Design Description Document

Binocular Retinal Eye Tracker

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Customer: C.Light Technology
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Revision History

Rev	Description	Date	Authorization
1	Initial Document	1-27-2017	All
2	DDD #2	2-09-2017	All
3	DDD #3	2-22-2017	All
4	Midterm DDD	3-02-2017	All
5	DDD #5	4-10-2017	All
6	DDD #6	4-28-2017	All
7	Final DDD	5-03-2017	All

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Schedule

January

- 11 – 13: Trip to C.Light Technology, Berkeley, CA to present the idea to the company and the investor.
- End of January: Component Research and Optical Design

February

- 9: Goals Meeting with C.Light Technology
- 13-17: Met with Julie Bentley for the Lens Design aspect of our project and with Tom Brown for help with Detector Comparison and Photon Budget
- 16: Completed comparison between the two detector options, cost/benefit analysis of various configurations of laser diodes
- 23: Detector Decision
- End of February: Opto-mechanical design meeting with Prof. Jon Ellis; Lens Design meeting with Prof. Bentley

March

- 2: Meeting to discuss the enclosure design
- 3: Midterm Design Review
- 9: Decide on the Front End Optical components and lenses, mirrors, scanners, and mounts, discussion of expectations for the project and design day.
- Rest of March: Opto-mechanics for the device

April

- Further Testing in Code V, and Opto-mechanical design
- Build a Demo for Design Day poster session

May

- 4: Provisional Patent filed by C.Light Technology
- 5: Design Day

1. Vision Statement

Our goal for this project is to create an optical design for a handheld, battery powered, binocular retinal eye-tracking system for field side use (in conjunction with current concussion screening procedures) to better diagnose concussions or traumatic brain injuries at near moment of impact. In addition, the device must be robust, durable, and cost effective (must remain within the budget that we have been given).

2. Project Scope

The responsibility of our design team is to develop and test the optical design for the binocular retinal eye tracking. This system must be designed to be operated at approximately 850 nm. In addition to developing the optical design, the design team is responsible for determining the exact components needed to build the device (such as the lenses, mirrors, laser source, etc). The team is also responsible for creating a preliminary design for the enclosure of the handheld probe. As there is a budget constraint, the team is also responsible for doing a cost analysis of each of the elements to choose the most cost effective component without sacrificing device performance.

The team is not responsible for any software development or any component analysis not pertaining to the optical design of the device.

3. System Starting Point

We started our design process with two separate systems that have previously been built and successfully used for retinal tracking. The first system was a large binocular reflective system (shown below). This system is currently being used in a concussion study by the UC Berkeley athletic training department. While this system provided inspiration, there are a few points that lead to it not being an ideal device for field side use as it is neither portable. The device weighs approximately fifty pound and has a 30x60 cm footprint. The large footprint is caused by using three reflective 4f telescopes to properly scan in both the x and y direction using the two scanning mirrors.

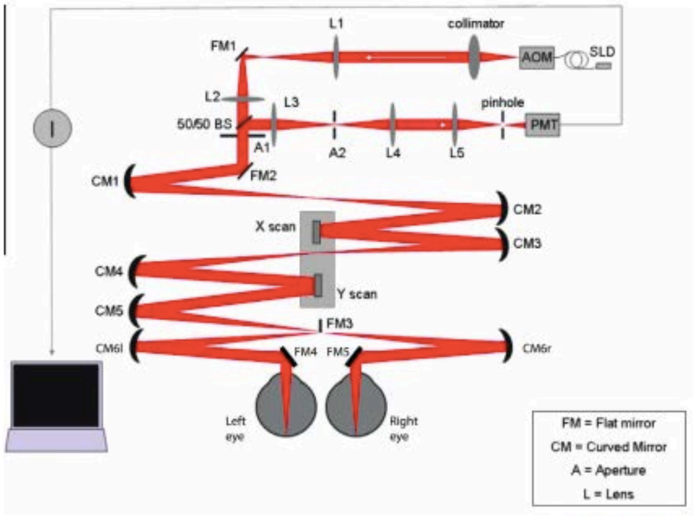


Figure 1: Reflective tracking scanning laser ophthalmoscope (TSLO) system (Sheehy et al. 2012, Stevenson et al. 2015). This design was modified from a monocular TSLO system (Sheehy et al. 2012) by adding a knife edge mirror to split the beam into two paths so that both the left and right retina could be imaged at the same time. The X-scan is done at 15.4 kHz allowing an image to form in approximately 26 μs. [2]

The second design that inspired our design is a small, handheld optical coherence tomography (OCT) and SLO system that was designed to perform measurements and tests on patients, such as small children, who would have difficulties using a standard eye tracking device. This design (shown below) utilizes a microelectromechanical systems (MEMS) scanning mirror and refractive optics to minimize the probe weight and footprint. Because the OCT/SLO probe worked using refractive optics and a MEMS device, we are choosing to pursue using refractive optics in binocular device that we are designing.

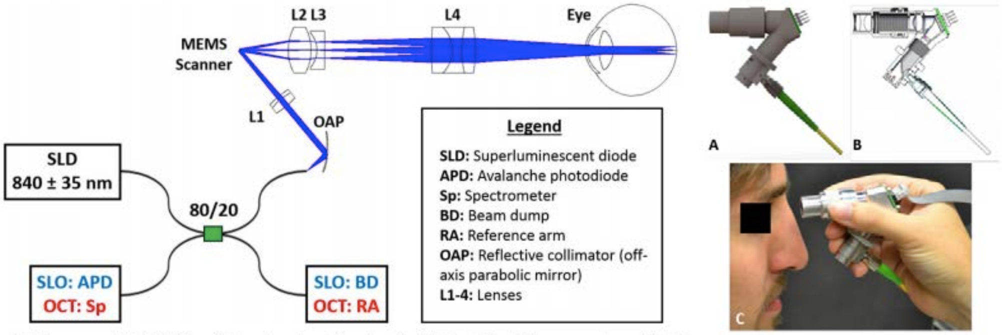


Figure 2: (left) The device schematic and optical design for the OCT/SLO handheld probe. (right) (A) Exterior CAD model of the device (B) Section view showing the interior of probe. (C) The assembled probe in use. [1]

After finding the two designs that had major features that are desired in the new device, we constructed a table to compare the two previous devices with the new device we are designing.

	Reflective Binocular System	LaRocca Refractive Monocular System	Desired Device
FOV	10 degrees	7 degrees	7 degrees
Handheld	No	Yes	Yes
Probe/scanner weight	~50 pounds	94 grams	Ideally <20 pounds Must be <50 pounds
Cost	N/A	N/A	<$35,000
#scanning mirrors	2	1	2 (one for each eye)
Battery Powered	No	No	Yes
Wavelength (nm)	840	840	852

Table 1: Comparison of the two devices that are motivation and the device that needs to be designed.

4. System Overview

4.1 Design Constraints/Performance

- The system needs to be able to generate a 512x512 pixel image
- Wavelength: 852 nm
- Retinal scan ± 3.5 degrees
- Diffraction limited imaging

4.2 Device Layout

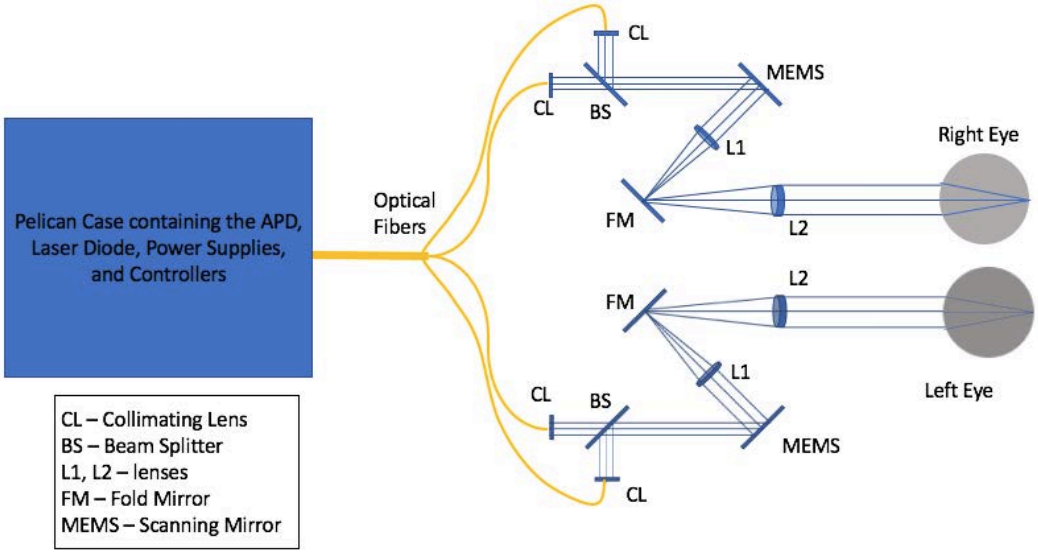


Figure 3: Device Schematic showing the optical components required for imaging both eyes simultaneously. The components are all labeled and the key can be found in the lower left corner. Identical components are labeled with the same abbreviations.

In the current system, we have a Keplerian telescope with a 3.5x magnification, that expands the beam after it is incident on the MEMS scanner and expands the beam diameter. The magnification was determined by the clear aperture (CA) of the MEMS scanner and the desired 3 mm beam diameter at the surface of the eye. Though the CA of the MEMS is 1.2 mm, the usable portion is about two thirds of the total CA as the MEMS is positioned at a 45° angle to the incident beam. The MEMS is placed at the entrance pupil of the telescope as it allows the angle of the beam incident on the eye to be controlled. The angle at which the light enters the telescope is equal to the angle exiting the telescope. There is also a fold mirror at the intermediate image plane allowing for another degree of freedom when aligning the system for retinal tracking as it can be used to reposition the beam on the retina. While it is not shown in the above schematic, we have made the decision to add an aperture prior to the beam splitter to clip the beam rather than using the MEMS to clip the beam as light could reflect from the area surrounding the MEMS introducing stray light to the system.

In an effort to reduce cost and weight, a fiber coupled laser diode is being used as the light source for the system. This also allows for a fiber coupler instead of a beam splitter to be used to split the light from the source into two separate components. The durability of the device is increase by choosing a fiber coupled laser diode as it does not need to be aligned by the user, and the probability of misaligning the detector is less than that of an uncoupled device. Having fiber coupled devices also allows for the detector and the source to be place in a separate enclosure than the imaging optics reducing the number of components and the weight of the handheld portion of the device.

4.3 Optical Design

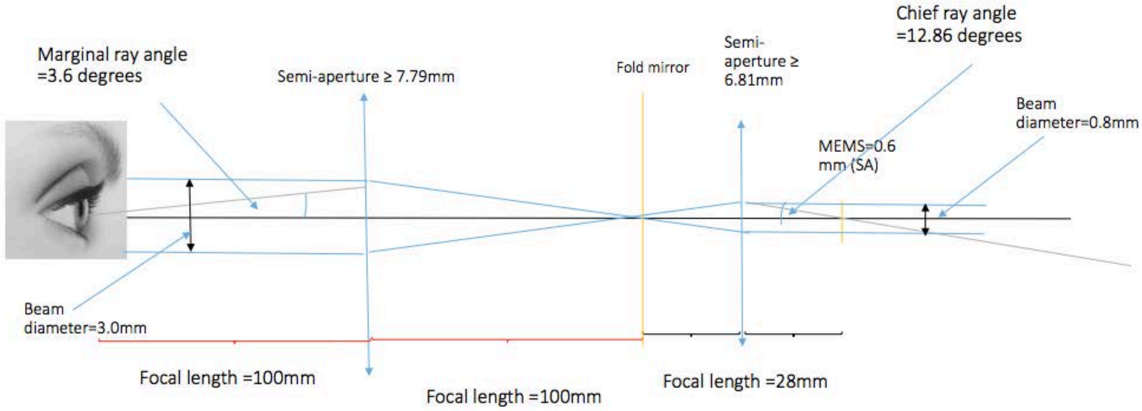


Figure 4: Optical ray tracing schematic of our afocal system (duplicate in fellow eye for binocular system) using the properties of a Keplerian telescope. Note the entrance beam size, use of a bi-directional MEMs scanning mirror, focal lengths & diameters of lenses, as well as the beam size as it hits the human pupil.

	Parameters	units
Field of View	7	degrees
Wavelength	852	nm

Eye relief distance	>100	mm
Entrance Pupil Diam.	3	mm

Table 2: Specifications necessary for the optical design of the device

We have decided to pursue a Keplerian telescope design for the afocal portion of the device. For collimating the light and collecting the light, we have chosen to use Thorlab fiber collimators. In order to keep the system symmetric, we will be using the same model for both collimating and collecting the beam. The MEMS and the fold mirror simply fold the optical path, so for ease of design, the above design has the surfaces as ghost surfaces. After completing the design with ghost surfaces the design was modeled with both the MEMS and the fold mirror folding the beam path.

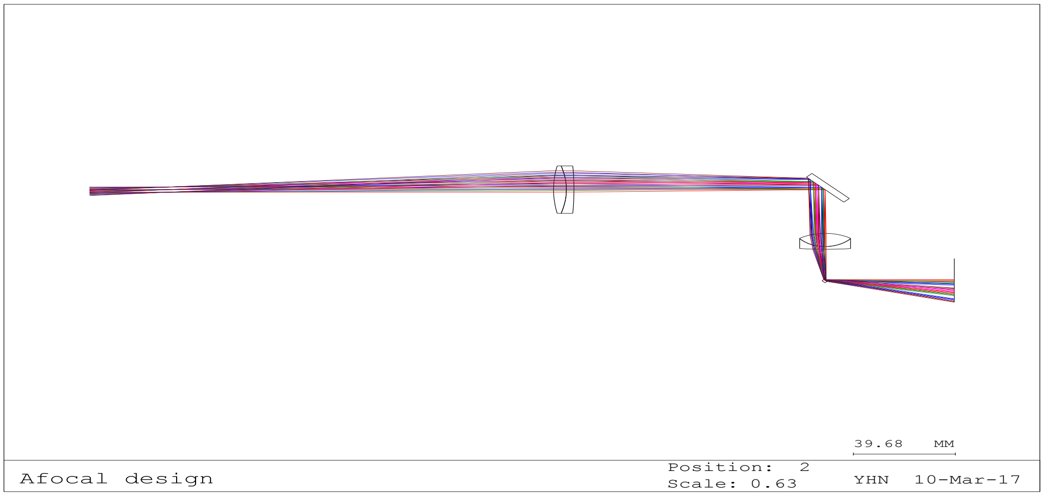


Figure 5: Afocal telescope assemble modeled into Code V. For performance, we verified RMS values throughout the scan field, each with a RMS WRE of 0.07 waves or less for a "diffraction limited" design using our wavelength and beam size.

In figure 4, the ideal lenses are depicted, but due to our desire to reduce cost, we chose to use catalog lenses instead of custom lenses. The lens depicted as having a 100 mm focal length is an Edmund Optics doublet that has a focal length of 120 mm and a diameter of 40 mm, and the lens depicted as having a 28 mm focal length is an Edmund Optics doublet with a 22.5 mm focal length and a 18 mm diameter. Though the two lenses are not the ideal lenses for the device, the performance of the device is not compromised by using them.

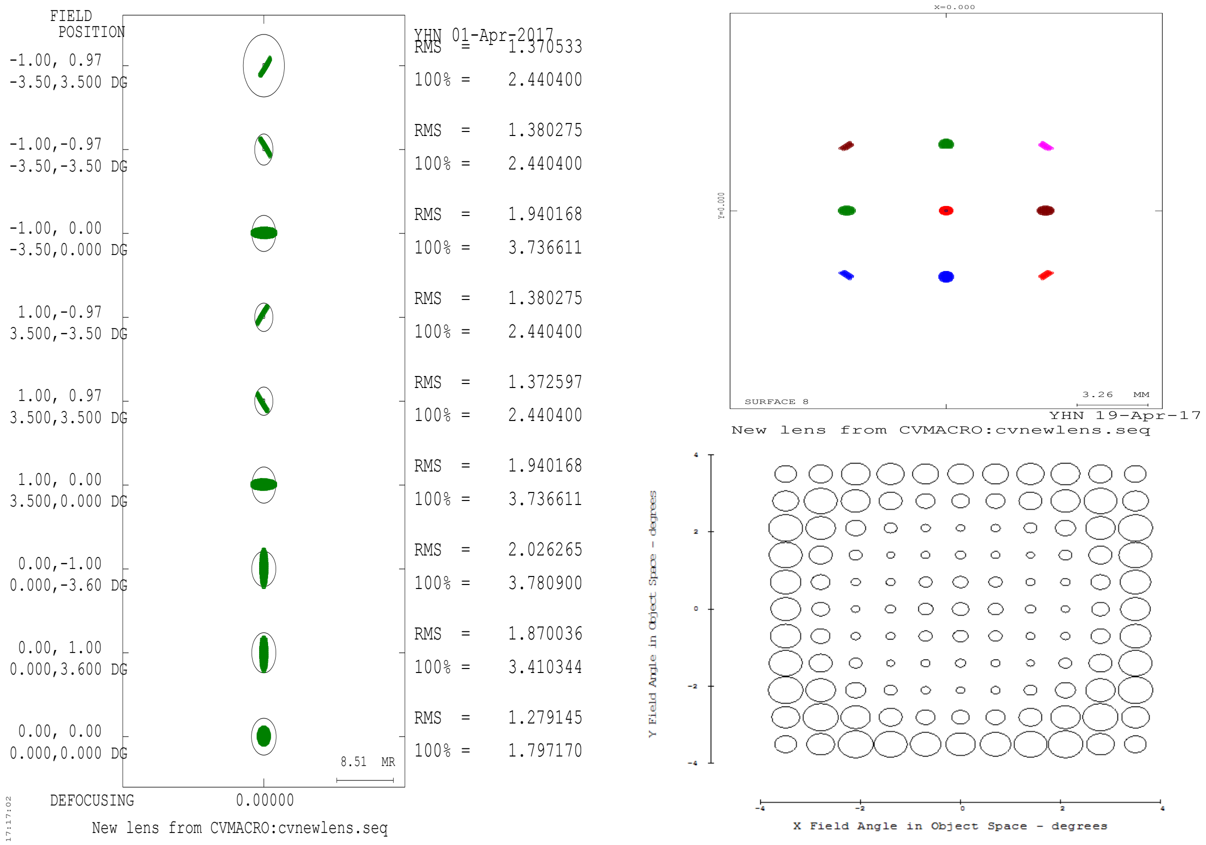


Figure 6: (left) Spot Diagram for the optical system. (right, upper) Spot diagram of the optical system showing the 9 scan points within the ~ 7° scan field (see scale bar). (right, lower) x and y field angles depicted in object space.

5. Components and Cost Analysis

In this section, we have documented all the components that were decided on as well as their cost. During the design process, we split the device into three major components, the light delivery arm, the light collection arm, and the front end optical component. The light delivery arm pertains to the components prior to the beam splitter when following the optical path, the light collection arm is all the components after the beam splitter, and the front-end optics are all the components between the beam splitter and the human eye, including the beam splitter. In choosing components both cost and performance were considered, as in some cases increases in performance outweighs the cost and in some cases the opposite holds true.

We chose to use optical fibers to relay the light as it gives additional freedom in using the device. There is not a fixed position that the patient must be in to perform the testing. The patient only needs to be able to have the device held up to their face.

5.1 Light Collection Arm

Part	Company	Product Number	No	Cost (per unit)	Total Cost
Detector: APD	Hamamatsu	C12703 series	2	APD: $700 with the FC attachment	APD: ~$1400
Pinhole	Thorlabs	P75S	2	$60	$120.00
Focusing Lens	Thorlabs	F280FC-850	2	$145.00	$290.00
Optical Fiber (/m)	Thorlabs	780HP	5	$5.40	$27.00
		Current Total			**~$2000**

Table 3: Components for the light collection arm of the device.

We are choosing to use a Hamamatsu Avalanche Photodiode (APD) as the detector in our system as it cost significantly less than the Hamamatsu Photo Multiplier Tube (PMT) that was being used in the reflective TSLO set-up without sacrificing a significant amount of performance. The APD also has the added benefit of weighing 38 grams each, which is a fraction of the weight of the PMT. The APD also had the advantage of being able to be fiber coupled, which increases the durability of the device and the alignment. We chose this particular APD model as it is the same model as the one used in LaRocca's compact handheld design, so we know that it can be used in retinal imaging. The focusing lens is needed in order to redirect the light into the fiber for detection. For the sake of symmetry this focusing lens is the same model as the collimating lens being used in the light delivery arm.

5.2 Light Delivery Arm

Part	Company	Product Number	Quantity	Cost (per unit)	Cost for parts
Laser Diode (852 nm)	Thorlabs	LP852-SF30	1	$709.00	$709.00
Fiber Coupler	Thorlabs	TW850-R5F1	1	$320	$320.00
Optical Fiber (/m)	Thorlabs	780HP	5	$5.40	$27.00
Fiber Collimator	Thorlabs	F280FC-850	2	$145.00	$290.00
				Total	**$1,427.00**

Table 4: Components for the light delivery arm

In order to improve the durability of the device, we are deciding to use a fiber coupled laser diode. The diode is more expensive than its non-coupled counterpart, but by reducing the number of components that we must keep in alignment, the durability is increased. Having the laser fiber coupled also allows for the use of a fiber coupler to provide light to both eyes simultaneously. The fiber collimator is the same lens that is being used in the light collections arm.

5.3 Front End Optics

Part	Company	Product Number	Quantity	Cost/unit	Cost
MEMs + drivers	Fraunhofer	N/A-P2	2	$5900	$11800
Fold Mirror	Thorlabs	BB1-E03	2	$75.10	$150.20
Lens	Edmund	49-381	2	$135	$270
Lens	Edmund	49-955	2	$92.50	$185
Beam Splitter	Thorlabs	BSX11	2	$115	$230.00
				Total	**$12405**

Table 5: Components for the Front-End Optics

The MEMS device was chosen by our customer as it has the correct scanning frequency to produce the necessary images for eye tracking. We have verified that the device has the mechanical ability to scan the desired field of view. There is a fold mirror included in the system that can reposition the image on the retina allowing for the beam to start in the correct position on the retina for each scan. The lenses are catalog lenses which reduces cost and lead time. We have carefully chosen the catalog lenses so that performance is not compromised while still reducing cost.

5.4 Cost Compiled and Status

Component	Cost to Date	Parts Still TBD
Enclosure	TBD	All
Optomechanics	TBD	All
Front End	~$12,500	Power Supply for the MEMS device
Collection Arm	~<$2000 (APD)	Power Supply, Mounts/Rails
Delivery Arm	~$1,500	Power Supply, Mounts/Rails
Totals So Far	$16,000	Remaining Budget: ~$19,000

Table 6: Compiled cost sorted by components

We have completed the selection of optical components for the project and started a preliminary design for the probe enclosure, but all mounts, enclosures and power supplies will be decided on at a later date by either the customer or a future design team.

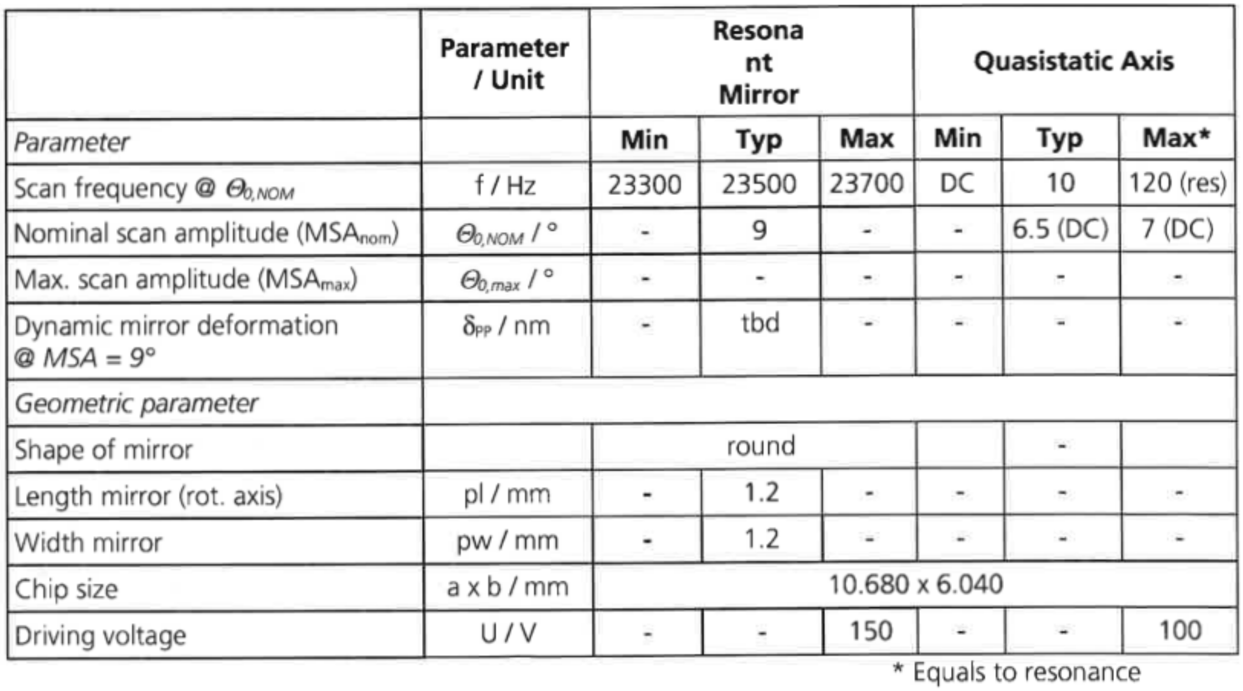
6. Conclusions and Future Works

We have completed the preliminary optical design for the device, making sure to consider cost, weight, and performance when choosing each element of the design. We also began work on the enclosure design for the handheld portion of the device. A provisional patent (Application No.: 62/501,480) of the optical design has been filed.

Though we have made great progress on this project, there are still a few elements that will need to be finished: (1) determine power supply, (2) finalize the binocular probe enclosure, and (3) optimize the controller/electronics housing.

Appendixes

Appendix A: MEMS Specs



	Parameter / Unit	**Resonant Mirror**			**Quasistatic Axis**		
Parameter		**Min**	**Typ**	**Max**	**Min**	**Typ**	**Max***
Scan frequency @ $\Theta_{0,NOM}$	f / Hz	23300	23500	23700	DC	10	120 (res)
Nominal scan amplitude (MSA_{nom})	$\Theta_{0,NOM}$ / °	-	9	-	-	6.5 (DC)	7 (DC)
Max. scan amplitude (MSA_{max})	$\Theta_{0,max}$ / °	-	-	-	-	-	-
Dynamic mirror deformation *@ MSA = 9°*	δ_{PP} / nm	-	tbd	-	-	-	-
Geometric parameter							
Shape of mirror		round				-	
Length mirror (rot. axis)	pl / mm	-	1.2	-	-	-	-
Width mirror	pw / mm	-	1.2	-	-	-	-
Chip size	a x b / mm	10.680 x 6.040					
Driving voltage	U / V	-	-	150	-	-	100

* Equals to resonance

Table 1: MEMS specifications taken from the quote for the Fraunhofer MEMS device.

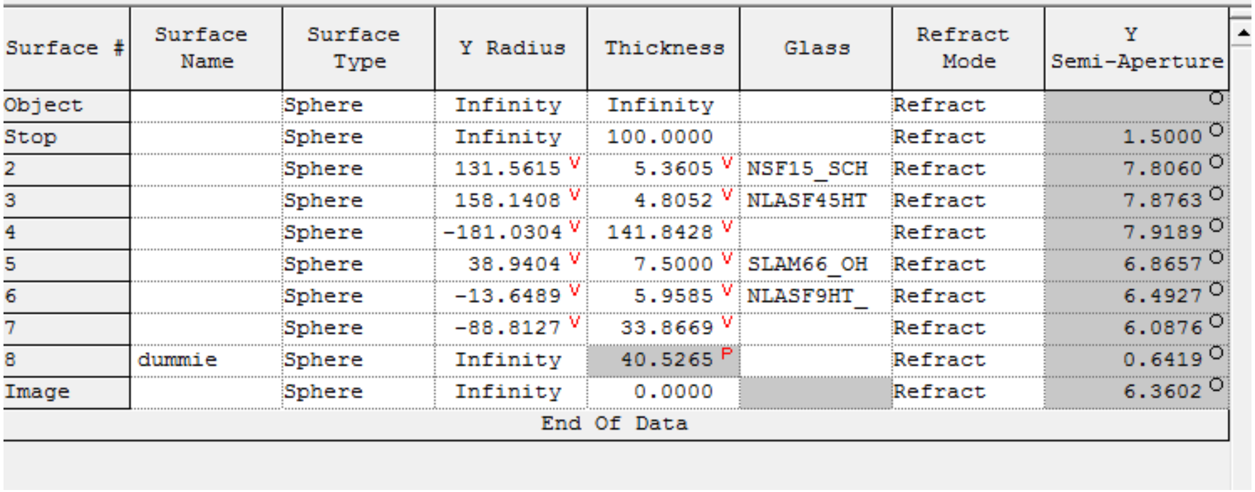
Appendix B: Detector Comparison

Detector Comparison to Date

Detector	PMT	APD - 1	APD - 2
Usable Area	0.5 mm	1.5 mm	3.0 mm
Wavelength Range	380 - 890	400 - 1000	
Peak Wavelength	800 nm	800 nm	
Dimensions	56.0 x 36.0 x 104.0 mm	80x50x22	
Input Voltage	+11.5 to +15.5 V	Based on the data sheet it seems to be +/- 12 V	
Max Input Voltage	18V	16V	
Operating Temperature	+5 to +35 ℃	0 to 60 C	
Storage Temperature	-20 to +50 ℃	-20 to +70 ℃	
Weight	400 g	38 g	
Coupling	none	can request SMA or FC	
Noise Equivalent Power	TBD	.2 pW/Hz^1/2	0.02 pW/Hz^1/2
Radiant/Photoelectric Sensitivity	Cathode:90 mA/W Anode: Standard: 2.5E4	1.5E6 V/W	-1.5E8 V/W
Maximum Input Light Level	TBD	60 μW	0.06 μW
Minimum Detection Limit	TBD	.63 nW rms	0.0063 nW rms

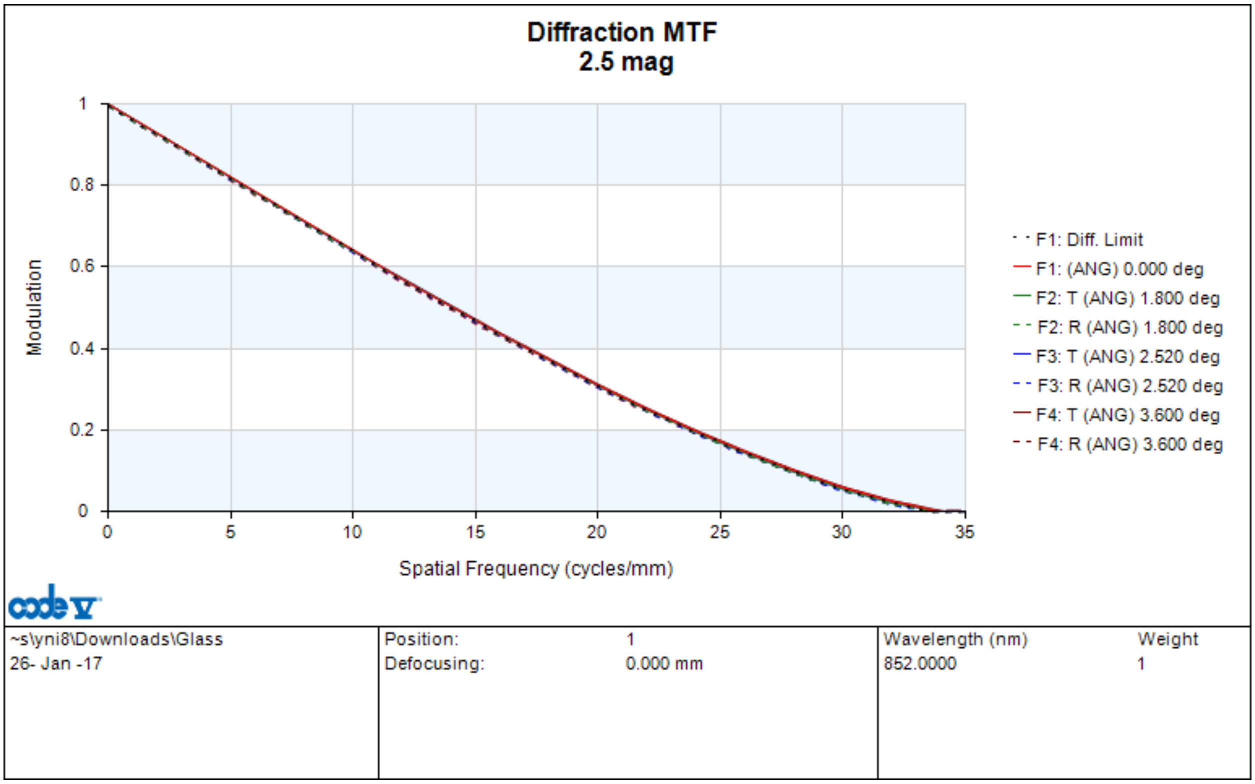
	APD	PMT	
Gain	30	1	
Responsivity before gain	0.5	0.05	A/W
Responsivity with gain	15	2.50E+04	A/W
Transimpedance gain	10000	500	V/A
Dark Current		0.5	nA
Thermal Noise			
Shot Noise	5.2915E-13		
Peak Output signal (volts)	0.2625	21.875	
Detector Equivalent input noise (spectral density)	0.2	1.13E-01	pW/sqrt(Hz)
Total Noise power	4E-19	1.28E-19	W^2
Total Signal Power	3.0625E-18	3.0625E-18	W^2
Signal to Noise Ratio	7.65625	23.92578125	
Signal to Noise Ratio (dB)	8.84016106	13.78866128	

Appendix C: Original Optical Layout



Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	Infinity		Refract	○
Stop		Sphere	Infinity	100.0000		Refract	1.5000 ○
2		Sphere	131.5615 V	5.3605 V	NSF15_SCH	Refract	7.8060 ○
3		Sphere	158.1408 V	4.8052 V	NLASF45HT	Refract	7.8763 ○
4		Sphere	-181.0304 V	141.8428 V		Refract	7.9189 ○
5		Sphere	38.9404 V	7.5000 V	SLAM66_OH	Refract	6.8657 ○
6		Sphere	-13.6489 V	5.9585 V	NLASF9HT_	Refract	6.4927 ○
7		Sphere	-88.8127 V	33.8669 V		Refract	6.0876 ○
8	dummie	Sphere	Infinity	40.5265 P		Refract	0.6419 ○
Image		Sphere	Infinity	0.0000		Refract	6.3602 ○

End Of Data



~s\yni8\Downloads\Glass	Position:	1	Wavelength (nm)	Weight
26- Jan -17	Defocusing:	0.000 mm	852.0000	1

Since this design, we have changed the magnification, as we realized that with the MEMS being on an angle we had a smaller working area.

Appendix D: RMS values of the optical Design

```
FIELD                      BEST INDIVIDUAL FOCUS                   BEST COMPOSITE FOCUS
     FRACT   DEG     SHIFT      FOCUS     RMS      STREHL     SHIFT      FOCUS      RMS     STREHL
                     (MR )      (DIO)    (WAVES)              (MR )      (DIO)    (WAVES)

 X    0.00   0.00   0.000000   3.081797   0.0000   1.000    0.000000  -2.120693   0.0696   0.826
 Y    0.00   0.00   0.000000                                0.000000

 X    0.00   0.00   0.000000  -4.213917   0.0431   0.929    0.000000  -2.128085   0.0500   0.906
 Y    1.00   3.60   0.081760                                0.114333

 X    0.00   0.00   0.000000  -5.030204   0.0480   0.913    0.000000  -2.128059   0.0605   0.865
 Y   -1.00  -3.60  -0.006288                               -0.006644

 X    1.00   3.50   0.012558  -4.479612   0.0451   0.923    0.009505  -2.127924   0.0536   0.893
 Y    0.00   0.00   0.000000                                0.000000

 X    1.00   3.50   0.683320  -4.355926   0.0127   0.994    0.511019  -2.119179   0.0301   0.965
 Y    0.97   3.50   0.608486                                0.455288

 X    1.00   3.50   0.683242  -4.339053   0.0127   0.994    0.507302  -2.118979   0.0302   0.965
 Y   -0.97  -3.50  -0.609760                               -0.447499

 X   -1.00  -3.50  -0.012559  -4.479639   0.0451   0.923   -0.009505  -2.127907   0.0536   0.893
 Y    0.00   0.00   0.000000                                0.000000

 X   -1.00  -3.50  -0.683313  -4.339099   0.0127   0.994   -0.507302  -2.118777   0.0302   0.965
 Y   -0.97  -3.50  -0.609823                               -0.447496

 X   -1.00  -3.50  -0.682719  -4.364551   0.0127   0.994   -0.511460  -2.118976   0.0302   0.965
 Y    0.97   3.50   0.608448                                0.455573
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Appendix E: Sheehy's Reflective System Abstract

In relation to our product:

Our initial thought was trying to reduce the amount of mirrors that are used in her design such that we can decrease the weight and size, but it was not enough so that the device can be hand held. Thus, we decided to look for other similar designs, that used refractive relays instead of reflective ones. The number of elements could also not be reduced as the scanning mirrors need to remain in pupil conjugate positions in order to correctly scan and de-scan the retinal image.

Abstract:

The development of high magnification retinal imaging has brought with it the ability to track eye motion with a precision of less than an arc minute. Previously these systems have provided only monocular records. Here we describe a modification to the Tracking Scanning Laser Ophthalmoscope (Sheehy et al., 2012) that splits the optical path in a way that slows the left and right retinas to be scanned almost simultaneously by a single system. A mirror placed at a retinal conjugate point redirects half of each horizontal scan line to the fellow eye. The collected video is a split image with left and right retinas appearing side by side in each frame. Analysis of the retinal motion in the recorded video provides an eye movement trace with very high temporal and spatial resolution. Results are presented from scans of subjects with normal ocular motility that fixated steadily on a green laser dot. The retinas were scanned at 4 eccentricity with a 2 square field. Eye position was extracted offline from recorded videos with an FFT based image analysis program written in Matlab. The noise level of the tracking was estimated to range from 0.25 to 0.5 arc min SD for three subjects. In the binocular recordings, the left eye/right eye difference was 1–2 arc min SD for vertical motion and 10–15 arc min SD for horizontal motion, in agreement with published values from other tracking techniques.

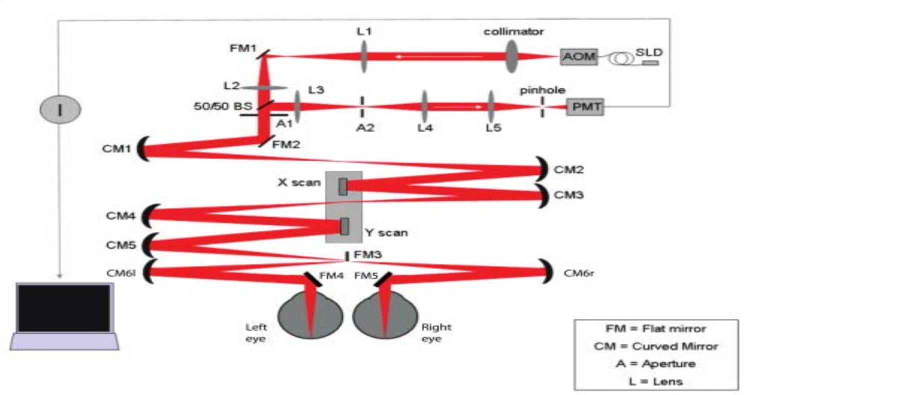


Fig. 1.
Schematic layout of the binocular modification to the Tracking Scanning Laser Ophthalmoscope (modified from Sheehy et al., 2012). Mirror FM3 is placed at a retinal conjugate point, splitting the field into left eye and right eye halves. Each half of the scan is reflected by a concave mirror and a flat mirror into the respective eyes. The resulting scan produces a split field image with left and right retinal images side by side in the each frame. The horizontal scanner is a polished bar resonating at 15.4 kHz and images are collected during a 26 μs time window during one direction of scan, so left and right eye samples are collected about 13 μs apart. Eyes are not shown to scale.

Figure 1: Our customer's current design for a reflective Binocular System

Appendix F: LaRocca Compact OCT/SLO Abstract

In relation to our product:

This scholarly article is our inspiration and starting point for our design. It is light weight, handheld and capable to capture the retinal imaging. Through this paper, we see the potential of making our project possible and apply to normal adults. The challenges in adapting this approach to work for our design is that we need to expand the field of view and create it in a way that both eyes can by imaged simultaneously.

Abstract:

Handheld scanning laser ophthalmoscopy (SLO) and optical coherence tomography (OCT) systems facilitate imaging of young children and subjects that have difficulty fixating. More compact and lightweight probes allow for better portability and increased comfort for the operator of the handheld probe. We describe a very compact, novel SLO and OCT handheld probe design. A single 2D microelectromechanical systems (MEMS) scanner and a custom optical design using a converging beam prior to the scanner permitted significant reduction in the system size. Our design utilized a combination of commercial and custom optics that were optimized in Zemax to achieve near diffraction-limited resolution of 8 µm over a 7° field of view. The handheld probe has a form factor of 7 x 6 x 2.5 cm and a weight of only 94 g, which is over an order of magnitude lighter than prior SLO-OCT handheld probes. Images were acquired from a normal subject with an incident power on the eye under the ANSI limit. With this device, which is the world's lightest and smallest SLO-OCT system, we were able to visualize parafoveal cone photoreceptors and nerve fiber bundles without the use of adaptive optics.

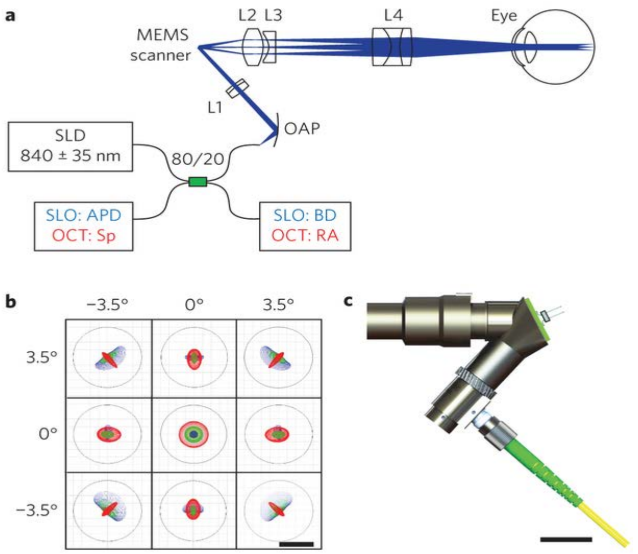
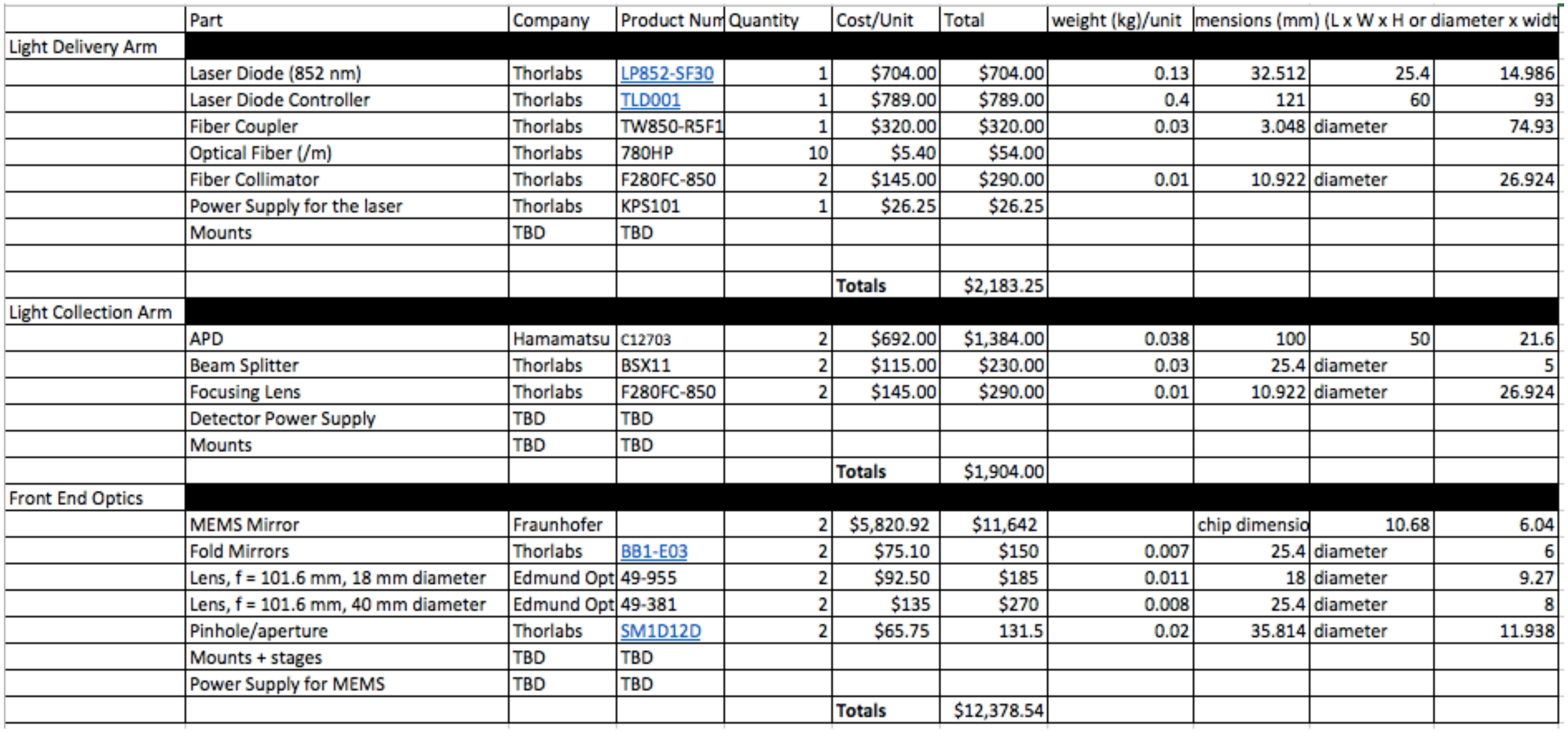


Figure 1: Layout of the design with spot diagram color coded for three wavelengths for both SLO and OCT illuminating on to the retinal with a field of view of 7 degrees.

Appendix G: Cost and Weights compiled



	Part	Company	Product Num	Quantity	Cost/Unit	Total	weight (kg)/unit	mensions (mm) (L x W x H or diameter x widt		
Light Delivery Arm										
	Laser Diode (852 nm)	Thorlabs	LP852-SF30	1	$704.00	$704.00	0.13	32.512	25.4	14.986
	Laser Diode Controller	Thorlabs	TLD001	1	$789.00	$789.00	0.4	121	60	93
	Fiber Coupler	Thorlabs	TW850-R5F1	1	$320.00	$320.00	0.03	3.048	diameter	74.93
	Optical Fiber (/m)	Thorlabs	780HP	10	$5.40	$54.00				
	Fiber Collimator	Thorlabs	F280FC-850	2	$145.00	$290.00	0.01	10.922	diameter	26.924
	Power Supply for the laser	Thorlabs	KPS101	1	$26.25	$26.25				
	Mounts	TBD	TBD							
					Totals	$2,183.25				
Light Collection Arm										
	APD	Hamamatsu	C12703	2	$692.00	$1,384.00	0.038	100	50	21.6
	Beam Splitter	Thorlabs	BSX11	2	$115.00	$230.00	0.03	25.4	diameter	5
	Focusing Lens	Thorlabs	F280FC-850	2	$145.00	$290.00	0.01	10.922	diameter	26.924
	Detector Power Supply	TBD	TBD							
	Mounts	TBD	TBD							
					Totals	$1,904.00				
Front End Optics										
	MEMS Mirror	Fraunhofer		2	$5,820.92	$11,642		chip dimensio	10.68	6.04
	Fold Mirrors	Thorlabs	BB1-E03	2	$75.10	$150	0.007	25.4	diameter	6
	Lens, f = 101.6 mm, 18 mm diameter	Edmund Opt	49-955	2	$92.50	$185	0.011	18	diameter	9.27
	Lens, f = 101.6 mm, 40 mm diameter	Edmund Opt	49-381	2	$135	$270	0.008	25.4	diameter	8
	Pinhole/aperture	Thorlabs	SM1D12D	2	$65.75	131.5	0.02	35.814	diameter	11.938
	Mounts + stages	TBD	TBD							
	Power Supply for MEMS	TBD	TBD							
					Totals	$12,378.54				

Appendix H: Preliminary CAD

Figure 1: This is the preliminary exterior CAD model for a single eye, there will be two of these attached together to view both eyes. The will attached in a way that the Inter-pupillary distance (IPD) is adjustable.

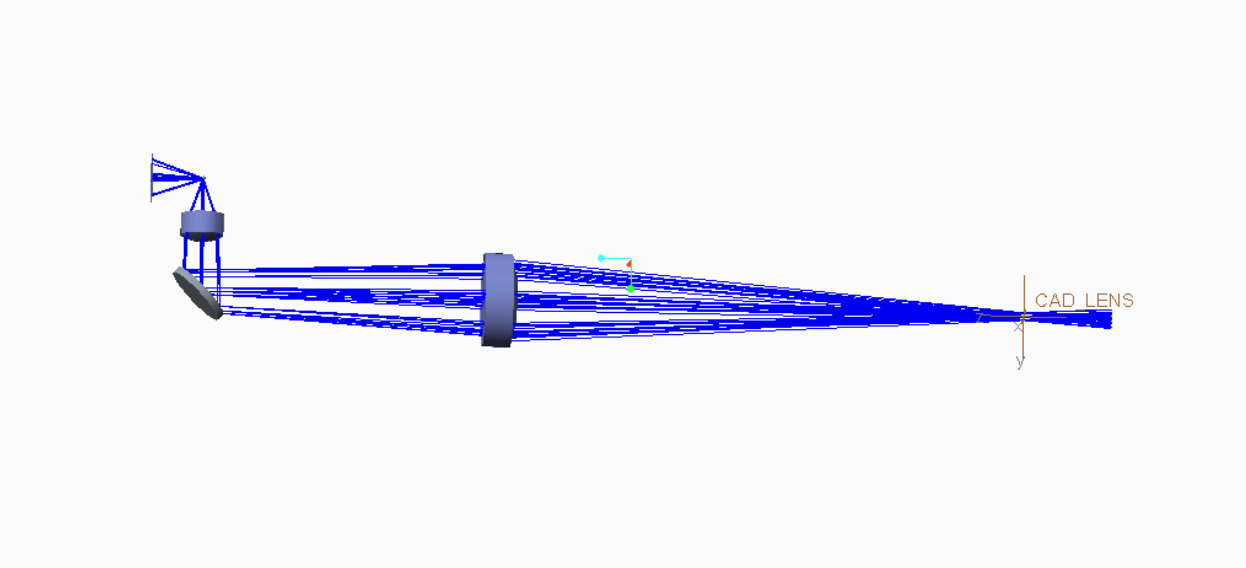


Figure 2: Lens CAD produced by exporting the system from Code V.

Appendix I: Design Day Demo

Figure 1: Various angles of the optical set-up used as a design day demonstration.

References

1. Larocca, Francesco, Derek Nankivil, Theodore Dubose, Cynthia A. Toth, Sina Farsiu, and Joseph A. Izatt. "In Vivo Cellular-resolution Retinal Imaging in Infants and Children Using an Ultra Compact Handheld Probe." *Nature Photonics* 10.9 (2016): 580-84. Web.

2. Stevenson, S.b., C.k. Sheehy, and A. Roorda. "Binocular Eye Tracking with the Tracking Scanning Laser Ophthalmoscope." *Vision Research* 118 (2016): 98-104. Web.