Prototype Design of a Photonic Retinal Prosthesis

By

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Preface & Acknowledgements

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I am very grateful to my parents, sister, and fiancée for all their support throughout my college career. They have backed my every decision and encouraged all my endeavors. I could not have made it this far or be the person I am today without your love and inspiration.

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1. Introduction

Retinitis pigmentosa (RP) affects approximately 1 in every 4,000 individuals. RP covers a group of genetic disorders associated with loss of photoreceptors and recognized by pigment deposits covering the retina (Hamel). Symptoms of RP include night blindness, light sensitivity, loss of peripheral vision, tunnel vision and eventually blindness. RP typically evolves slowly in the individual and allows for early diagnosis; however, there are no current solutions to prevent or halt the progression of RP or to restore normal vision in these individuals (Hamel).

There exist some invasive options to generate artificial excitation in the retina for individuals with RP. These systems take advantage of the fact that although photoreceptors in those with RP can no longer sense light, other retinal cells can be activated using electrical stimulation. One such successful system is the Argus II retinal prosthesis made by Second Sight Medical Products, Inc. It has been implanted in over 350 individuals with RP or similar afflictions. The device requires implantation of a microelectrode array on the retina. The array consists of 60 electrodes each spaced 575 µm apart in a 6x10 matrix (Weiland and Humayan). The array is connected to a miniature camera mounted on a pair of glasses. The signals picked up by the camera are then translated into the electrode array and used to excite neuronal cells to recreate an image (Finn, Grewal and Vajzovic). Although approved retinal prostheses exist, all current devices utilize microelectrode arrays to create artificial vision (Bloch, Luo and da Cruz).

Limitations of these devices come with their design and invasive nature. The design of these devices greatly restricts resolution for the user. The typical retina contains roughly 91 million rods and 4.5 million cones (Purves, Augustine and Fitzpatrick), but these systems only allow a number of excitation points equal to the number of electrodes on the implant. These devices do not have single cell resolution and instead excite several cells at once and allow for the an unintended flow of current in retinal media as the contact points are physically touching the retina (Bloch, Luo and da Cruz). This means if one cell or group of cells is electrically stimulated via implant, the surrounding cells that were not targeted are still likely to receive that electrical signal and elicit a response as well. This results in extremely low visual resolution and shows only motion detection, edge detection, and in some cases single letter detection, limiting the best visual acuity of the restored vision to far below that of legal blindness (20/200).

These implants cover a micrometer level portion of the retina whereas the central retina is considered within 6 mm around the fovea. There is a large group of cells unattended in these systems and a much greater area that could be utilized (Kolb) and therefore these implants have a small visual field. These systems are also not always successful. A study done on the Argus II examined 30 patients with the implant, with 40% of them reporting significant adverse effects either from surgery or the device. Many of these adverse effects required invasive surgery or caused greater damage to the eye (Bloch, Luo and da Cruz). The functionality of the device decreased after 3 years to 5 years of device use based on patient's reports, although it is unclear if the loss of function is statistically significant (Finn, Grewal and Vajzovic).

Due to the limitations of these invasive microelectrode devices, a new external device is proposed. The primary aspect that sets this design apart from present-day solutions is external stimulation and thus requires a laser source to generate thermal excitation of the retina as opposed to electrical stimulation. Previous studies determined infrared (IR) excitation caused tissue damage and limited signal strength (Aly and Mohamed). To avoid these adverse effects, near infrared (NIR) light can be used. NIR stimulation has negligible water absorption such that it does not have the bulk heating issues of IR stimulation. Coincidentally, the NIR excitation does not generate much heat. To generate greater heat to reach the excitation threshold, gold nanorods (AuNRs) can be deployed to the site and tuned to a specified wavelength to generate a highly localized heat signal (Lee, Eom and Byun).

To take advantage of this type of stimulation, the proposed design will utilize a camera, NIR laser and collimator, and galvanometer to recreate an image on the retina. The major objective of this thesis is to design a prototype headset for human use in the future. Design of a medical device for immediate clinical use requires a number of regulatory considerations and documentations. As this thesis is the initial phase of the prototype design, considerations here focus more on exploring technical feasibility, including hardware selection, packaging design, optical design, and optical mathematics. The major focus lies in efficacy rather than safety: how to create higher resolution artificial sight compared to current solutions for individuals with RP.

2. Hardware Component Selection

Camera

To relay an image on the retina, the device must first be able to capture an image. Thanks to recent advances in the machine vision camera industry, we have a wide range of available options for cameras to include in the device design. A camera does not need built-in Image Signal Processing (ISP) as this will be done by the embedded system. The main requirement for the image sensor is that it contains the number of pixels desired for the system and runs at a speed greater than the desired number of frames per second. Considering very high pixel numbers and frame rates of recent generic complementary metal-oxide-semiconductor (CMOS) sensors, it is likely that those values would be limited by galvanometer control before they will be limited by a camera. For testing purposes, a Lenovo EasyCamera webcam was used with a resolution of 640 x 480 pixels. At 10 frames per second, this resolution is much higher than the laser modulator's maximum speed as only 1,000 pixels are required for the laser modulator to hit its maximum. Therefore, this camera fits the needs of the project as it has a greater resolution than needed and can easily be resized. For a standalone prototype, however, Omnivision makes the OV01A10 device which is a 1 Megapixel camera that runs at a rate of 60 frames per second and is an economic CMOS device. The device also has a low power consumption of 82.2 mW. This was used for the mechanical design assembly of this project which will be discussed further.

Laser, Collimation, and Driver

To relay an image to the retina, the device will need a laser for thermal excitation. The laser chosen (LP785-SF100 from ThorLabs) is a pigtailed laser diode with 785-nm NIR wavelength for use with AuNRs, although any 785-nm laser with a small aperture would fit the system. Pigtailed diodes allow for flexible delivery from the power source to the desired target using fiber optics. This allows the power source to be external to the prototype as it would not fit in the design. This laser delivers up to 100 mW of power which we have proven to safely photothermally excite the AuNRs. The operating temperature is from 0° to 50° C allowing for use in normal conditions. The laser has a 2.5-mm beam diameter which needs to be reduced via collimation.

The collimator chosen was the F230FC-780 collimator from Thorlabs. It has a focal length of 4.51 mm, a numerical aperture of 0.55, is configured for 780 nm, and the output beam diameter is 0.98 mm. It has a power consumption of 600 mW. The collimator also has an FC/PC connector to connect to the LP785-SF100 laser. Optical calculations for the system have been made using this laser and collimator configuration. Unfortunately, this collimator does not reduce the beam diameter as much as desired. It is possible for future use that a customized collimator or lens system will need to be developed to reduce the beam size further.

The modulator must run at a frequency of the number of image pixels times the number of frames per second (fps). For instance, if the pixels are 64x48 and the system runs at 10 fps, the modulator must run at a speed greater than 30,720 Hz. This assumes each time step of the laser turning on and off is equal; however, this is not the case as the timing of the on/off function will be non-linear due to the optics of the eye, so a higher modulation frequency is desired. Laser modulation can be easily achieved by a laser current driver, which typically has a much higher modulation speed than the galvanometer driver. Thus, the overall system speed will be limited by galvanometer control before it would be limited by laser modulation. Several types of high-speed laser current drivers are available for the chosen pigtailed laser while supporting laser modulation. The LDM9LP from Thorlabs is a temperature controlled pigtailed laser diode mount that allows for external modulation. The mount has a 7 W cooling capacity while modulating the laser at a frequency of 200kHz to 1 GHz. The power supply required is 3 V with a 4.5 A current.

Galvanometer

The last component is the galvanometer, an instrument that allows for the delivery of a laser to be redirected anywhere within a specified XY grid of a target plane. For purposes of this project, this apparatus will control the laser beam's location on the retina. It does so with two mirrors attached to servo motors. The laser points at one mirror, which reflects the beam in the X direction onto the second mirror, which then reflects the beam in the Y direction. This will allow the device to relay an image in an XY grid on the retina.

The factors considered for the galvanometer included size, weight, response time, and maximum scanning angle. Several micro-galvanometers (Table 1) were considered, and the ScannerMax Compact 506 turned out the most suitable for our design. The size and weight of the selected galvanometer are minimal, weighing in at around 12.8 grams per servo motor and 48 x 36 x 45 mm in size. The system has a 180 µs step response and a 20° maximum scanning angle. It is also a 16-bit system configured for 100° allowing a minimum scan angle of approximately .0015° (100°/64,536 distinct values). The system requires an input of 24 volts with a current of 5 A. The cost of the system is economical in comparison to similar systems evaluated at $1,095.

Table 1: Galvanometer Options

Parameters	Galvo Scanner Set				
	Cambridge Tech: 8310K	SCANLAB: dynAxis T	Canon GM1010	ScannerMax: Saturn 9B	ScannerMax: Compact 506
Scan Angle	40 Degrees	12 Degrees	30 Degrees	27.5 degrees	20 degrees
Weight	13.3 g	40 g	200 g	36 g	12.8 g
Size	3 mm mirror | 27.3 x 19.1 mm	16.5 x 35 mm	78 x 33 mm	8-10 mm mirror | 64.05 x 23.75 mm	Up to 1" mirror | 48x36x45 mm (with mount)
Aperture Size	3-7 mm	8.5 mm	10 mm	8-10 mm	8-10 mm
Step Response	130 us	230 us	280 us	300 us	180 us
Pixels/Frame	~7,692	~4,347	~3,571	~3,333	~5,555
Lines/Frame	~769	~434	~357	~333	~555
Driver Board Size	6.9 x 4.0" | 3.9 x 4.0"	–	5x2x1.5"	4x3x1.3"	4x3x1.3"
Driver Board Weight	1400 g	–	350 g	170 g	170 g
Price	$2,211/set	$1,820/single	$6,650/set	$2,495/set	$1,095/set

Table 1: Comparison of micro-galvanometers for use with the system. Pixels per frame for a 1:1 ratio image was found by dividing 1 second by the step response. Lines per frame was then calculated by dividing pixels per frame by the number of frames per second.

3. Mechanical Design

In order to deliver the image to the eye, packaging had to be developed to include necessary components and allow for retinal alignment. This was done using SolidWorks 2019 software. Many design constraints were considered when creating the following design. These included the diameter of the pupil, the alignment to the eye, the distance from the eye, the ability to include necessary hardware, heat dissipation, and the comfortability of the user.

One of the necessary designs included a custom mount to align the laser to the galvanometer. The ScannerMax website contained a computer aided design (CAD) file of the Compact 506 system, including a mount. This file was imported into Solidworks and edited to add an attachment for the laser that would line up with the center of the first mirror when assembled. The design was created to both align the laser to the servo motors as well as allow for 3D printing as the provided mount by ScannerMax weighs 48.8 grams. Using DIN 128 standard plastic, the new 3D printed mount would weigh only half of that at approximately 24 grams. It also contained threads to allow for #5-40 screws to secure the servo motors in place (Figure 1, Figure 2).

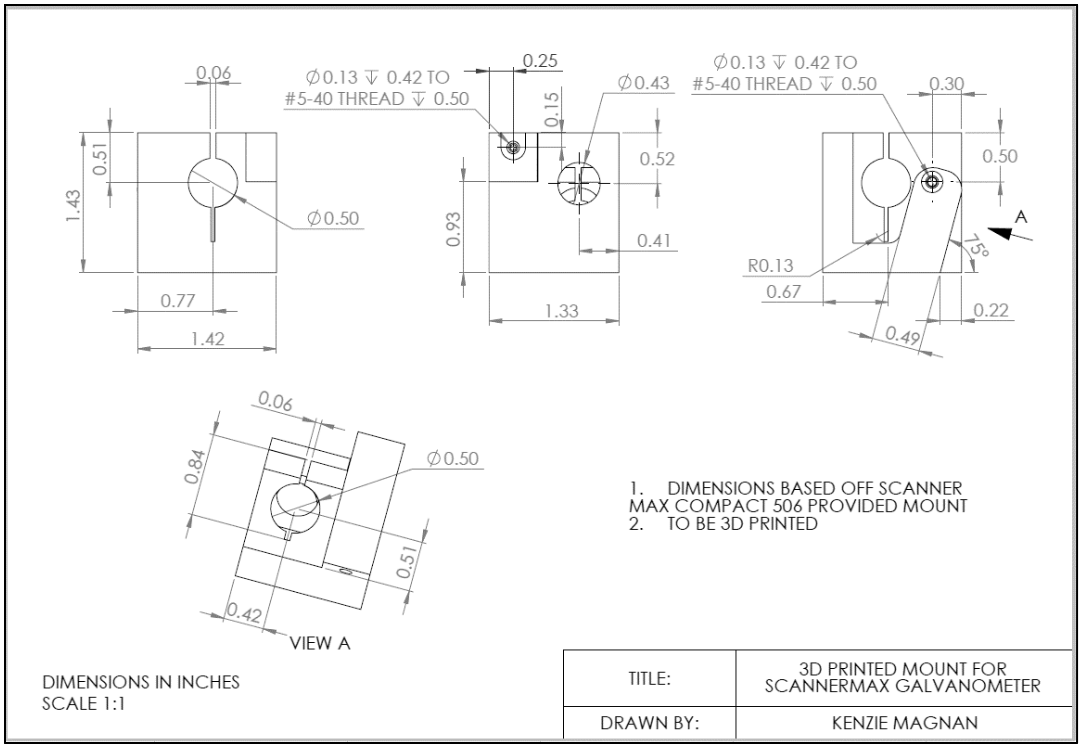


Figure 1: Technical Drawing of the Designed Galvanometer Mount

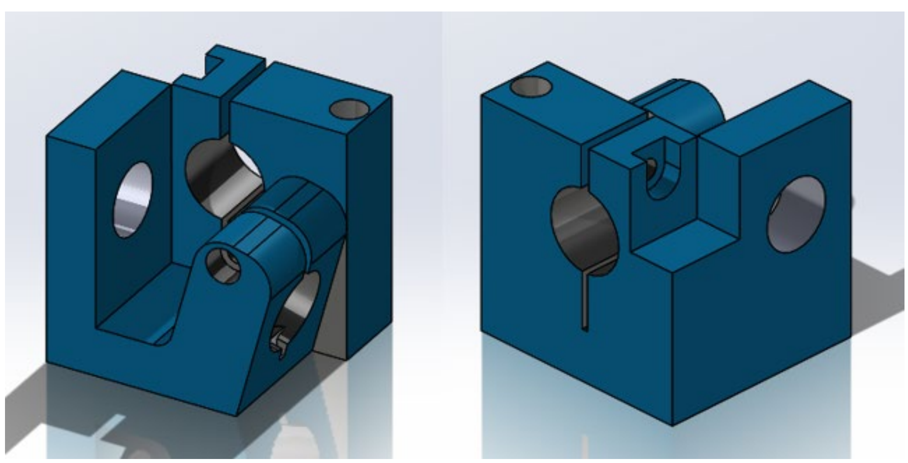


Figure 2: SolidWorks Rendering of Galvanometer Mount (front and back)

After the mount was designed, an assembly (Figure 3, Figure 4) was created to show the attachment of the laser to the collimator, the collimator to the mount, and the servos to the mount.

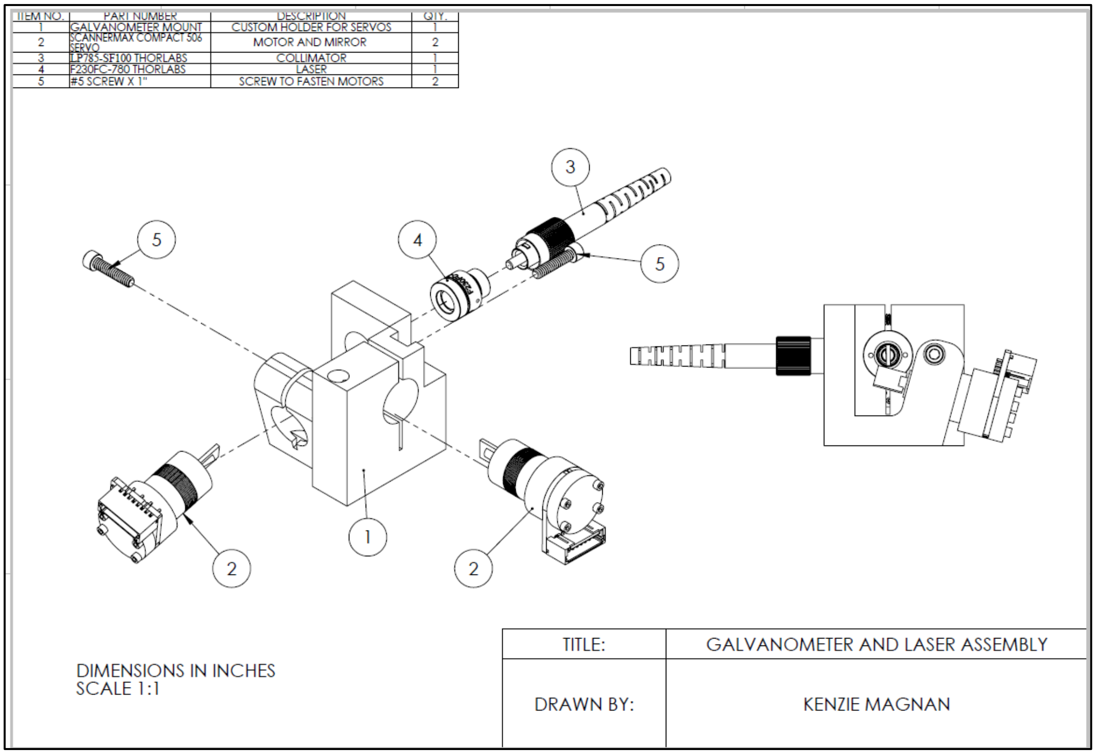


Figure 3:Technical Drawing of Laser, Collimator, and Galvanometer Assembly

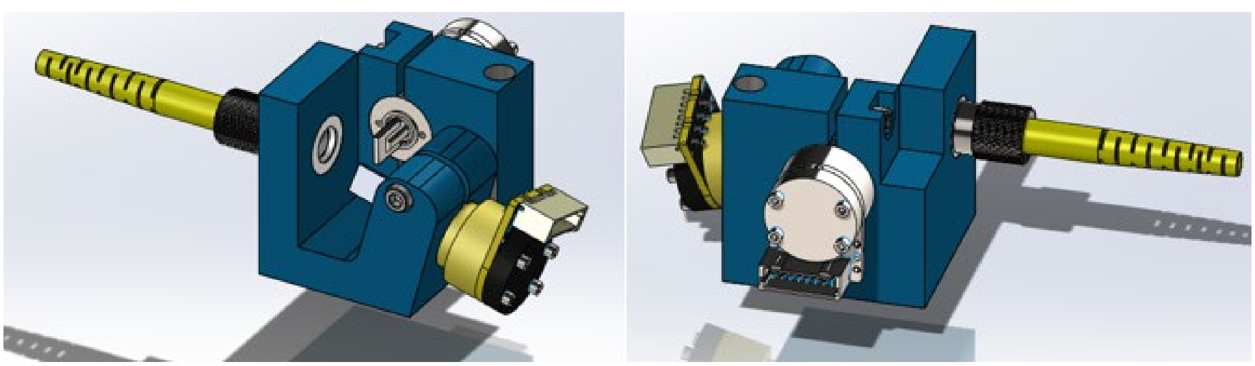


Figure 4: SolidWorks Rendering of Laser, Collimator, and Galvanometer assembly (front and back)

After creating the laser and galvanometer assembly, a way to adjust the beam to align with the eye was necessary. By keeping the galvanometer in a fixed position, there is little assurance that it would line up correctly with the center of the pupil as every individual's eye location is different. For more suitable placement, a 3-axis stage was designed for the galvanometer mount to sit on. The first step was to design a platform for the 3-axis stage to attach to (Figure 5). This platform was designed to be stationary while allowing movement in the X, Y, and Z directions using the other stages. It was designed with guards on the side to hold the remaining portions of the assembly in place and mechanically blocking movement in unwanted directions.

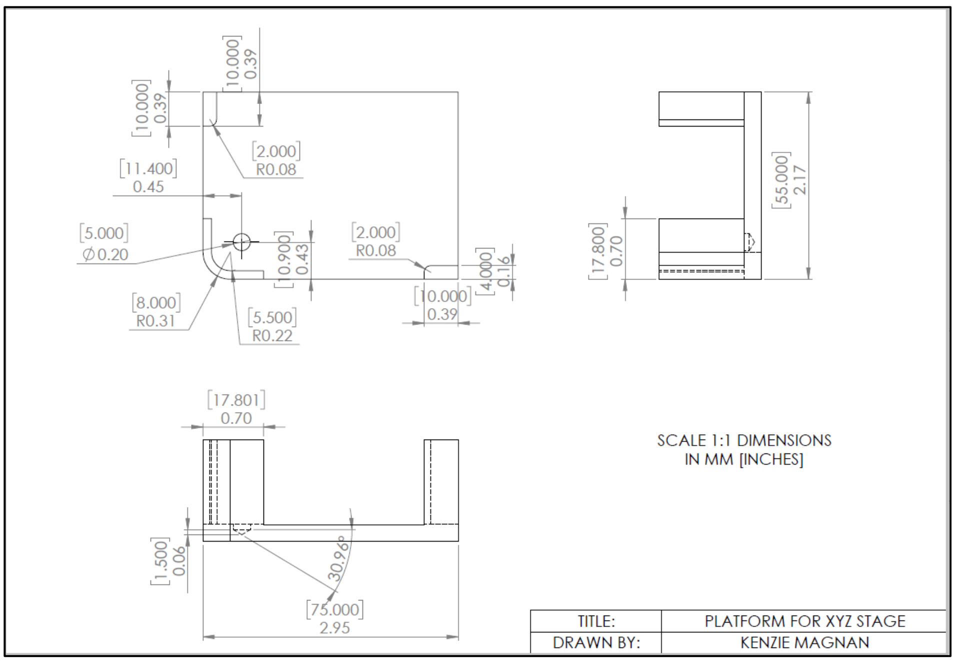


Figure 5: Technical Drawing of Bottom Platform for XYZ Stage

After this, a stage was created to move in the Z direction (Figure 6). This stage was created to fit the platform while having an internal thread to allow mechanical movement via a custom screw design. It also held slots on the sides for the XY stage of the assembly to move freely.

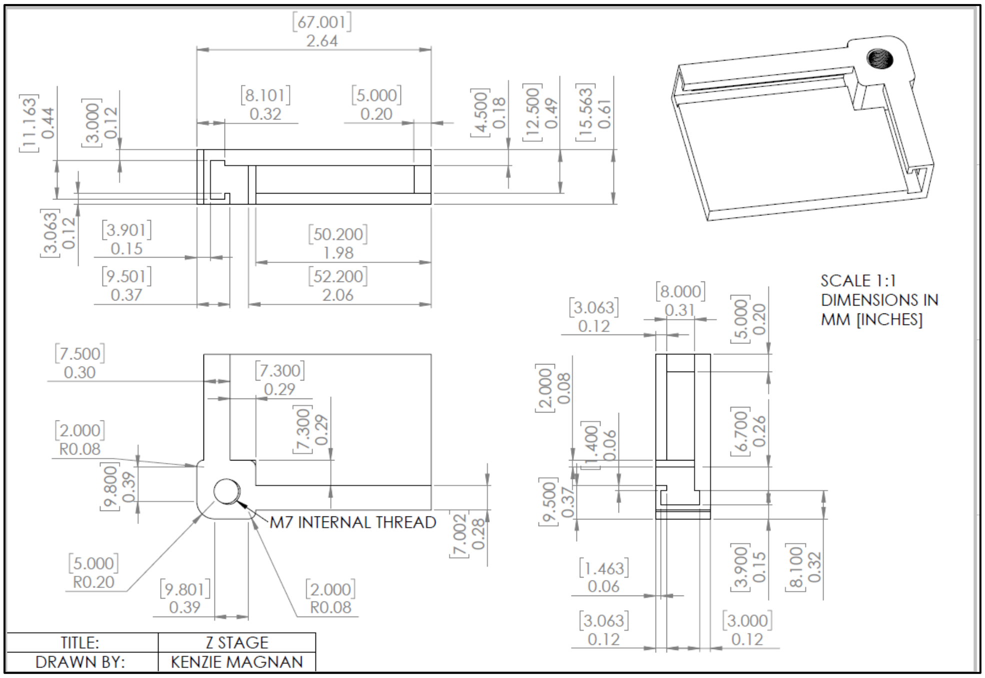


Figure 6: Technical Drawing of Z Stage

Next, a stage was created to move in the X and Y directions (Figure 7). This stage fit the Z stage while containing slots to attach custom screws for movement.

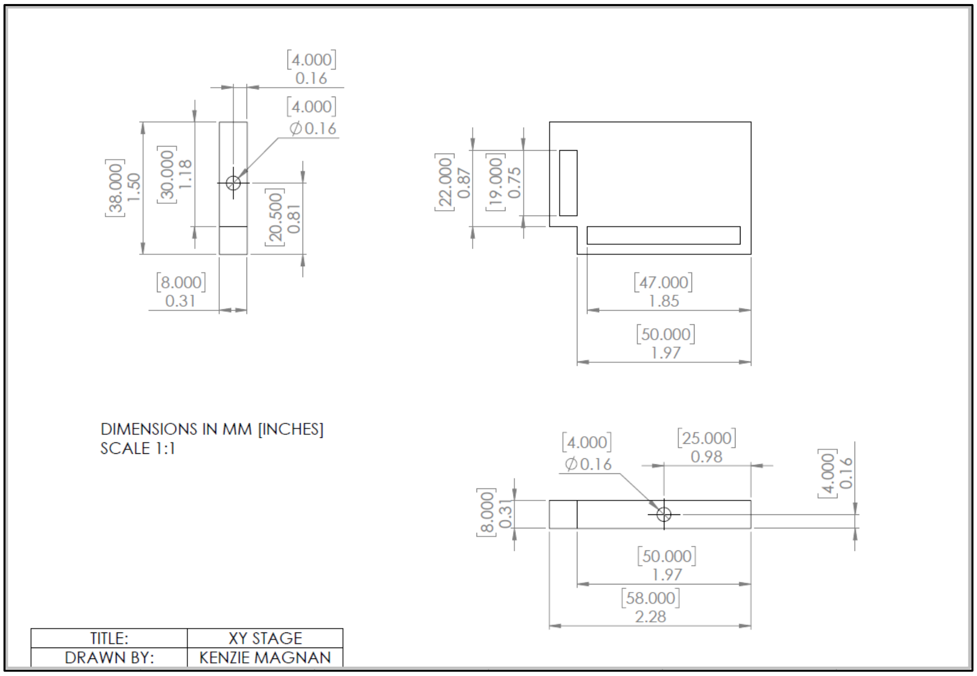


Figure 7: Technical Drawing of XY Stage

Custom screws, as discussed previously, were developed (Figure 8, Figure 9) to allow for turning and moving each stage without being attached to anything other than a free-standing hex nut. Without any fixation, these screws were able to turn freely and only be limited by the physical dimensions of the XY and Z stages. Blocks were also created (Figure 10) that slide into the Z stage and are fixated in the Z direction but have internal threads to allow movement in the X and Y directions using the custom screws. This allows for the XY stage to move using the custom screws.

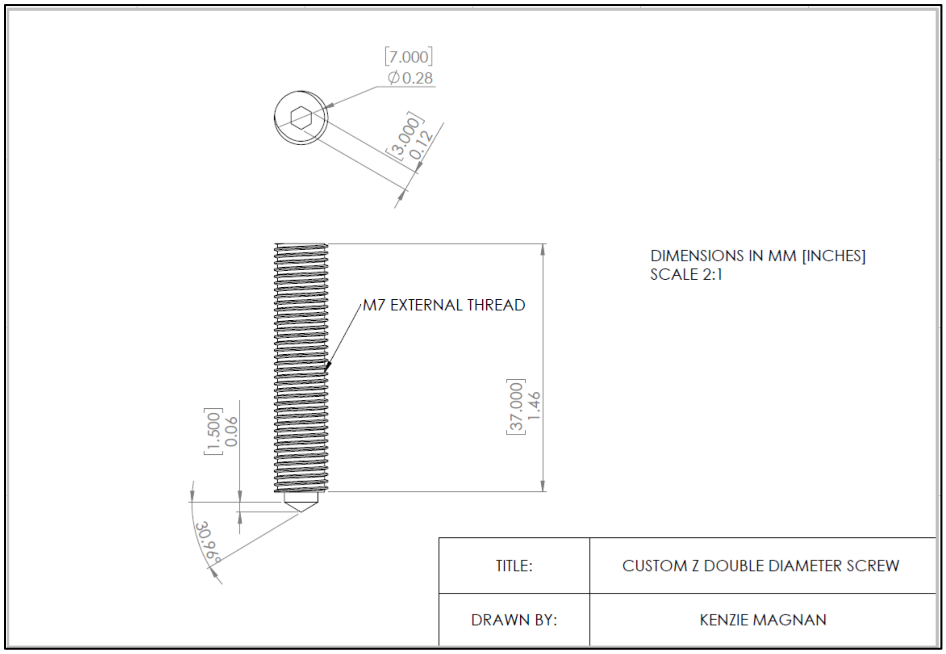


Figure 8: Technical Drawing of Custom Screw for Z Stage

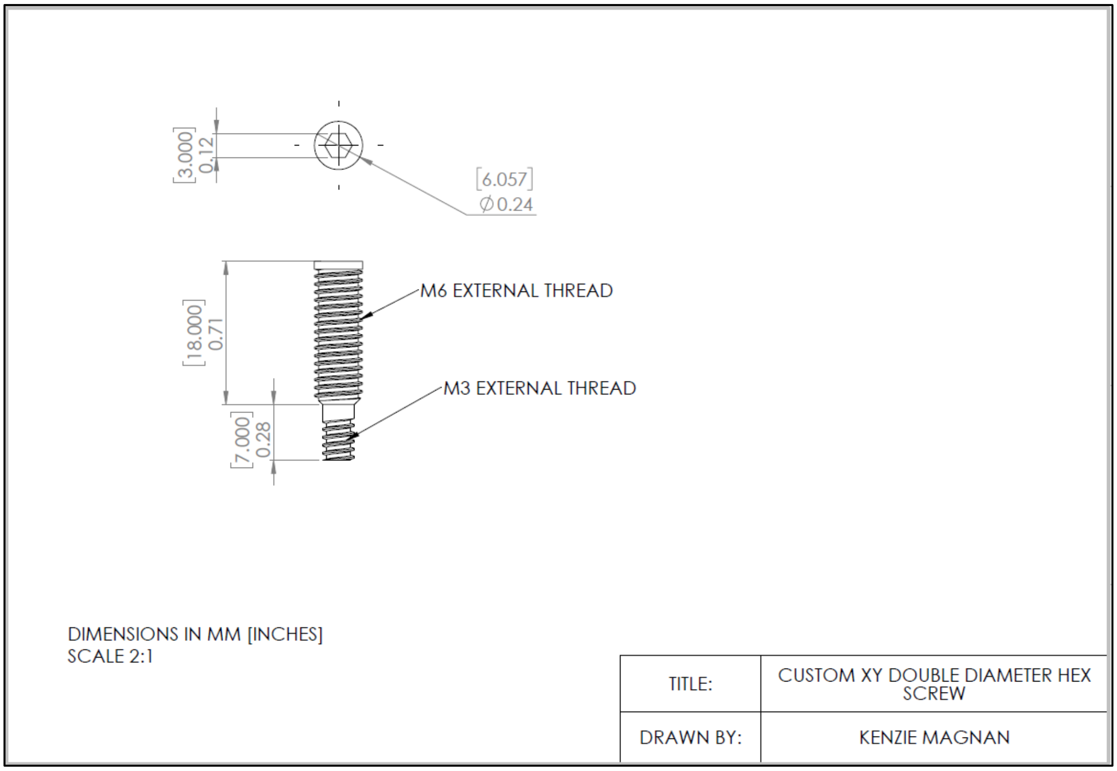


Figure 9: Technical Drawing of Custom Screw for XY Stage

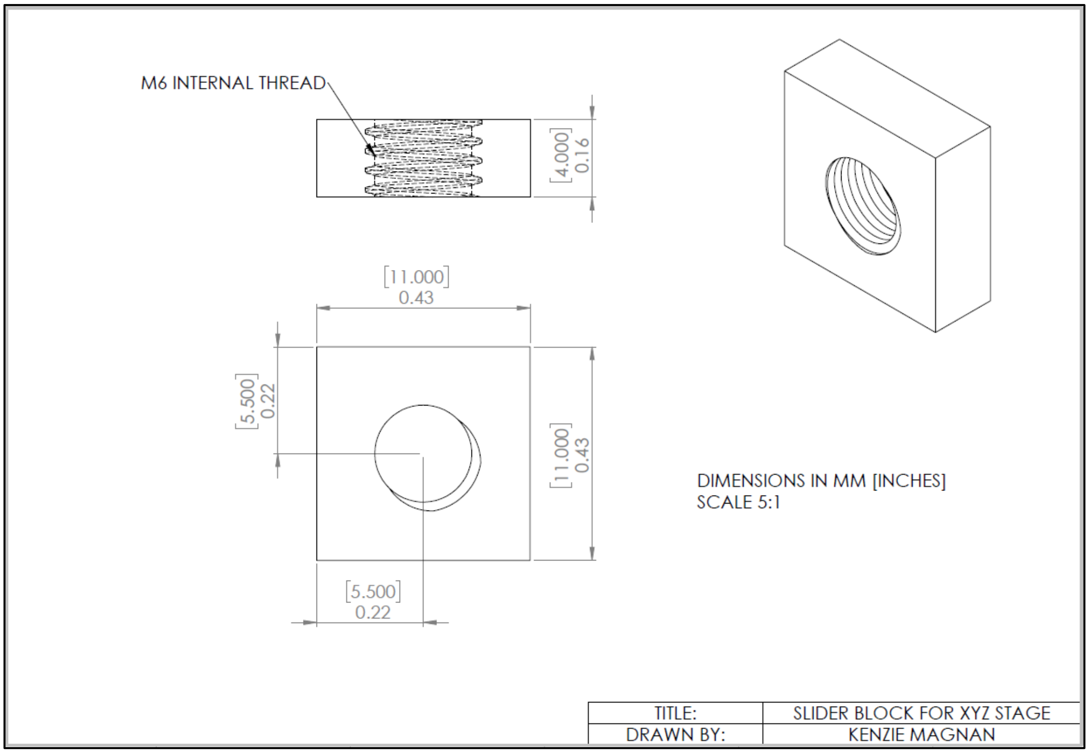
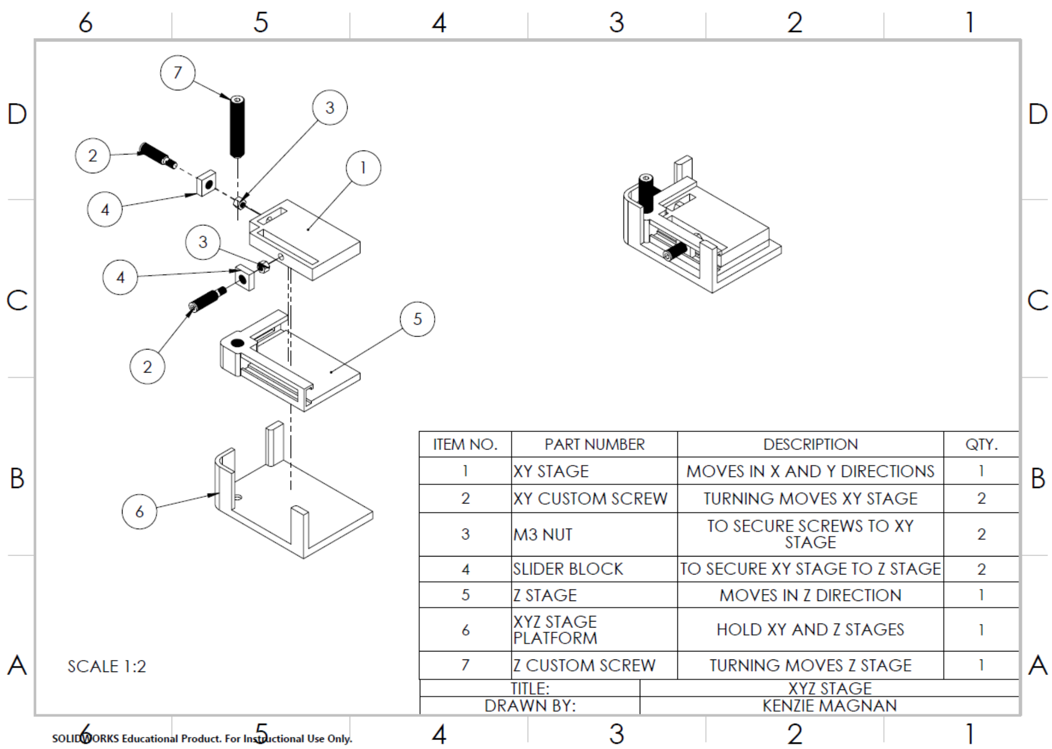


Figure 10: Technical Drawing of Slider to move XY Stage

Lastly, an assembly was created to show the XYZ stage as a whole and its ability to move in each direction (Figure 11).



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	XY STAGE	MOVES IN X AND Y DIRECTIONS	1
2	XY CUSTOM SCREW	TURNING MOVES XY STAGE	2
3	M3 NUT	TO SECURE SCREWS TO XY STAGE	2
4	SLIDER BLOCK	TO SECURE XY STAGE TO Z STAGE	2
5	Z STAGE	MOVES IN Z DIRECTION	1
6	XYZ STAGE PLATFORM	HOLD XY AND Z STAGES	1
7	Z CUSTOM SCREW	TURNING MOVES Z STAGE	1
TITLE:	XYZ STAGE		
DRAWN BY:	KENZIE MAGNAN		

Figure 11: Technical Drawing of XYZ Stage Assembly

The following diagram of the assembly shows how the XYZ stage moves in each direction (Figure 12).

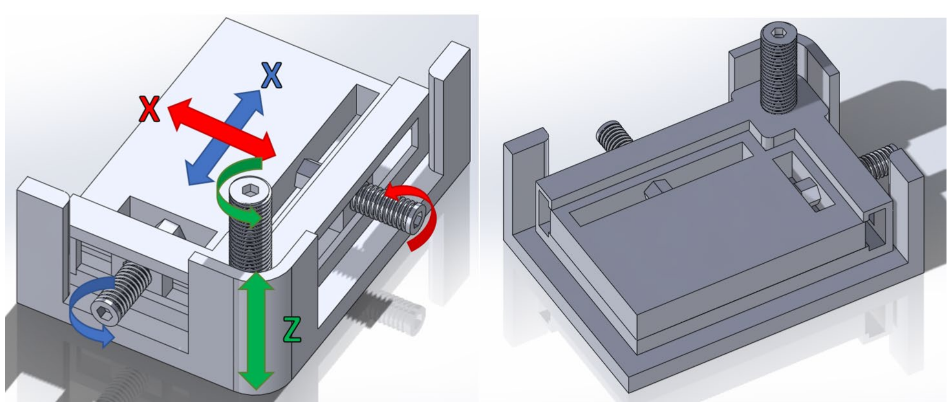


Figure 12: SolidWorks Rendering and Diagram of XYZ Stage Movement

Next, the packaging to hold all components needed to be constructed. The packaging needed to be lightweight, large enough to hold necessary components, and be able to attach to the user's head. To accommodate these requirements, the design mimicked a headset similar to those in virtual reality gaming. The headset was fashioned to fit the components as well as meet the typical average size of a virtual reality headset. It was designed with holes for straps to go around and over the head to keep the headset in place. It was designed with a hole for the camera to sit flush with the external front of the device. Another hole was cut in the device for the laser to be connected externally to the driver. It was developed with slits in the top to allow for ventilation and heat to escape. It contained a cut-out for the nose for comfortability. The headset also had a pitted area for the galvanometer assembly to sit in (Figure 13).

The distance between the galvanometer and the pupil of the eye, was determined using simplified optical analysis. When focusing on an infinitely far object, the focal length of the eye is less than or equal to the diameter of the eye. The scanning distance on the retina can then be described as the distance of the galvanometer multiplied by the system's maximum scan angle. In any other scenario, the focal length of the eye is less than the diameter of the eye. Therefore, the scanning distance is less than the product of the galvanometer distance and the maximum scan angle. The required lower limit of the galvanometer distance can then be expressed as:

$$d_{Galvo} > \frac{xRetina}{\theta_{max}} \qquad \text{Eq. 1}$$

The upper limit of the galvanometer then needs to be calculated. The scanning step on the retina can be expressed as the product of the galvanometer distance and the step angle of the system. The step angle is a nonlinear parameter, as each angle step is not the same distance apart.

However, for determining this lower limit value, we will assume that each step angle is the same. If this is the case, then the upper limit of the galvanometer can be expressed as:

$$d_{galvo} < \frac{dxRetina}{\theta_{min}} \qquad \text{Eq. 2}$$

Based on these assumptions and assuming the scanning distance will be similar to the average size of the pupil (6 mm), the galvanometer distance can be anywhere from 17 mm to over 3 m from the eye. The design allows for approximately 24 mm to 51 mm and fits within these limits, while choosing a value beyond the average focal length range for better focus.

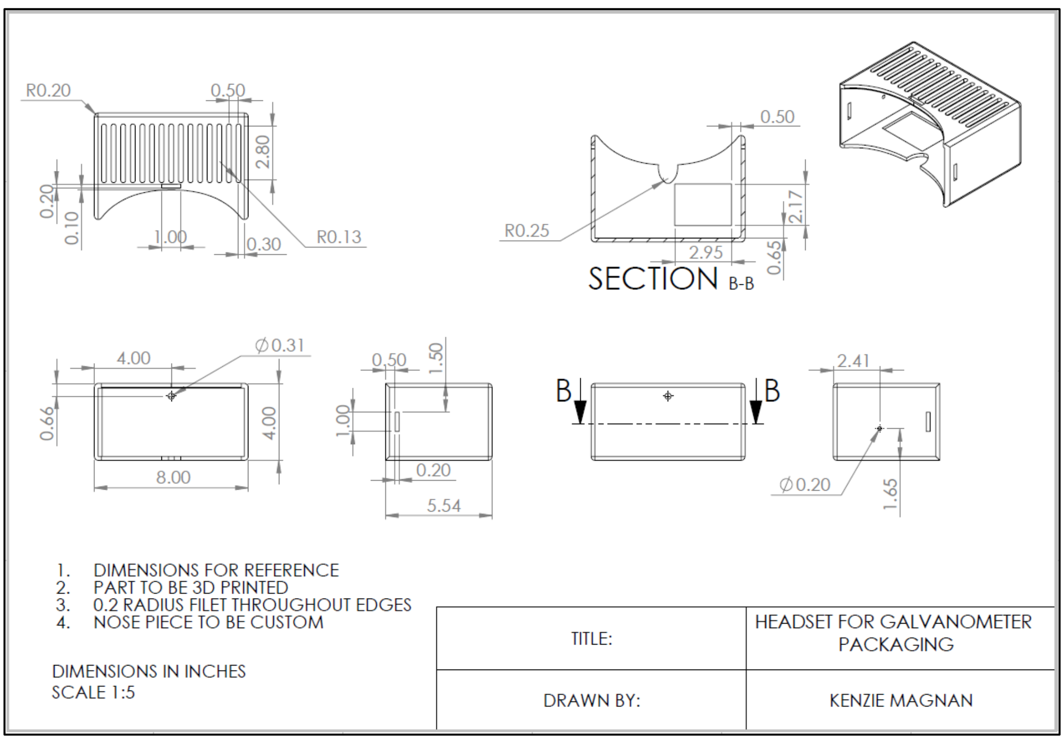


Figure 13: Technical Drawing of Headset Design

Lastly, an assembly was created to include all components of the device and straps for attachment to the head (Figure 14, Figure 15, Figure 16, Figure 17). For prototyping purposes, the laser modulator and power source would have to be located outside of the device in an adjacent holder that would allow for direct access to the device. They would not fit or be lightweight enough to be added to the user's headset in a first-in-human prototype. Once an embedded system is put together, it is possible this could be incorporated in the final headset design.

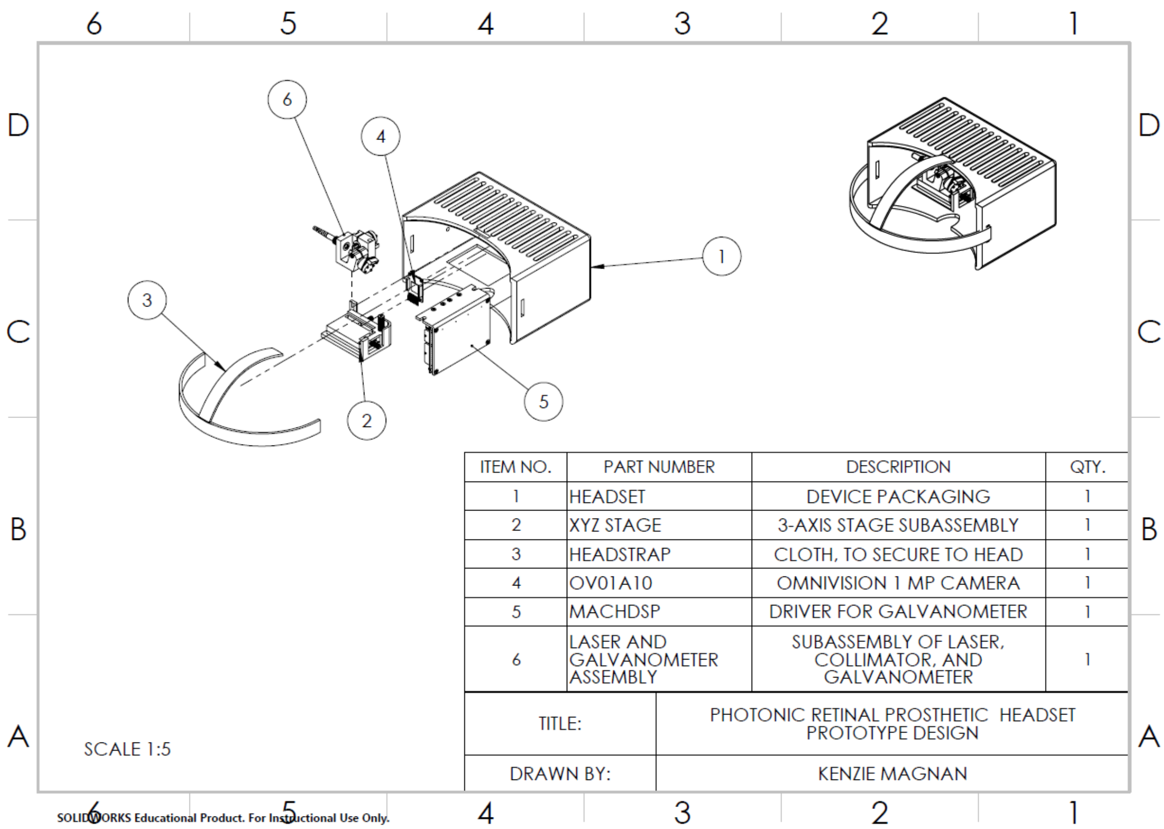


Figure 14: Technical Drawing of Prototype Assembly

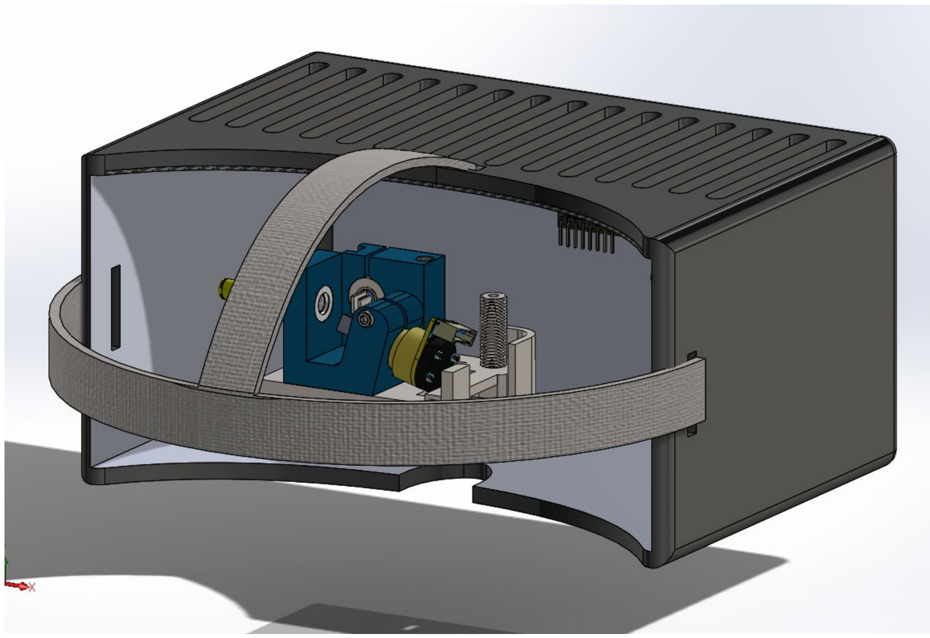


Figure 15: SolidWorks Rendering of Prototype Assembly (back view at galvanometer)

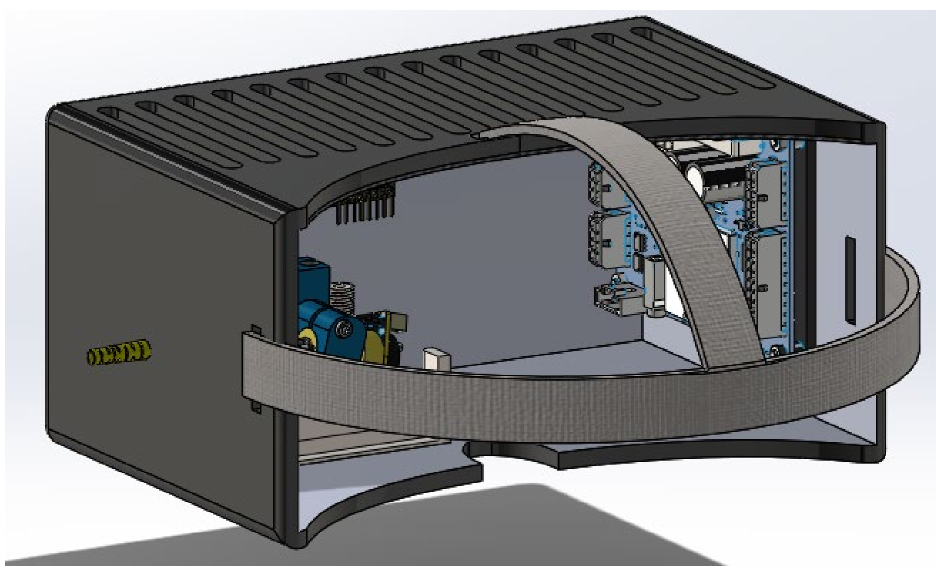


Figure 16: SolidWorks Rendering of Prototype Assembly (back view of galvanometer driver)

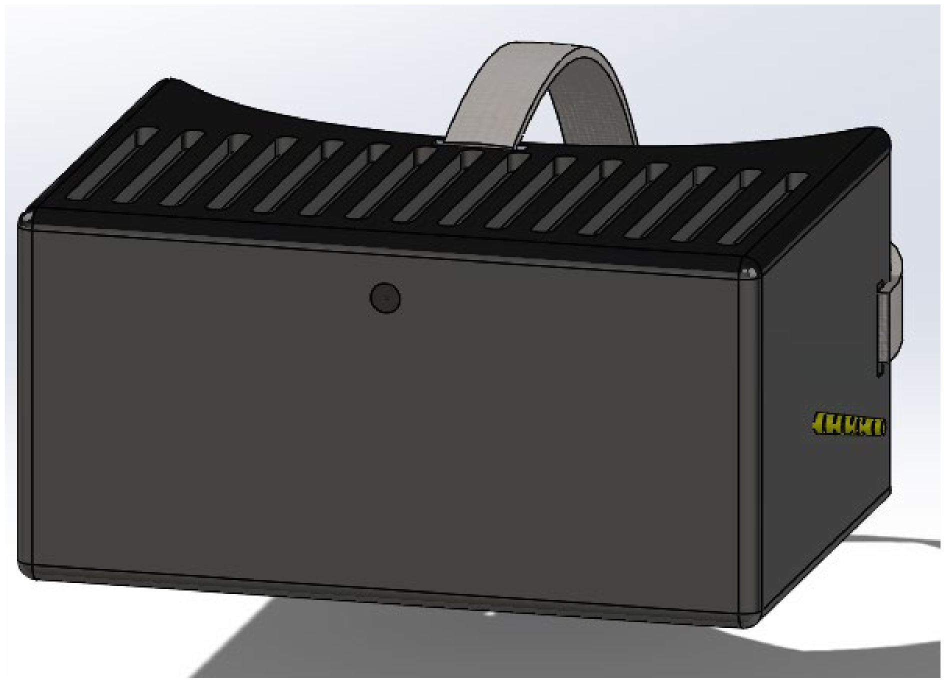


Figure 17: SolidWorks Rendering of Prototype Assembly (front view)

All the SolidWorks design files have been submitted to the thesis supervisor.

4. Optical Design

Galvanometer Control

A simplified optical analysis was conducted to determine how the optics will interact with the given hardware. The main purpose for the optical analysis is to present the constraints of the chosen hardware on the optical analysis and simulate how the optical analysis would interface with the device. There are many input and output parameters to be calculated and utilized in the optical design. They have been organized in the following tables (***Table 1***, ***Table 2***):

Table 2: Inputs Required for Optical Analysis. Variables are bolded.

Inputs	Symbol	Range	Source
Focal Length of the Eye	f_{Eye}	16-24 mm	(Cicala)
Diameter of Eye	d_{Eye}	22 mm	(Bekerman, Gottieb and Vaiman)
Distance of Eye (Pupil) to Galvanometer	d_{Galvo}	23-50 mm	To be optimized per individual, chosen beyond f_{Eye} for better focusing
Distance from Collimator Ouput to Eye	x_{beam1}	14.1+ d_{Galvo}	Per the Hardware Design (14.1 mm from collimator output to the second mirror)
Pupil Diameter	d_{Pupil}	2-8 mm	(Spector)
Maximum Angle of Galvanometer	θ_{Max}	20°	Galvanometer Capability per Datasheet
Minimum Angle of Galvanometer	θ_{Min}	.0015°	Galvanometer Capability: 16 bit and condigured for 100 degrees (100/36,365 = ~.0015°)
Laser Collimator Focal Length	$f_{collimator}$	4.51 mm	Collimator Datasheet
Beam Waist following Collimator	w_1	4.6 µm	Collimator Datasheet
Laser Wavelength	λ	785 nm	Laser Datasheet
Frequency of the System in frames per second	F	10 fps	Chosen as a reasonable speed regarding human perception
Maximum Voltage Input	V_{max}	24 V	Per galvanometer datasheet
Voltage Noise	V_{noise}	–	Measurable
Image Height in Pixels	$ImageHt_{pixels}$	–	Dependent on Camera Pixels
Image Width in pixels	$ImageWd_{pixels}$	–	Dependent on Camera Pixels and Ratio

Table 3: Outputs Calculated Using Optical Analysis

Outputs	Symbol
Beam Diameter on Pupil	d_{beam1} (mm)

Beam Waist After Human Lens	w_2 (mm)
Beam Diameter on Retina	d_{beam2} (mm)
Image Height on Pupil	$ImageHt$ (mm)
Image Width on Pupil	$ImageWd$ (mm)
Image Height on Retina	$xRetina_{Ht}$ (mm)
Image Width on Retina	$xRetina_{Wd}$ (mm)
Step Distance on Retina (Height)	$dxRetina_{Ht}$ (mm)
Step Distance on Retina (Width)	$dxRetina_{Wd}$ (mm)
Angle Step of Galvanometer (Height)	θ_{stepHt} (°)
Angle Step of Galvanometer (Width)	θ_{stepWd} (°)
Position on Retina from Origin (Height)	$positionHt$ (mm)
Position on Retina from Origin (Width)	$positionWd$ (mm)
Sine Wave for Galvanometer Control (Width)	x
Timing for Modulation	$TimeStamp$ (s)
Step Function for Galvanometer Control (Height)	y

The optical analysis began with the size of the image area as projected on the eye pupil while the galvanometer scans its full range and redirects the laser beam. First, when the pixel number of the camera is $ImageHt_{pixels}$ and $ImageWd_{pixels}$ in the height and width, respectively, the pixel number in the diagonal direction is simply given by:

$$ImageDiag_{pixels} = \sqrt{(ImageHt_{pixels})^2 + (ImageWd_{pixels})^2} \qquad Eq.\ 3$$

It was assumed that the optics are optimized such that the image area is maximal at the pupil, that is, the pixel number in the image area's diagonal fits the pupil diameter, d_{pupil}. Then, the physical size of the rectangular image area can be expressed by:

$$ImageHt = \frac{d_{pupil} \times (ImageHt_{pixels})}{ImageDiag_{pixels}} \qquad \text{Eq. 4}$$

$$ImageWd = \frac{d_{pupil} \times (ImageWd_{pixels})}{ImageDiag_{pixels}} \qquad \text{Eq. 5}$$

Based on these values, the required maximum scan angle (θ_{maxHt} & θ_{maxWd}) of the galvanometer is determined to be:

$$\theta_{maxHt} = 2 \times \tan^{-1}\left(\frac{ImageHt/2}{dGalvo}\right) \qquad \text{Eq. 6}$$

$$\theta_{maxWd} = 2 \times \tan^{-1}\left(\frac{ImageWd/2}{dGalvo}\right) \qquad \text{Eq. 7}$$

where $dGalvo$ is the distance between the galvanometer and the pupil.

These maxima cannot exceed the capability of the galvanometer. Using these equations, it is clear this would only occur for the ScannerMax Compact 506 system if the second mirror of the galvanometer was within 14 mm from the eye. As the distance, $dGalvo$, has been chosen to be further out than the focal length of the eye, 16-24 mm, this would not occur.

While the maximum scan angles have the constraint above, the minimum scan angle is constrained as follows. From the galvanometer's capable maximum scan angle (θ_{max}), the maximum voltage input (V_{max}), and the voltage noise (V_{noise}) of the system, the minimum scan angle (θ_{min}) can be calculated as:

$$\theta_{min} = V_{noise} \times \frac{\theta_{max}}{V_{max}} \qquad \textit{Eq. 8}$$

This practical minimum scan angle cannot be smaller than the minimum capability of the galvanometer system. For instance, the ScannerMax Compact 506 system is a 16-bit system and therefore contains 65,536 distinct values. The driver for the system (ScannerMax MachDSP Driver) is configured for 100° and therefore $100° \div 65{,}356 \cong 0.0015°$ minimum scan angle. Even when we control this galvanometer using a data acquisition board that has an extremely low noise (V_{noise}=> 0), the θ_{min} cannot become smaller than 0.0015 deg.

The total height ($xRetina_{Ht}$) and width ($xRetina_{Wd}$) on the retina could be calculated using the maximum scanning angles. For a convex thin lens and assuming the focal length and diameter of the eye are similar, this calculation can be simplified as (Ling, Sanny and Moebs):

$$xRetina_{Ht} = f_{eye} \times \tan(\theta_{maxHt}) \qquad \textit{Eq. 9}$$

$$xRetina_{Wd} = f_{eye} \times \tan(\theta_{maxWd}) \qquad \textit{Eq. 10}$$

These scanning distances will be optimized such that as many pixels as possible are projected on the retina, over as broad of a retinal area as possible. From the total height and width on the retina, a scanning step distance (*dxRetina*) on the retina can be determined as:

$$dxRetina_{Ht} = \frac{xRetina_{Ht}}{ImageHt_{pixels}} \qquad \textit{Eq. 11}$$

$$dxRetina_{Wd} = \frac{xRetina_{Wd}}{ImageWd_{pixels}} \qquad \textit{Eq. 12}$$

To make the laser beam hit the desired position or pixel (step # = $-\frac{ImageHt_{pixels}}{2}$ or $-\frac{ImageWd_{pixels}}{2}$, $-\frac{ImageHt_{pixels}}{2} + 1$ or $-\frac{ImageWd_{pixels}}{2} + 1, \ldots, \frac{ImageHt_{pixels}}{2} - 1$ or

$\frac{ImageWd_{pixels}}{2} - 1, ImageHt_{pixels}/2$ or $ImageWd_{pixels}/2$), the galvanometer's angle for the specific step # from the origin should be:

$$\theta_{stepHt} = \tan^{-1}\left(\frac{dxRetinaHt \times step\ \#}{f_{Eye}}\right) \qquad \textit{Eq. 13}$$

$$\theta_{stepWd} = \tan^{-1}\left(\frac{dxRetinaWd \times step\ \#}{f_{Eye}}\right) \qquad \textit{Eq. 14}$$

This angle must not be smaller than the minimum step angle capability of the system. From this step angle, and assuming the focal length of the eye is similar to the diameter of the eye, the calculation for the position for the laser can be simplified as:

$$positionHt = d_{galvo} \times \tan(\theta_{stepHt}) \qquad \textit{Eq. 15}$$

$$positionWd = d_{galvo} \times \tan(\theta_{stepWd}) \qquad \textit{Eq. 16}$$

Timing of Laser Modulation

The simplified optical analysis allows us to understand how the galvanometer will need to be controlled. The galvanometer is controlled by voltage level. As the voltage is increased, the angle of the motors is increased. To scan back and forth quickly, a sine wave can be input to the system with the desired frequency. For the motor to move in the x direction, or width, the amplitude of the sine wave can be calculated as a function of the total angle used by the system (θ_{stepWd}) calculated at the last step number over the maximum angle width (θ_{maxWd}). This ratio indicates how much of the maximum voltage level is being used by the system. This can then be multiplied by the maximum voltage (V_{max}) to determine the amplitude required by the system to scan back and forth to the required angle. The voltage level is then divided by 2 as the amplitude represents +/-V_{max} which is double the maximum voltage. For the same reason, the equation must also add an additional $V_{max}/2$ to shift the equation to represent values from 0 to V_{max} instead of $-V_{max}/2$ to $V_{max}/2$. The sine wave can then be represented as:

$$x = \left[\left(\left(\frac{\theta_{stepWd}}{\theta_{maxWd}}\right) \times \left(\frac{V_{max}}{2}\right)\right) \times \sin\left(2\pi \times F \times ImageWd_{pixels} \times t\right)\right] + \left(\frac{V_{max}}{2}\right) \qquad \textit{Eq. 17}$$

The frequency F multiplied by the width in number of pixels must be below the 1250 Hz capability of the galvanometer system.

The timing of the system can be calculated using the position of the system at a given pixel. The width position can be converted to a time value by comparing the position to the total width and multiplying the value by the desired frequency. As the height increases, an additional period $\left(\frac{1}{F \times ImageWd_{Pixels}}\right)$ should be added to the function. This allows the system to go from one row to the next. The timing can be represented as the following function:

$$Time\ Stamp\ (height, width) = \left(\left(\frac{positionWd}{imageWd \times 2}\right) \times \left(\frac{1}{F \times ImageWd_{pixels}}\right)\right) + \left(\frac{Height\ Step\ \#}{F \times ImageWd_{pixels}}\right) \qquad \textit{Eq. 18}$$

The height of the image changes with each "row" of the input sine wave (x) for the width of the image. Therefore, there is a voltage change for the height associated servo motor at each period of the sine wave. Unlike the width associated timing, the timing of the height change is constant but the voltage change (or actual height of the laser beam) is not. The voltage change for the height is a function of the position of the laser, similar to how the timing of the width is a function of the position of the laser. The function is the ratio of the angle at the largest step

(θ_{stepHt}) to the maximum possible angle (θ_{maxHt}) multiplied by the maximum voltage level (V_{max}). The voltage level is then divided by 2 as the amplitude represents +/-V_{max} which is double the maximum voltage. For the same reason, the equation must also add an additional $V_{max}/2$ to shift the equation to represent values from 0 to V_{max} instead of -$V_{max}/2$ to $V_{max}/2$. It is then multiplied by the ratio of the current height of the laser ($position_{Ht}$) to the total possible height ($ImageHt$). This will give the voltage change required to hit the correct height on the retina. The function can be represented as:

$$y = \left(\frac{V_{max}}{2}\right) \times \left(\frac{\theta_{stepHt}}{\theta_{maxHt}}\right) \times \left(\frac{positionHt}{imageHt}\right) \qquad \textit{Eq. 19}$$

Once the timing has been determined, the laser modulator is only required to switch the laser on/off at each time stamp if the image pixel value at the specific position changes from 0 to 1 or 1 to 0 from its previous value.

Visual Field and Resolution

The beam diameter that hits the pupil (d_{beam1}) can be calculated anywhere along its propagation axis following the focal length. This requires a known beam waist radius (w_1) which is given on the collimator's data sheet as well as the distance from the collimator to the eye (x_{beam1}). The diameter can be calculated as such (Gaussian Beam Optics):

$$d_{beam1} = 2\sqrt{w_1^2\left(1 + \frac{\lambda(x_{beam1} - f_{collimator})}{\pi w_1^2}\right)} \qquad \textit{Eq. 20}$$

After calculating the beam diameter that hits the eye, the beam waist following the eye's lens needs to be calculated. The beam waist is the minimum radius of the beam at its focal point along its propagation axis. This can be calculated as:

$$w_2 = \left(\frac{2\lambda}{\pi}\right)\left(\frac{f_{eye}}{d_{beam1}}\right) \qquad \textit{Eq. 21}$$

After finding the beam waist, the spot size on the retina can then be calculated as:

$$d_{beam2} = 2\sqrt{w_2^2\left(1 + \frac{\lambda\left|f_{eye} - d_{eye}\right|}{\pi w_2^2}\right)} \qquad \textit{Eq. 22}$$

After finding the beam diameter, resolution can be calculated as the distance between two beams divided by the diameter of the beams. The distance between beams on the retina is $dxRetina_{Ht}$ and $dxRetina_{Wd}$. The resolution can be calculated in both directions as:

$$Resolution_{Ht} = \frac{dxRetina_{Ht}}{d_{beam2}} \qquad \textit{Eq. 23}$$

$$Resolution_{Wd} = \frac{dxRetina_{Wd}}{d_{beam2}} \qquad \textit{Eq. 24}$$

Visual field can also be calculated for the system. One degree of visual field covers approximately .288 mm on the retina (Kolb). Therefore, visual field is simply the height or width on the retina divided by this value. It can be represented as:

$$Visual\ Field_{Ht} = \frac{xRetina_{Ht}}{.288} \qquad \textit{Eq. 25}$$

$$Visual\ Field_{Wd} = \frac{xRetina_{Wd}}{.288} \qquad \textit{Eq. 26}$$

Lastly, visual acuity can be calculated using the scanning step distance on the retina and the visual field conversion. Typically, visual acuity is calculated in arc minutes using the distance and size of a resolvable object; however, the "object" is artificial in this system so visual acuity will be calculated in degrees. This can be calculated as:

$$Visual\ Acuity_{Ht} = \frac{dxRetina_{Ht}}{.288} \qquad \textit{Eq. 27}$$

$$Visual\ Acuity_{Wd} = \frac{dxRetina_{Wd}}{.288} \qquad \textit{Eq. 28}$$

5. Matlab Implementation

Galvanometer Simulation

Matlab was implemented to carry out the optical analysis of the system given specific hardware and inputs. Constant inputs were added to the system while any inputs that had a range of values were added as adjustable sliders to be changed by the user depending on the individual's biology and system configuration.

The focal length of the eye (f_{eye}) is typically between 16-24 mm (Cicala) while the diameter of the eye (d_{eye}) is typically 22 mm (Bekerman, Gottieb and Vaiman). The pupil size (d_{pupil}) can vary from 2 to 8 mm depending on dilation and individual (R. H. Spector). The laser beam diameter (d_{beam}) and wavelength (λ) of the laser and collimator were 0.98 mm and 785 nm respectively. The maximum scan angle (θ_{max}) of the ScannerMax Compact 506 system was 20°. The distance from the galvanometer to the eye (D_{galvo}) is arbitrary and can be anywhere between the focal length of the eye to 50 mm for best resolution and to fit within the headset design. The number of pixels needs to be within 1 MP to stay within the maximum speed of the galvanometer and laser modulator. The frequency in frames per second (*F*) can be chosen within the 1250 Hz capability of the galvanometer. From these parameters, all other system parameters can be calculated. Although the Matlab code allows the user to change the parameters per individual and system, the following walkthrough of the code will use an input image size of 640x480, a focal length of 22 mm, a pupil size of 6 mm, a distance of 25 mm from the eye, and a voltage noise of 0.10 V, and a voltage input of 24 V. The ScannerMax Compact 506 galvanometer and the headset design parameters are used for this system.

After determining all input parameters, the code intakes a video from any attached and specified camera on the computer. From this video, the code takes a snapshot and resizes the image into a specified number of pixels. The resolution of the webcam used was 640x480 and the captured image was resized to 64x48 to optimize the speed of the program. The code then takes the resized image and grayscales the image before finally binarizing the image. This step turns the image into a matrix of 1's and 0's which then can be used as on and off positions for the laser.

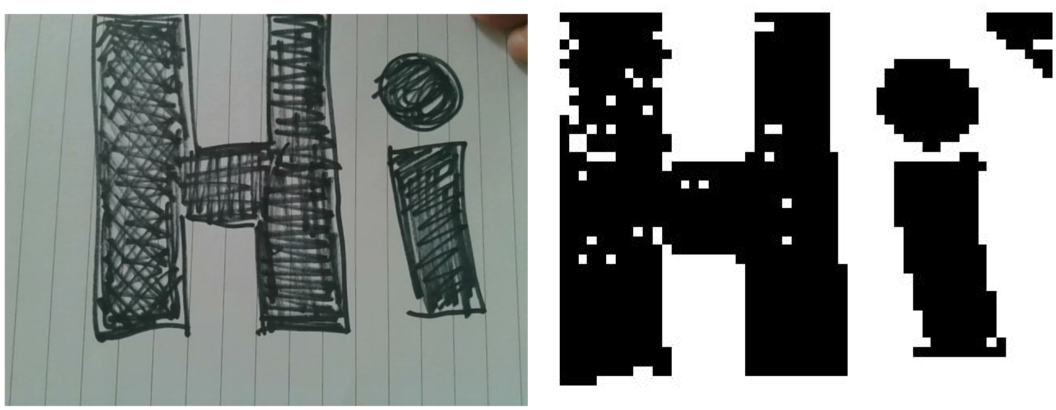


Figure 18: Original image taken by webcam (left) vs. the binarized and resized image (right)

The code takes the new image and stores the size in the x and y directions. It then uses Eq.3 and these values to create a ratio between the diagonal size of the image to the diameter of the pupil. This gives a conversion between the number of pixels and image size in millimeters (mm). It then uses Eq. 4 & 5 to calculate the size of the image at the pupil in mm for both the x and y directions based on this ratio, which in this scenario was 3.6 x 4.8 mm. After determining the size of the scannable area at the pupil, the maximum angle to scan is then calculated using Eq. 6 & 7. The Matlab code ensures this maximum angle is no greater than the capability of the given maximum value of the system and adjusts the maximum angle if this is the case.

After calculating the total scanning angle and size of the image at the pupil, the code then determines where the laser will hit the retina. Assuming the lens of the human eye is like a thin lens, the thin lens equation (Eq. 9 & 10) is used to calculate the size of the relayed image on the retina in millimeters, which for this case is 2.4 x 1.8 mm. The code then divides this value by the number of pixels in either direction (Eq. 11 & 12) to determine the distance between each relayed spot on the retina. After determining this scanning distance, the code ensures this distance is possible to achieve without exceeding the minimum scanning angle of the galvanometer.

To demonstrate the recreated image on the retina, the code iterates in a loop through each position on the retina and plots these values as a red dot only if they are recognized as a “1” in the image matrix. The code then calculates where at the pupil the laser must point to hit the retina in those spots using Eq. 13 & 14. It does this by iterating through a loop for each position on the retina. It plots these points as a blue circle on top of the same plot. This shows where the laser must hit the pupil compared to where it will excite the retina.

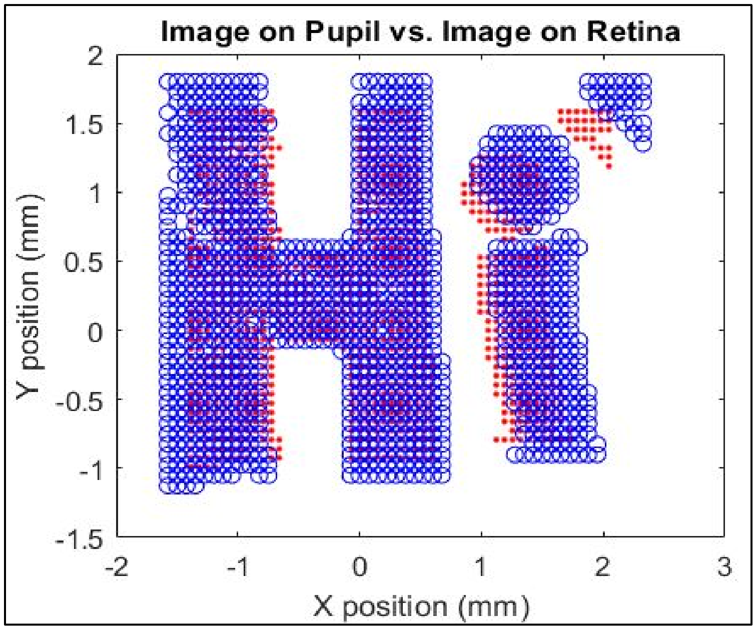


Figure 19: Laser position at the pupil (blue) vs. where it relays on the retina (red)

In the same loop, the code uses each position at the pupil to create a timestamp for the laser modulator to turn on or off. It does so using Eq. 18. The timestamps that correlate with the "on" position are stored. This will indicate for the laser modulator to turn the laser on or keep the laser on at these times. While cycling through positions, the code also saves the voltage change required for the second galvanometer mirror using Eq. 19. As previously stated, the galvanometer motors change angle with voltage input. A sine wave can be input to the first galvanometer mirror to allow scanning back and forth. The Matlab code plots this sine wave shown in Eq. 17. It then plots the timestamp against this sine wave which shows how this would recreate the image using a laser modulator. The code also plots the voltage change for each position of the second galvanometer mirror on the same plot. This gives an overall view of how the image should be delivered.

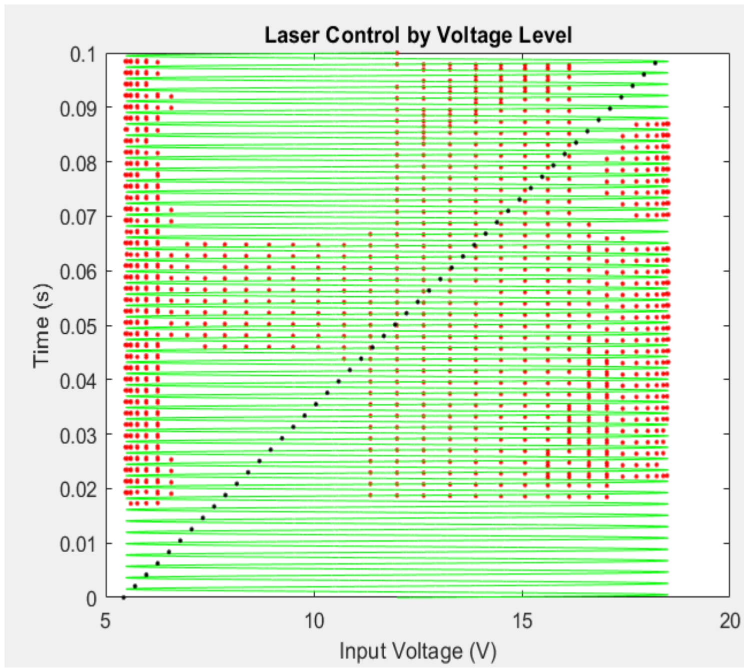


Figure 20: Visual Representation of Galvanometer Control and Modulation

Lastly, the code calculates the visual field and resolution of the system. To do this, the beam diameter is found using Eq. 20-22 assuming the same distances between laser aperture and eye in the 3D design as well as the collimator parameters for the F230FC-780 collimator. The beam diameter on the retina in this scenario is found as 0.09 mm. It then uses Eq. 23 & 24 to calculate the resolution in the x and y directions. The resolution is a ratio of the image size on the retina in mm to the beam diameter in mm and is unitless. The resolutions in both directions were found to be 0.56. A resolved system is considered to have a value of 1.5 as this means the beams have only 15% overlap. For solid objects however (similar to the image of “Hi!” used in this example), this resolution issue would only affect the edges of the excited portions of the image. For images with more single pixel details, the resolution would be very poor. Next, the visual field was calculated using Eq. 25 & 26. The image on the retina in this scenario correlates to

14.7° x 11.0° in the x and y directions respectively. This corresponds to 18.3° in the diagonal. Lastly, the visual acuity of the system was calculated using Eq. 27 & 28 and found to be 0.23°.

Prototype Testing

A second Matlab code was created that followed the same optical analysis as the first; however, this second code did not plot any of this information. Instead, this code output the required angle of the galvanometer for each step to a servo motor. It does so by using the Arduino library within Matlab and connecting a servo motor to the Arduino board. This code allows for testing of the optical analysis step by step. Before attempting to perfect laser modulation timing, this is an ideal way to ensure the optical analysis is doing what it should. Unfortunately, the servo used for prototyping (SG90 hobby servo) did not have a small enough step angle or repeatable data to be used with this code. This code will hopefully serve to assist future testing.

6. Conclusion and Future Considerations

This thesis presents the hardware selection, mechanical design, and optical analysis for a photonic retinal prosthesis. The thesis provides information on the hardware needs of the device, including the requirements for a laser, collimator, galvanometer, driver and camera. It also provides limitations to current solutions and ways this device may bypass those limitations. The designed headset is also presented for prototype testing and setup. This provides a way to attach the system to the user while allowing for customized adjustments to the eye. Lastly, a simplified optical analysis was conducted, and a prototyping code was developed to represent how the optics can be translated to the specified hardware.

The proposed device shows promise in comparison to the only FDA approved retinal prosthetic, the Argus II by SecondSight Medical, Inc. The Argus II has a 20° diagonal visual field (Stronks and Dagnelie), while the proposed design has a comparable 18.3° visual field. The human eye has approximately a 120° field of view horizontally and vertically (R. H. Spector). Though the visual field of the proposed system is significantly less than this, it is comparable to the only FDA-approved device. The Argus II also has a 4° visual acuity (Stronks and Dagnelie) while the proposed system has a 0.23° visual acuity, which is significantly better and closer to the 0.008° visual acuity of the human eye (R. H. Spector).

Unfortunately, further instrumentation and testing have been suspended by the lab shutdown due to COVID-19. As all of the CAD design files and Matlab codes have been submitted to the supervisor, we expect the remaining instrumentation and testing to be continued when the lab opens.

Some future considerations for the system include increasing resolution of the system by decreasing the beam diameter via greater collimation. Other ways to increase resolution are to decrease the distance from the laser to the galvanometer as much as possible and keep the voltage noise of the system low. Another consideration for the system is speed. The galvanometer chosen allows for approximately 1250 Hz but should this improve, the system could contribute greater frames per second or could increase the number of pixels used with the assumption that resolution has been increased.

When the remaining instrumentation is completed, a beam profiler can be used to test the beam diameter at different distances. A representative lens similar to the human eye should be used at different distances as well to determine the beam diameter on the “retina” as well as the relayed area on the retina using the beam profiler. This will allow for parameter adjustments based on true values from the exact system. The prototyping code can also be used to test a simplified version of the system to ensure a more robust optical analysis is translating to the hardware correctly.

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Appendix

Appendix A: Matlab Code: Galvanometer Simulation

```
fEye = 19; %16-23  https://wolfcrow.com/notes-by-dr-optoglass-eye-geometry/
dEye = 22;
%https://www.researchgate.net/publication/268881487_Variations_in_Eyeball_Diam
eters_of_the_Healthy_Adults
dGalvo = 58; %adjustable
dPupil = 6; %https://www.ncbi.nlm.nih.gov/books/NBK381/'
galThetaMin = 0.0015; %16 bit galvo, configured for 100 degrees gives minimum
step of 0.0015 deg (100/65,535 distinct values)
thetaMax = 20; %capability of galvo
vMax = 24; %voltage source
vNoise = 0.1; %ranges
lambda = .000785; %785 nm for NIR laser
w1 = 0.0046; %4.6 microns per datasheet
dLasertoM1 = 9.1; %mm distance from laser to mirror of galvo
dM1toM2 = 5; %mm distance from mirror 1 of galvo to mirror 2
fcollimator = 4.51;
beamDiameter = 0.98




%%%%%%%%%%%%%%%%%Taking picture%%%%%%%%%%%%%%%%%%%%%
imaqInfo = imaqhwinfo %gives info on attached camera information

% Access an image acquisition device.
vidobj = videoinput('winvideo');

%preview(vidobj) %shows input video in real time


data = getsnapshot(vidobj); %grabs a snapshot of the input video
imshow(data); %previews the image
[x,y]=size(data); %gives pixel size of image
pixelatedImage = imresize(data,.1); %resizes the image
imshow(pixelatedImage); %previews pixelated image
[x2,y2]=size(pixelatedImage); %gives pixel size of resized image
BW = rgb2gray(pixelatedImage); %puts image in black and white
global final;
final = imbinarize(BW); %binarizes the image into a matrix of 1's and 0's
figure(1); imshow(final) %shows resized binarized image
sz = size(final)%size of image
```

```
rw = sz(:,1) %number of rows
cl = sz(:,2) %number of columns




%%%%%%%%%%%%%% Using image size ratio to determine grid size %%%%%%
imageHtPix = rw; %height in pixels
imageWdPix = cl; %width in pixels
dScanPix = sqrt((imageHtPix^2) + (imageWdPix^2)); %number of pixels across
diagonal of image


%grid size of inscribed rectangle
imageHt = (dPupil*imageHtPix)/dScanPix; %calculation of scannable height on
pupil
imageWd = (dPupil*imageWdPix)/dScanPix; %calculation of scannable width on
pupil


%%%%%%%%%%% Calculating thetaMax for height and width %%%%%%%%%%%%%%%%
thetaMaxHt = atand((imageHt)/dGalvo); %maximum scanning height on pupil in
degrees
if thetaMaxHt > thetaMax
    thetaMaxHt = thetaMax; %can't be greater than galvo capability
end


thetaMaxWd = atand((imageWd)/dGalvo);
if thetaMaxWd > thetaMax %maximum scanning width on pupil in degrees
    thetaMaxWd = thetaMax; %can't be greater than galvo capability
end


%%%%%%%%%%%%%%%%%%%%%% Calculating thetaMin %%%%%%%%%%%%%%%%%%%%%%%%%
thetaMin = (thetaMax/vMax)*vNoise; %minimum possible scanning step in degrees
(will be affected by noise) as galvo is controlled by voltage level


if thetaMin < galThetaMin
    thetaMin = galThetaMin %cannot be any smaller than galvo spec
end


%%%%%%%%%%%% Calculating number of steps possible/stepsize/stepAngle
%%%%%%%%%%%%
```

```
stepsHt = [-(imageHtPix/2):(imageHtPix/2)]; %total possible number of steps in
one direction
stepsWd = [-(imageWdPix/2):(imageWdPix/2)]; %total possible number of steps in
other direction




% %%%%%%%%%%%%% Using Thin lens equation %%%%%%%%%%%%%%%%%%
xRetinaHt = fEye*tand(thetaMaxHt); %total scanning distance on retina
dxRetinaHt = xRetinaHt/imageHtPix; %scanning distance between steps on retina
to show all pixels
xRetinaWd = fEye*tand(thetaMaxWd); %total scanning distance on retina
dxRetinaWd = xRetinaWd/imageWdPix; %scanning distance between steps on retina
to show all pixels


% %%%%%%%%%%%%% Calculating Visual Field %%%%%%%%%%%%%%%%
visFieldConversion = 1/.288; %https://webvision.med.utah.edu/book/part-xiii-
facts-and-figures-concerning-the-human-retina/
visualFieldHt = xRetinaHt*visFieldConversion %degrees
visualFieldWd = xRetinaWd*visFieldConversion %degrees
dbeam1 = 2*sqrt((w1^2)*(1+((lambda*(dGalvo+dLasertoM1+dM1toM2-
fcollimator))/(pi*w1^2)))); %gaussian optics to calc beam diameter on pupil
w2 = (((4*lambda)/pi)*(fEye/dbeam1))/2; %gaussian beam optics to calculate
beam waist after lens of eye
dbeam2 = 2*sqrt((w2^2)*(1+((lambda*(abs(fEye-dEye)))/(pi*(w2^2))))); %gaussian
optics to calc beam diameter on retina


resolutionHt = (dxRetinaHt)/(dbeam2)
resolutionWd = (dxRetinaWd)/(dbeam2)


%%%what we want to recreate on retina


for(l = 1:1:imageHtPix)
    for(f = 1:1:imageWdPix)
        if (final(l,f)==0) %if we need to excite retina
            plotSpotHt = [-(imageHtPix/2):(imageHtPix/2)];
            plotSpotWd = [-(imageWdPix/2):(imageWdPix/2)];
            plot(dxRetinaWd*plotSpotWd(f),-(dxRetinaHt*plotSpotHt(l)), 'r .');
%plotting each excited spot on the retina dxRetina away from each outher
            hold on
        end
```

```
        f=f+1;
    end
    l=l+1;
end


timeStamp = [];

totalAngleHt = atand((xRetinaHt)/fEye); %total possible scanning angle in
height
totalAngleWd = atand((xRetinaWd)/fEye); %total possible scanning angle in
width
```

```
%%where we have to shoot laser%%
for(i = 1:imageWdPix)
for(h = 1:imageHtPix)


            angleHtNext = atand((dxRetinaHt*stepsHt(h))/fEye);
            angleWdNext = atand((dxRetinaWd*stepsWd(i))/fEye);
            positionHt = dGalvo*tand(angleHtNext);
            positionWd = dGalvo*tand(angleWdNext);

voltageStampHt(h,i)=((totalAngleHt/thetaMaxHt)*(vMax/2)*(positionHt/(imageHt))
*2)+(vMax/2); %voltage change needed at each row


        if (final(h,i) == 0 ) %if we need to excite retina
            plot(positionWd,-positionHt,'b o');
            hold on;
             timeStamp(h,i) =
(positionWd/(imageWd))*(1/(10*rw))+((1/(10*rw))*h);
            hold on;

        end
                    h=h+1;


    end
```

```
                    i = i+1;
end
 title('Image on Pupil vs. Image on Retina')
 xlabel('X position (mm)')
 ylabel('Y position (mm)')
hold off;


timeCode = timeStamp(:); %turning time code to array nstead of matrix
timeStamp = nonzeros(timeStamp); %removing zeros




timeCodeHt = voltageStampHt(:,1); %each column is same so grabbing 1 column of
voltageStampHt


for j = 1:length(timeCode)

    y =
((totalAngleWd/thetaMax)*(vMax/2)*sin(2*pi()*10*rw*timeCode(j)))+(vMax/2);
%laser control at timestamps
    plot(y, (-timeCode(j))+.1, 'r.');
    hold on;
    j = j+1;

end


 t = [0:.0000001:.1];
 y4 = ((totalAngleWd/thetaMax)*(vMax/2)*sin(2*pi()*rw*10*t))+(vMax/2);
%sine wave for galvo control
 title('Laser Control by Voltage Level');
 xlabel('Input Voltage (V)') ;
 ylabel('Time (s)') ;
 plot(y4, t,'g');


 hold on;
  tstep = [0:1/((rw*10)-1):.1]; %voltage changes each row

plot((totalAngleWd/thetaMax)*timeCodeHt+((totalAngleWd/thetaMax)*10),tstep
, 'k .');
 hold off
```

Appendix B: Matlab Code: Prototyping

```
a = arduino('COM9', 'Mega2560', 'Libraries', 'Servo');

s = servo(a, 'D3', 'MinPulseDuration', 700*10^-6,
'MaxPulseDuration', 2300*10^-6);
v = servo(a, 'D4', 'MinPulseDuration', 700*10^-6,
'MaxPulseDuration', 2300*10^-6);



fEye = 23; %16-23  https://wolfcrow.com/notes-by-dr-optoglass-
eye-geometry/
dEye = 22;
%https://www.researchgate.net/publication/268881487_Variations_in
_Eyeball_Diameters_of_the_Healthy_Adults
dGalvo = 46;
dPupil = 25; %https://www.ncbi.nlm.nih.gov/books/NBK381/'
galThetaMin = 0.125;
thetaMax = 25;
vMax = 24;
vNoise = 0.1;
lambda = .000785;
beamWaist = .0046; %based on chosen collimator at focal length of
eye https://www.thorlabs.com/drawings/b09689590d340310-24A2179F-
A979-7FE2-EFC8D8A534205A6B/F230FC-780-AutoCADPDF.pdf
divAngle = lambda/(pi()*beamWaist);
dFtoG = dGalvo - fEye;


%%%%%%%%%%%%%%%%%Taking picture%%%%%%%%%%%%%%%%%%%%%%

imaqInfo = imaqhwinfo;


% Access an image acquisition device.
vidobj = videoinput('winvideo');

%preview(vidobj)


%set(vidobj, 'FramesPerTrigger', 10);

data = getsnapshot(vidobj);
%imshow(data);
```

```
[x,y]=size(data);
pixelatedImage = imresize(data,.05);
[x2,y2]=size(pixelatedImage);
BW = rgb2gray(pixelatedImage);
global final;
final = imbinarize(BW);
figure(1); imshow(final);
sz = size(final);
rw = sz(:,1);
cl = sz(:,2);


%%%%%%%%%%%%% Using image size ratio to determine grid size
%%%%%%
imageHtPix = cl;
imageWdPix = rw;
dScanPix = sqrt((imageHtPix^2) + (imageWdPix^2)); %used as ratio
of pixels to mm

%grid size of inscribed rectangle
imageHt = (dPupil*imageWdPix)/dScanPix;
imageWd = (dPupil*imageHtPix)/dScanPix;


%%%%%%%%%%% Calculating thetaMax for height and width
%%%%%%%%%%%%%%%%
thetaMaxHt = atand(imageHt/dGalvo);
if thetaMaxHt > thetaMax
    thetaMaxHt = thetaMax; %can't be greater than galvo
capability
end

thetaMaxWd = atand(imageWd/dGalvo);
if thetaMaxWd > thetaMax
    thetaMaxWd = thetaMax; %can't be greater than galvo
capability
end

%%%%%%%%%%%%%%%%%%%%% Calculating thetaMin
%%%%%%%%%%%%%%%%%%%%%%%%%
thetaMin = (thetaMax/vMax)*vNoise;

if thetaMin < galThetaMin
    thetaMin = galThetaMin; %cannot be any smaller than galvo
spec
end
```

```
%%%%%%%%%%%% Calculating number of steps
possible/stepsize/stepAngle %%%%%%%%%%%
stepsHt = [-imageHtPix:imageHtPix]; %total possible number of
steps
stepsWd = [-imageWdPix,imageWdPix];


% %%%%%%%%%%%%% Using Thin lens equation %%%%%%%%%%%%%%%%%%

xRetinaHt = fEye*tand(thetaMaxHt); %total scanning distance on
retina
dxRetinaHt = xRetinaHt/stepsHt;

xRetinaWd = fEye*tand(thetaMaxWd); %total scanning distance on
retina
dxRetinaWd = xRetinaWd/stepsWd;



angleHt = atand(dxRetinaHt)/fEye
angleWd = atand(dxRetinaWd)/fEye




for stepNumberHt = 1:imageHtPix
    for stepNumberWd = 1:imageWdPix
        if (stepNumberWd <= stepsWd)
            angleHtNext =
atand((dxRetinaHt*stepsHt(stepNumberHt))/fEye); %movement in x
            writePosition(s, angleHtNext/180);%movement in x
            writeDigitalPin(a, 'D5',
final(stepNumberWd,stepNumberHt); %laser output
            pause(.5);
            stepNumberWd = stepNumberWd+1;
        end
        else if (stepNumberWd > stepsWd)
                for stepNumberWd = stepsHt:-1:1 %scan downward
for x (mimicks sine wave going back and forth)
                    writeDigitalPin(a, 'D5',
final(stepNumberWd,stepNumberHt); %laser output
                end
            end
    end
```

```
    angleWdNext = 
atand((dxRetinaWd*stepsWd(stepNumberWd))/fEye);%movement in y
    writePosition(v, angleWdNext/180); %movement in Y
    stepNumberHt = stepNumberHt+1;
    pause(1);
end
```