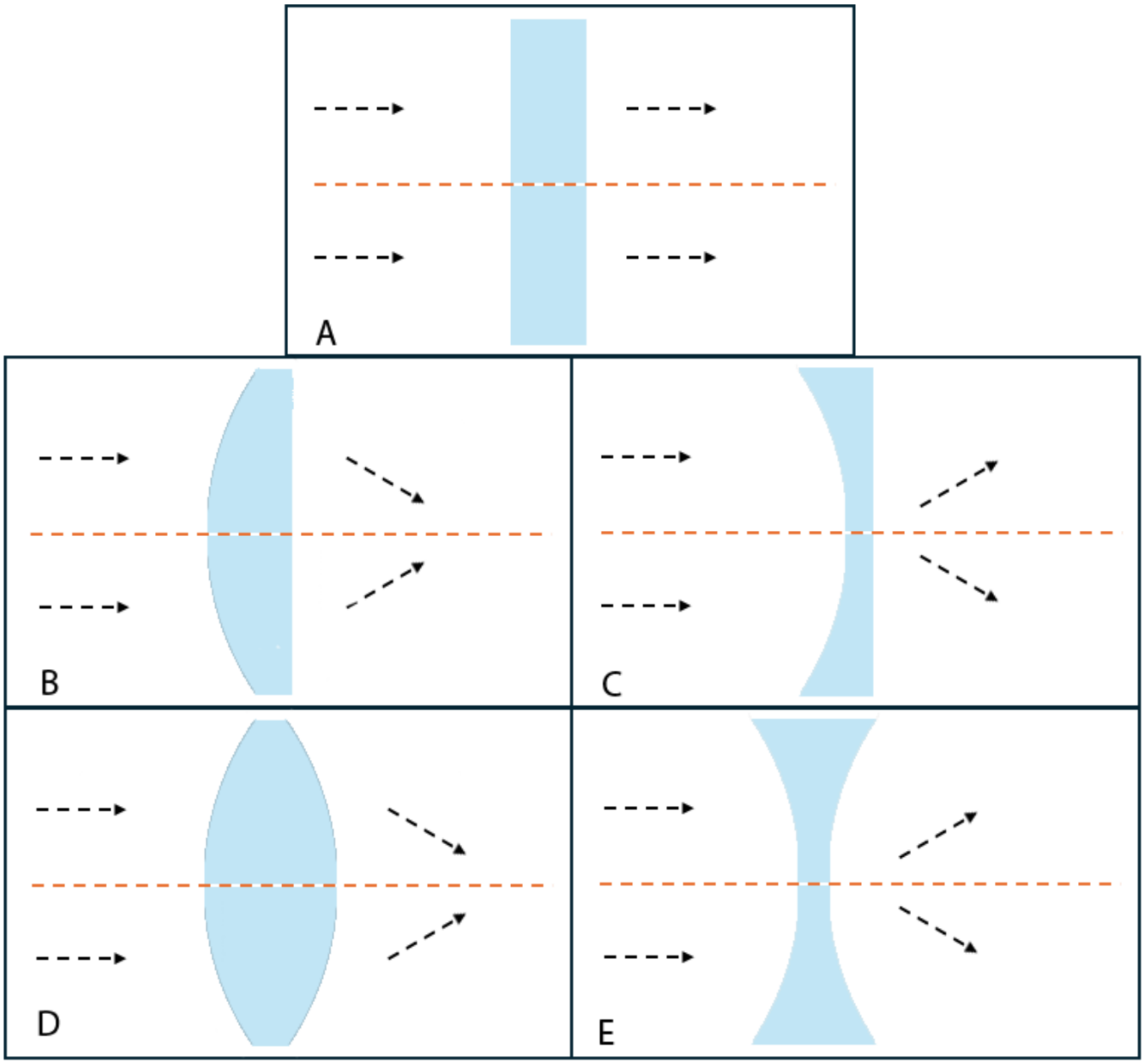

Figure 3.4.1 Typical Lens Shapes

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[17]. 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[17].

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[17].

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 very 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[19].

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[20]. 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[21]. 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[22].

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[23].

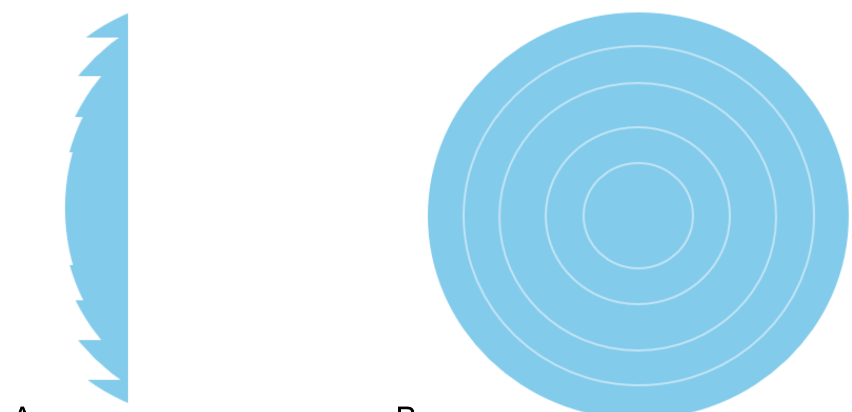

Figure 3.4.3 Fresnel Lens (A) Side View (B) Front View

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[24].

To begin with, glass has hundreds of available materials for making optics, while plastic is very 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[24].

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[24]. 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[25].

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[26]. 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[27]. 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[28]. 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's 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[29].

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

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

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[30].

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[31]. 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[32].

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[33].

All these coatings have unique benefits, but none are absolutely necessary for our system to function properly. That being said, the AR and UV coatings are the most beneficial for our purposes. The AR coating would be ideal for our color identification system as it would improve the transmission of the different wavelengths for each color. The UV coating would be beneficial for the lenses the user will see through as it would prevent 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 are 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. One lens will be utilized as a focusing lens and the remaining two lenses will be utilized to provide the variable optical power.

3.4.6 Lens Selection

When choosing lenses for our auto-focusing system, our largest restrictions are the size, weight, and shape. Since our system will be worn, it would be ideal 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 must select lenses with relatively high positive and negative optical powers. Both converging and diverging lenses will be necessary to accomplish this. 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[34]. 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 is a large hinderance which will certainly impact 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 seem to be the cheapest as well, which is great, since we plan 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 lists all the specifics of the lens, including material and lens thickness, and coating if there is one. This information is crucial for the accuracy of a lens system. It’s certainly something to consider when choosing exact lenses.

Edmund Optics offers all sorts of AR coating options such as MgF_2, 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’s not even considering the coated options. If we do choose to go with some lenses from Edmund Optics, we would only utilize a few for the most compact aspects of our system, such as the lens system that is 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 will consist of two lens systems, one that the user will use to adjust their focus and the other which will adjust the focus on the CMOS sensor. For the lens system that the user will see through, lenses with a diameter of 25, 38 or 50 mm would be preferred. In addition to this, we require a negative and a positive lens in each system to keep the lens system compact. More specifically, the negative lens should be more powerful than the positive lens to cover the optical power range of -1.5 D to +2.5 D that we desire. Shorter focal lengths will also result in a more compact system as they'll have larger optical powers. For this reason, we are primarily considering lenses with focal lengths at 200 mm or less. All the lenses that meet these criteria are highlighted in blue on Table 3.4.1. As for the lens system need for the CMOS sensor. Eisco seems to have all the lenses necessary for this at affordable prices.

As for the lenses necessary for the CMOS sensor's lens system, they must meet the same requirement, aside from the diameter size. Depending on the exact size of the CMOS sensor we choose, we'll be able to choose lenses with a smaller diameter. The smaller the sensor, the smaller the lens of course. For the CMOS lens system, we can also consider the lenses highlighted in green on Table 3.4.1. Unfortunately, these smaller lenses are much more expensive. Eisco is still our choice for this lens system, unless it's absolutely necessary that we need smaller lenses. Our top choices for the lenses are 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, 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 Motors

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

3.5.1 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 will need 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 will benefit us. 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 3.5.1 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 [35]. But, for our design purposes we don't need high speed as that could detriment our design if we are to use high speed (>2,000 rpm). On the downside if we were to choose a stepper motor, we would need to incorporate drivers, as that will help us get precise movement of the lenses using a written code to operate it. This could affect our design as that means adding this to our overall costs.

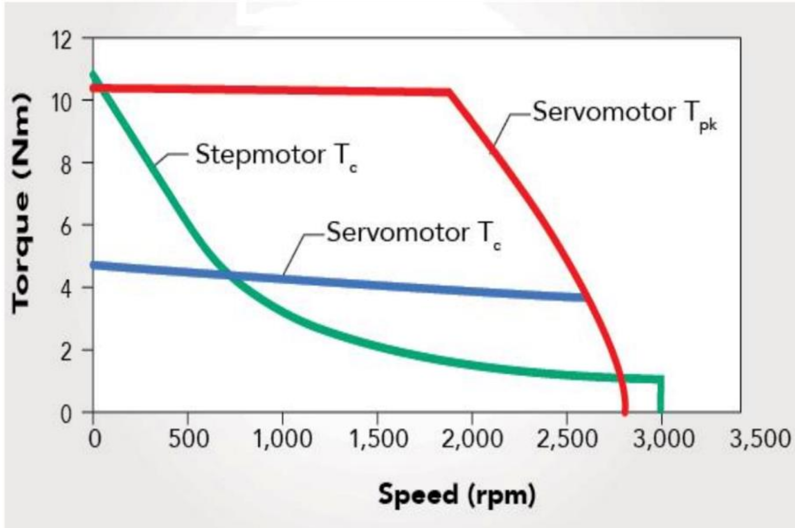

Figure 3.5.1 Torque vs Speed of Stepper Motor and Servo Motor

3.5.2 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 [35] 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 [35]. But we should take into consideration if we want this feature in our servo motor it will cost significantly more. As our design requires input from a sensor for position instructions, having a servo motor that can connect to an MCU is more beneficial than any of the other motors. Another feature of the servo motor is it can rotate in both directions, forward and backwards.

3.5.3 Motor Selection

Taking into consideration the research found on stepper motors and servo motors, we decided on the stepper motor for our design. Considering we will require two motors we will focus on low-cost stepper motors. Since we are selecting a stepper motor, we will also need to select a driver to make our motor programmable.

3.5.3.1 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 is a good option based on our design criteria, because it typically has a 1.8° per step. Considering we will need movement of small increments for our lenses this motor is a great option. NEMA 17 will require 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.

3.5.3.2 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 in 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. And will require a driver to be programmable an example of compatible drivers is: DM542 and DRV8711.

3.5.3.3 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. And its greatest setback is the general cost for a lead screw actuator, ranging in the pricier side.

3.5.3.4 Stepper Motors Comparison Table

Parameters	NEMA 17 Stepper Motor	NEMA 23 Stepper Motor	Lead Screw Actuator
Type	Bipolar	Bipolar	Integrated System
Step Angle	1.8 ° (200 steps/rev)	1.8 ° (200 steps/rev)	0.9 ° (400 steps/rev)
Lead Screw Pitch	2mm	4mm	5mm

Cost	\$15-\$30	\$30-\$70	\$50-\$100
Load Capacity	5kg	10kg	1.5kg
Compatible Driver	A4988 DRV8825	DM542 TMC2208	Comes in the design
Motors Dimensions	Width: 43.2mm Height: 43.2mm	Width: 43.2mm Height: 43.2mm	Width: 38-76mm Height: 51-152mm

Table 3.5.1 Stepper Motor Comparison Table

3.6 Logic Devices

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

3.6.1 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’s 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 can be 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’re 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.[36]

3.6.2 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.[37]

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.

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 3.6.1 MCU vs. FPGA Comparison Table

Overall, the best choice for our project given the comparison above is the MCU. Although the FPGA would give 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 need multiple connectors for a camera, motors, and different sensors, the MCU overall convers our general requirements. Additionally, even though we would have more computing power with the FPGA we really should have more than enough with only the MCU.

3.6.3 Microcontroller Boards

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

3.6.3.1 Raspberry Pi 4

The Raspberry Pi 4 is 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 can save money with a simpler board. The higher processing power also means that this board is less ideal for portable, battery-powered applications like our wearable glasses as battery life would be shortened as a result. It also lacks real-time processing capabilities which leaves potential problems in the future. Timing is also hindered by its reliance on a full Linux OS which can result in longer boot times. [38]

3.6.3.2 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 could be a dealbreaker since we are dealing with image processing which can require 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. [39]

3.6.3.3 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 would be utilizing for this project. This can speed 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've 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 be difficult to incorporate capturing and processing images. [40]

3.6.3.4 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 be quite useful for this project if we 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 start to bring in accessibility issues. But overall, the biggest concern with this board is its pricing. It is much more expensive than the other boards listed here and its additional need for cooling and power could cause some additional expenses that could be avoided. 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 might not be the best board for this project given price and power requirements. [41]

3.6.3.5 Raspberry Pi Pico

The Raspberry Pi Pico is another version of a Raspberry Pi board that's 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 26 multi-functional GPIO pins, 3 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 benefits us in terms of power the most since it operates with specific sleep modes to help us maximize battery life. Although Pico doesn't support the most complex image processing, it does have enough power to do simple image processing quite efficiently. The only concern is it wouldn't have enough processing power for our project.[42]

Features	**Raspberry Pi 4**	**ESP32-S3**	**Seeeduino Lotus**	**Raspberry Pi 5**	**Raspberry Pi Pico**
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
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
Connectivity	2 USB 3.0 ports, 2 USB 2.0 ports, 1 micro-HDMI ports, 2.5mm audio jack and HDMI audio output, 2-lane MIPI	USB 1.1 with OTG, SPI/I2C/I2S/UART/CAN interface support, camera interface support	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

	CSI, 2-lane MIPI DSI, 40-pin GPIO header			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)
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, PCIe 2.0 interface, USB-C	16 PWM channels, USB power supply, SWD interface
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
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

Table 3.6.2 MCU Board Comparison Table Pt.1

3.7 Communication Protocols

3.7.1 Wired Communication Protocols

Wired communication protocols consist of communication via a wire medium. Wired communication is known to be more secured than wireless as it requires physical connection between devices. The most 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 will focus on four main wired communication protocols: I2C, UART and SPI. [43]

3.7.1.1 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.[43] 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 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 of 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[43].

3.7.1.2 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. [43]

3.7.1.3 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 [43]. 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 [43]. 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. [44]

3.7.1.4 Wired Communication Comparison Table

When it comes to our design, we will consider all the features from Table 3.7.1 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 will be incorporating I2C protocols as it gives the better coverage considering the placement of most of our electronic components.

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 3.7.1 Wired Communication Comparison Table

3.7.2 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 need to only use short-range wireless protocols meant for local devices so we will look at Wi-Fi, Bluetooth, Zigbee, and Infrared.

3.7.2.1 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.

3.7.2.2 Bluetooth

Bluetooth is a wireless communications protocol designed for short-range, low-powered connectivity between local devices. Typically, it’s 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.

3.7.2.3 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’s 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 its ideal for devices that need to operate for years without frequent battery changes like smoke detectors, doors locks, or motion sensors.

3.7.2.4 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.

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)

3.10 Batteries

Our design requires batteries for the MCU and motors. We will select our MCU with the batteries included, therefore the research is for choosing batteries that will power our motors. To choose a battery we will take into consideration factors like battery life, rechargeability and cost. We want a battery that will last enough and not require constant recharging. For batteries that accomplish these factors we will research four different types of batteries.

3.10.1 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 is to be considered and can be a driving force on what battery we will be selecting. 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. [45]

3.10.2 Nickel-Metal Hydride (NiMH)

Nickel-Metal Hydride batteries are of higher capacity than NiCd, these batteries are 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. [45]

3.10.3 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. [45]

3.10.4 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. [45]

3.10.5 Comparison Table of Batteries

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 3.10.1 Batteries Comparison Table

3.10.6 Batteries Selection

To select a battery to power our motors, we will look at all our requirements for a successful design. Take into consideration the rated current and voltage of our motors, the price of the batteries, the durability of the batteries, etc. Based on the research results we have gathered; we will be selecting the Lithium Polymer batteries.

3.11 Converters

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

3.11.1 Data Converters

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

3.11.1.1 Analog-to-Digital Converters (ADC)

ADCs are converters that take a continuous analog signal and converts it into a digital signal that can be processed by digital devices such as microcontrollers, computer or digital signal processors. They can be categorized into three main steps in its process. The first step is sampling, an ADC samples from a continuous signal at regular intervals. The frequency of this 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. [46]

3.12 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 will research on voltage regulators for our design purposes.

3.12.1 Voltage Regulators

Voltage regulators are a very common type 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.

4 Standards and Design Constraints

4.1 Standards

Standards set the norm for technological development. Standards are essentially agreed upon 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’s 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[47].

4.1.1 Lens Standards

There are many standards that we may need to consider regarding our lens design. Table 4.1.1 below lists potentially relevant lens standards.

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 19 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'll 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[48].

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[48, 49].

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[48].

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[48].

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 will not be utilized in our auto-focusing system, it may be useful for our color identification[49].

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 [49].

4.1.2 Imaging Sensor Standards

Table 4.1.2 lists some standards for CMOS sensors that we may need to take into account and include anything ranging from color to shading.

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 is crucial to our color identification system. It establishes a uniform method for measuring color and characterizing colorimetric systems and introduces 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.

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

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.

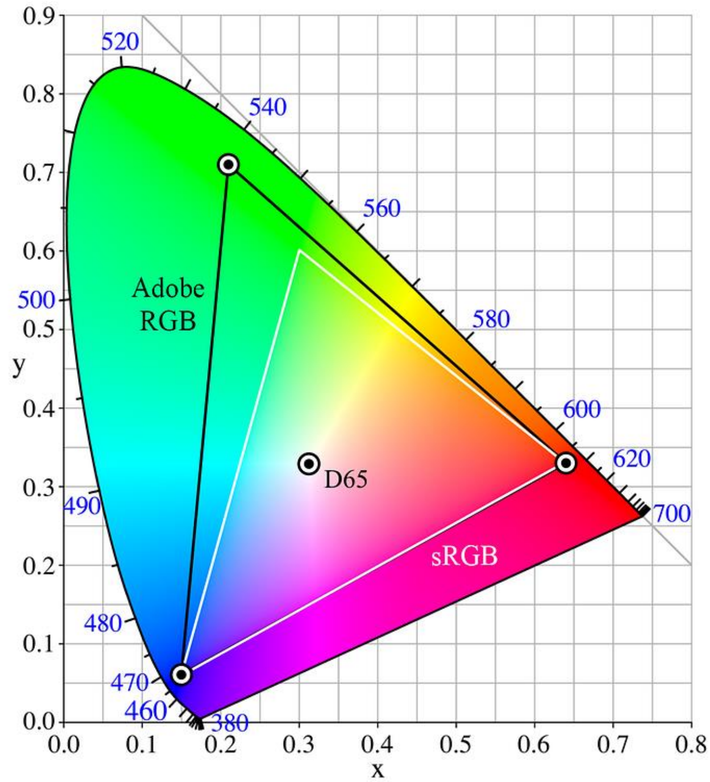

Figure 4.1.1 Color Gamuts

Another of these standards to take particular interest in would be 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.

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.

The final, and perhaps most important for us, is 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.

4.2 Design Constraints

Much like any project, our system has many constraints that we must conform to in order to successfully produce a working system. While we have the flexibility of imposing some of these constraints on ourselves, others, such as time, are set by existing deadlines. Each constraint is just as important as the others as they challenge 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 make to the lenses will produce significant changes in vision for our user. One of our main technological components is an ultrasonic sensor. We use it to measure the distance of the lenses to their immediate surroundings to do an initial setup for the glasses. It isn't 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 300 meters. In addition to that, our choice of an MCU board can have quite a large impact on how well our autofocusing system works. Because we want the autofocusing to complete in less than five seconds, 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 do not have any sort of sponsorship at this time to help cover some 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 leaves us with a total of $1000 to carefully plan and use over the next 2 semesters. The money needs to cover all the costs of supplies and parts, and still leaves spare money in case a product gets 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 is time constraints. The Senior Design course consists of only two semesters. During which most of our team members have jobs that require their time or are enrolled in more than three courses each semester. This is to be worked around and 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 can be 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 is mandatory. The advanced technology and information available today are beneficial, with most of the information we need just one search away. This facilitates our research process yet having so many options of the same technology can become complicated and more difficult to pick just one. Having the tools to do research in a much more accurate and faster way is much to our benefit.

There is always the possibility of running into obstacles like a delay in receiving the components we have selected. Various factors contribute 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 will be ordering our parts ahead of time, with enough time that if the situation mentioned above did happen, we would have time to resolve it. And doing research on what sellers are to be trusted and who is not.

The assembly and testing of our assistive lenses will require a significant investment of time, as writing the report is only half of the design process and generally involves fewer potential problems than testing and assembling. To account for this, we will conduct longer meetings dedicating a lot of time to the lab, experimenting and testing. We would initially verify if all components in our design are working properly. And seek guidance from our mentors if we find ourselves facing obstacles. The testing phase is critical, as it involves mechanical and electrical components and software code that can all face challenges that will affect 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 is absolutely crucial that the total size and weight is taken into consideration.

Since our lenses are meant to be worn, it is important that the entire system is comfortable. The idea is that the visually impaired individual is capable of wearing the assistive utility lenses throughout their day as it gives them feedback and simplifies certain tasks 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 will not be capable of detecting a sharp image, leaving it inoperable and the user's vision will be locked into on 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 will certainly ensure more stability for the user as well.

The next consideration is the battery life of the system. This system will have several moving parts that will require motors. The heavier these parts are, the larger the motors that we'll require, which will in turn result in even more weight. The larger motors will also consume more power, draining our batteries at a quicker rate. While the system may not always be necessary and thus won't 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 is necessary.

The final consideration is debatable either the most important or the least important. The aesthetics of the assistive utility lenses should be taken into consideration. A large and bulky system will easily stand out and could garner unwanted attention. In a society when 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 may not end up the most aesthetically pleasing, we aim to minimize the bulkiness of the design as much as we can without sacrificing the functionality of the system.

As a worn technology, the size and weight of our system cannot be ignored for the reasons listed above. These constraints will ensure our system becomes the beneficial, assistive technology it is meant to be.

4.2.4 Human Anatomy Constraints

Joining the topic of size and weight, human anatomy itself becomes an issue that must be addressed and worked around. The power of the lenses we choose, the size of the system, and the weight of the instruments are important and are 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. Given that we are appealing to users who suffer from myopia for our autofocusing system, we need the lenses to provide at least -2.25 diopters to correct moderate nearsightedness. However, in doing so we must also take care of accounting for magnification. Reducing the effects of magnification as we have our two-lens system move in and out in conjunction with input from the CMOS will be crucial, as we want the user to experience the same benefits as normal corrective lenses when using the device.

We also must consider 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. Therefore, we need our CMOS sensor to be as accurate to the color gamut as possible. To do this, we can compare spectral sensitivity functions of the various sensors we are researching and see how they overlap with human color vision. The more accurate they are, the more accurate our results will be when we try to 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 is to include app functionality, we will also have 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 will streamline the use of the app so that it can appeal broadly to as many users as possible.

5 Comparison of ChatGPT and other Similar Large Language Models

5.1 Pros and Cons

Large language models (LLMs) 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. Having utilized a few LLMs such as OpenAI's ChatGPT, Google's Gemini, and Microsoft's Copilot, it's 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 isn't 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 B-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 5 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 isn't 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's 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 B-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's a compact integrated circuit that operated within an embedded system, but that does answer the question on what an MCU is. It just doesn't go into depth on it as that wasn't 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've 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's 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 6 reasons why it is convenient/easy-to-use and provides a little description on why. Finally, after that, it lists 4 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 wasn't 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 4 main benefits and leaves out less direct reasons why such as ease of development and real-time processing. Lastly it lists 3 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 doesn't 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 doesn't 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 5 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 5 source links. It didn't 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 didn't 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 wasn't 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 didn't see with ChatGPT and Gemini which is good to note.

5.4 A Prompt on Motors

Prompt B-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 B-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 don't 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.

10 Administrative Content

10.1 Budget and Financing

Component	Name	Price	Quantity
CMOS Sensor	EOS Rebel T3 12.2 MP APS-C CMOS sensor	$23.98	1
CMOS Lens	Garage sale	$20	1
Primary Lenses	Garage sale	$20	2
Secondary Lenses	Garage sale	$20	2
Railing	Linear Rail Guide Linear Sliding Guideway with 1pcs Linear Bearing Sliding Block	$12.80	3
Button	Adafruit mini	$0.50	5
Frame	3D Printed	-	1
Motor	STEPPERONLINE Stepper Motor Nema 17	$12.99	2
Photodiode	Comimark 5Pcs BPW34 Silicon PIN Photodiode DIP-2	$6.89	3
Pack of Color Filter	SAMNISOO 30 pc color filter	$17	1
Strobe Light	Evan Designs Quickburst Strobe Light	$5.85	1
Servo-Motor Controller			1
PCB	easyEDA	$70	1
Raspberry Pi 4	Raspberry Pi 4 4GB Starter PRO Kit – 4GB RAM	$139.99	1
Power Supply	Rechargeable power supply	$15	1

Table 10.1 Finance Table

10.2 Milestones

Senior Design 1	
Week	Goal
1-2	Form groups and finalize project concepts.
3	Divide and Conquer 10-Page due
4	Divide and Conquer review meeting w/t Chan/Wei
5-6	Post on website & Divide and Conquer Revision due
7	Create Gantt chart & Design Constraints and Standards due
8	Conduct research and initial design stages for 60-Page draft
9	Reach half point 30-pages of 60-Page draft
10	Finalize 60-Page draft and turn in.
11	Attend 60-Page draft review meeting and begin to make adjustments.
12	60-Page report revision due.
13	Begin work on 120-page paper and finalize designs.
14	Finish up 120-page paper
15	Final report and mini demo video due.

Table 10.2 Milestone Table

10.3 Declaration

We hereby declare that we have not copied more than 7 pages from the Large Language Model (LLM). We have utilized LLM for drafting, outlining, comparing, summarizing, and proofreading purposes.

Appendix

A. Copyright

B. Large Language Model Prompts

B-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

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- 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 yo u'd like to know?

B-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 **RAM** for temporary data storage1.
3. **Communication Interfaces**: Allow the MCU to communicate with other devices, such as UART, SPI, and I2C3.
4. **Input/Output (I/O) Ports**: Enable interaction with external devices like sensors 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 FPGAs4.
2. **Power Efficiency**: Designed for low power consumption, making them ideal 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, saving space1.
5. **Versatility**: Can be used in a wide range of applications, from home appliances to automotive systems1.

Sources:

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

B-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?

B-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?

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