



iPhone Virtual Reality Training Model for Microsurgical Practice

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Abstract

Microsurgical training is expensive, and surgical microscopes are inaccessible for students to practice on. Here we create a microsurgery training tool that works with the magnification feature of a smartphone to reduce the cost of training as well as make it easier to train from any location. The video from the smartphone must also be live streamed so instructors can view and give feedback in real-time. Also, the device will produce a stereoscopic video to replicate the depth perception given by an optical microscope used in the operating room. The team has created three possible designs and has decided to pursue a single phone camera-based design. The final design is a small housing of angled mirrors that attaches to the phone. The mirrors split the view into two images and feed it into the camera sensor simultaneously. This splitting creates binocular vision, thereby creating depth perception with a singular camera. Finally, this is streamed into a secondary phone in a VR headset. The student wears the headset while practicing in order to see depth. This depth will be tested by microsurgeons and also comparing results of a suture moving speed test on the microscope and then on the smartphone.

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1. Introduction

1.1 Motivation

There is an ever-growing need for microsurgeons, but access to resources available for training is limited and expensive. Especially during the COVID-19 pandemic, it is proved that virtual training is advantageous and preferred for medical students [1]. Using a smartphone for practice would increase the accessibility for training because of its good magnification, low cost, and portability. It only lacks the depth perception required to practice accurately. The goal is to improve the depth perception, while keeping a high-quality image, to resemble larger microscopes.

1.2 Problem statement

Make it easier for microsurgery students to practice by designing a training tool that uses a smartphone lens, creates depth perception, and has a high-quality resolution that is comparable to a surgical microscope.

2. Background

2.1 Surgical Microscopes

Surgical microscopes provide a view of the surgical site that has both depth perception and high resolution. They obtain this stereoscopic image through a series of prisms and lenses to enlarge the image while maintaining the quality [2]. These microscopes range anywhere from \$200,000 to \$1 million [3]. This project compares to a surgical microscope at Wisconsin Institutes for Medical Research that is approximately \$300,000. Alternatively, the iPhone 13 base price ranges from \$800 to \$1,000 [4]. Although the resolution and zoom are not the exact same as that of microscopes, it is suitable for training purposes.

2.2 Smartphone Cameras

Smartphones are widely accessible and provide flexibility of training locations that aren't restricted to the location and time availability of surgical microscopes. iPhones however don't provide the depth perception that microscopes have since most models can utilize only one of the lenses at a time.

2.3 Stereoscopic Display Technology

There are many options available for viewing stereoscopic images such as 3D glasses or VR headsets. Auto-stereoscopic displays are displays that allow for 3D depth perception without the need to wear a headset or glasses. A viable option for creating an auto-stereoscopic display would be to use a parallax barrier. A laptop screen can display the 2 different angles of the same subject interlaced between every other pixel. The parallax barrier works by blocking the left image from reaching the right eye and vice versa [5].

2.4 Clients

The team's clients are Dr. Ellen Shaffrey, Dr. Samuel Poore and Dr. Weifeng Zeng. They are all plastic surgeons at the UW Hospital in Madison, Wisconsin. They are looking for a way to affordably train many microsurgery students in a way that is similar to using a real microscope.

2.5 Previous Work

The clients previously used a Google Cardboard, an iPhone to record, an iPhone in the headset, and a laptop to transfer the 3D image. This achieved depth but lowered the accessibility and increased delay time. The previous BME team decided to combat this by developing a program that would create the 3D image internally, to reduce the delay between devices. However this program was slow to process, creating internal lag time.



Figure 1: Client's Google Cardboard design to increase depth and accessibility.

2.6 Product Design Specifications

The clients specified that the final product should allow for depth perception regarding where the trainee's hands are in the workspace. Additionally, the zoom capacity and resolution need to be high enough to clearly see sutures that are 0.070 mm in diameter. It must be inexpensive and widely accessible. Finally, it should have a streaming resolution of 10.2 megapixels and stream delay of no more than 0.5 seconds. To allow for max functionality this design will be mounted on an adjustable stand and be of a low weight of less than 4.5 kilograms as to not interfere with worksite.

2.7 Competing Designs

The team's design will try to emulate the experience of performing surgery through commercial surgical microscopes but at a fraction of the cost. Two surgical microscopes that are currently used are the Mitaka MM51 microscope and the Orbeye 4K 3D Orbital Camera System. The MM51 is an optical microscope that requires the surgeon to look through two eyepieces [6]. Because the microscope is restricted to a top-down perspective, the surgeon doesn't have as many possible viewing angles. Also, looking into the microscope restricts the surgeon's field of view. The Orbeye Camera System solves this issue by using a 4K camera mounted on an arm that transmits the video to a 3D stereoscopic display [7]. This allows for many different viewing angles as well as a more ergonomic seating position for the surgeon.

3. Preliminary Designs

3.1 Splitting Lens

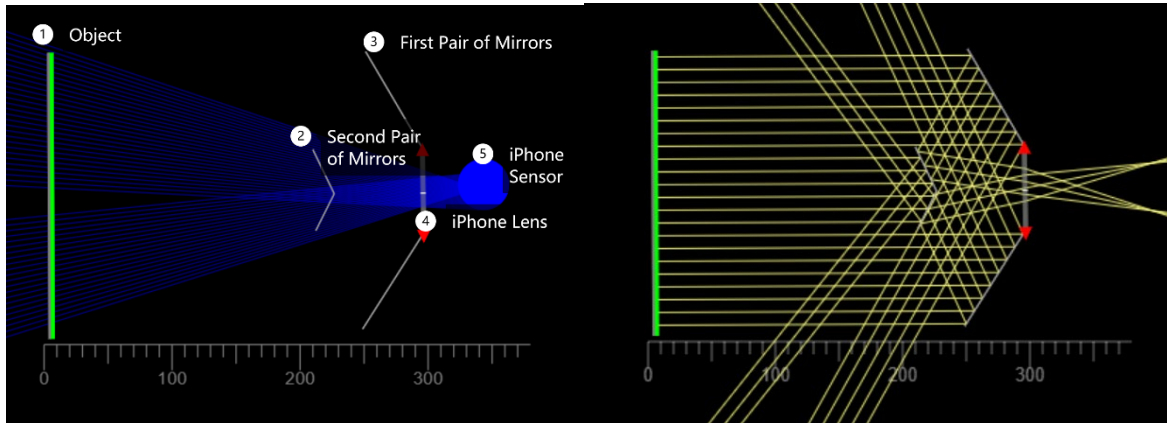


Figure 2: (Left) Imaging tracing diagram. The light will reach (3) the first pair of mirrors then to the second pair (2), and be reflected to the smartphone lens (4). The position and dimensions of the components are not in scale and are subject to change. (Right) Ray tracing diagram from the same set up. Dimensions and relative positions from both figures are arbitrary and are subject to change.

The splitting lens design captures the object from two different angles and combines the varying views into one image that projects onto the entire sensor of the smartphone. The mirrors are a cheaper alternative to using two separate lenses/cameras as it allows the viewer to obtain two different views but with the use of a single camera. The outer vision beams coming off the object are reflected off the first set of mirrors while the inner vision beams coming off the object are reflected off the second set of mirrors. Those altering sites come together to formulate an individual image that goes into the iPhone lens and is captured by the iPhone sensor.

From the image tracing diagram, the extended ray from light arriving at the sensor would be traced back to two spots at the object (1) in Figure 2. This provides the same effect as if two virtual cameras were put at the sensor, pointing toward the object at angles of the extended rays and capturing the same object at these angles.

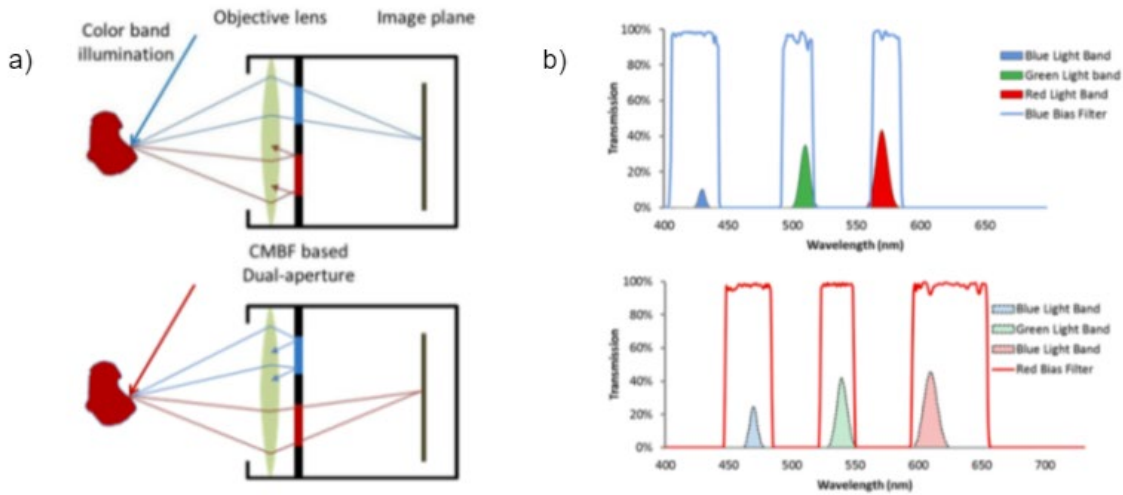


Figure 3: (a) A pair of complementary bandpass filters placed at the dual - aperture single objective lens. The scheme describes the two viewpoints made by the complementary bandpass filters. (b) An actual spectral plot of a pair of complementary triple - band bandpass filters [8]

The complimentary Multi-Bandpass Filter design is an attachment on the smartphone camera. As shown in Figure 3a, the attachment consists of a converging lens for light redirection, while two CMBF filters are installed right after the lens to produce a resulting image with two fields of view, each with a unique spectrum. The resulting image will be displayed on a monitor, and the user will wear a polarized goggle to obtain depth perception. Each CMBF filter has many passbands over the visible spectrum, so Red-Blue-Green spectral images can be imaged by each viewpoint. CMBFs are staggered, which means that none of the wavelengths transmitted by filters overlaps with any of the others. One of the downsides of this is that some regions in the color band will be skipped, and this can cause issues when viewing the image. However, this can be addressed by digitally correcting the colors and by choosing the correct set of CMBFs. Figure 3b shows an actual spectral plot of a pair of complementary triple-band bandpass filters purchased commercially off-the-shelf. The bell curves are light bands selected by a tunable filter from a broadband light [8].

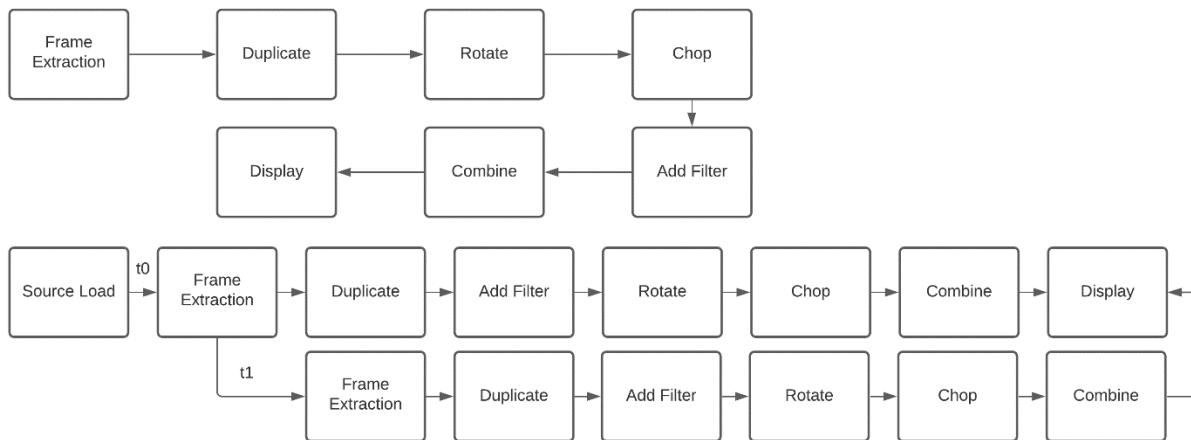


Figure 4: (Top) Original algorithm developed by the previous team. (Bottom) Proposed algorithm to enhance efficiency

The “efficient algorithm” design looks to improve upon an algorithm that was first created by last year’s BME group in MATLAB for generating an anaglyph, or 3D image. As shown in Figure 4, the frames of the footage were extracted, then duplicated, rotated, chopped, filter added, combined, and then displayed. The main issue with the previous algorithm was that its processing time was too slow; the footage was only being processed at around 2.4 fps when the target was 30 fps. The main focus of the new algorithm is to improve the processing time. The proposed algorithm will use the existing steps to process the video, but the proposed algorithm aims to utilize a buffer system, such that the streamlined video is extracted into frames while ensuring the frames are processed at the same time. This multi-threading process is expected to significantly reduce the process time. Additionally, stress on the hardware is expected to be reduced with decreased demand for RAM per iteration by reducing variables stored in the workspace.

4. Preliminary Design Evaluation

4.1 Design Matrix

Criteria	Weight	Splitting Lens Design		Complementary Multi-Bandpass Filter (CMBF)		Efficient Algorithm Design	
		Raw Score	Score	Raw Score	Score	Raw Score	Score
Effectiveness (Time Lag)	25	5/5	25	5/5	25	2/5	10
Quality (Optical Quality)	20	3/5	12	4.5/5	18	3/5	12
Ease of Use	20	5/5	20	4/5	16	5/5	20
Cost	15	3/5	9	2/5	6	5/5	15
Safety	10	4/5	8	4/5	8	5/5	10
Ease of Fabrication	5	4/5	4	1/5	1	5/5	5
Durability	5	4/5	4	2/5	2	5/5	5
Total	100	28/35	82	23.5/35	76	30/35	77

Table 1: Design matrix of proposed designs. The criteria assigned with a full score are highlighted in yellow. And the highest total score is highlighted in green.

4.2 Design Consideration

4.2.1 Effectiveness

Time lag, defined as the delay between image capture and streaming to the end user, was the major issue identified from the final deliverable of the previous design team. Thus, the most important factor is effectiveness, which focuses on reducing the time lag in video streaming to the end user. According to the PDS, the lag shall be at most 0.5 s in the design, and shorter expected lag time will lead to a higher score in this criterion. Meanwhile, since hand movement in 1 second is drastic under microscope, more delay increases the risk of failure in the microsurgery, thus effectiveness is given the highest weight among all criteria. Since image processing with MATLAB is highly dependent on the CPU processing speed, the Efficient Algorithm Design is still expected to have significant delay due to the limitations of the laptop processors. While processing time is saved by the Splitting Lens and the CMBF design by directly recording the videos with depth information included. Therefore, Efficient Algorithm Design receives the lowest score, and the other two are assigned with a full score for the criteria.

4.2.2 Quality

Quality of the design is determined by optical quality of the streamlined video. A minimal requirement on the resolution is 10.8 megapixels and to distinguish the sutures from the environment. Higher optical quality achieved with a reasonable amount of cost will be given a higher score on this criterion. Though all three designs utilize full resolution of the smartphone,

Seal *et al.* concluded that the Splitting Lens Design resulted in image distortion [9]. Similarly in the Efficient Algorithm Design, rotating frames from the video about an arbitrary axis will also lead to distortion. On the other hand, Bae *et al.* proved that CMBF design has little to no distortion, which leads to the highest score assigned for the criteria [8].

4.2.3 Ease of Use

Ease of use is determined by the expected training effort to use this deliverable as well as the ergonomic considerations of the design. The design shall have minimal interference on the trainee's practice during microsurgery, while simulating the surgical experience when using a real microscope. The first two designs are developed as attachments to the smartphone camera, while the third is software that can be executed in all operating systems. Therefore, all designs are relatively easy to use. Yet, prior to use, the CMBF design requires adjustment of the filters to minimize color pollution from the complementary filter, thus a point is deduced for the design [8].

4.2.4 Cost

Cost is one of the primary considerations in the project. As is stated in the problem statement and PDS, the project aims to provide a solution for less developed regions where a microscope is not available. Thus, while the previous three criteria cover the minimal requirement in an engineering design, cost is given the fourth highest weight. Lower cost in the design is preferred and thus given a higher score. The Splitting Lens Design and CMBF design consist of customized optic glassware, which increases the cost of the products. Thus, a score of 5 is given for the Efficient Algorithm Design that can be made free with open source, 3 for the Splitting Lens Design and 2 for the CMBF design with the highest cost.

4.2.5 Safety

Safety is an important factor in the design. While most of the risk during microsurgery practice comes from the surgical equipment (scalpers, tweezers, etc.), and since there is little to no physical interaction between the trainee and the design, it is given a lower weight in the design matrix. However, broken lenses and screens may be harmful to the users. Thus, less delicate, or sharp parts in the design will be given a higher score, and Efficient Algorithm Design receives a full score for no glass pieces required.

4.2.6 Ease of Fabrication

Ease of fabrication considers the difficulties in making the final deliverables, such as materials, manufacturing, and assembly. Since cost is listed as an individual criterion, ease of fabrication is not considered as important. However, there is still a foreseeable difficulty in accessing the design in less developed regions, which is taken into consideration for ethics and humanity. Easier fabrication will be given a higher score. CMBF receives a lowest score due to adjustment of the filters, while Efficient Algorithm Design receives a full score since only software development is required.

4.2.7 Durability

Durability focuses on how fragile a design is. The design should be able to withstand daily use and any accidental drops or hits, as is stated in the PDS. Because software is less subject to malfunction compared to the optic pieces, the Efficient Algorithm Design is scored the highest. The filter alignment from the CMBF design is likely to be altered during use, which affects the video quality and leads to lowest score for the criteria.

4.3 Proposed Final Design

After evaluating the designs against PDS and proposed criteria, the Splitting Lens Design receives the highest score, which thus becomes the proposed final design.

5. Fabrication/Development Process

5.1 Materials

Component	Use	Cost
Cardboard	Housing	Recycled
2.54 x 2.54 cm Mirrors	Reflect image	\$7.99
Google Cardboard	Stereoscopic display	Provided by client
Phone Boom Arm	Hold imaging device	Provided by client

Table 2: List of materials and cost

5.2 Methods

5.2.1 Calculation of the parameters

Variables and definitions

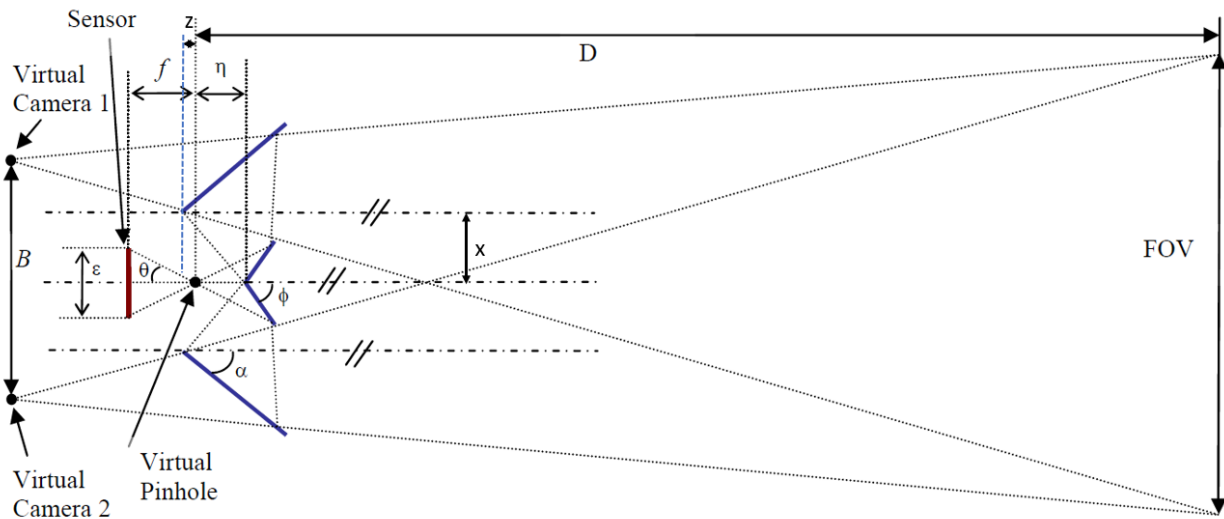


Figure 5: The catadioptric system showing the position of mirrors, sensor, lens, and definitions of the parameters. Adapted from Seal *et al.*

Equations used to calculate the parameters for the most compact design are adopted from Seal *et al* [9]. The figure above shows the definitions of the parameters. From left to right, B is the baseline of the design, which is the distance between two virtual cameras. Since the final design captures the operation station from two slightly different angles, it is equivalent to recording from two cameras (virtual camera 1 and 2). Though baseline is not an important factor

in prototype fabrication, it is listed to provide a reference of the size of the final deliverable. Meanwhile, since light reflected by the top and the bottom pairs of mirrors converges at a single point, acting as a pinhole for a pinhole camera, the virtual pinhole is labeled on the figure as well.

ϵ is the width of the camera sensor. Since the pixel size of iPhone 8 is $1.22 \mu m$ (λ) and there are 4032 pixels horizontally, the width of the pixel is the product of the values [10]:

$$\epsilon = 4032 * (1.22 * 10^{-3}mm) = 4.92mm \quad Eq(1)$$

f is the absolute focal length of the camera, and for iPhone 8, the value is 3.99 mm [10]. η , on the other hand, is the distance between the virtual pinhole and the vertex of the inner mirrors. The working distance D , according to the clients, is 305 mm (1 foot). Field of view (FOV) is the size of the station that can be recorded by iPhone 8 with the final prototype. Though not being labeled on the figure, d is the depth resolution of the design. Depth resolution determines the minimal depth difference that can be distinguished from the design, which is set to be the diameter of sutures used by the clients (0.07 mm, feasibility discussed in later sections and Figure 7).

To find the exact angles for the mirrors, the angle between the sensor tips and the pinhole (θ), the angle between the inner mirrors and the horizon (ϕ), and the angle between outer mirrors and the horizon (α) are taken into consideration. All angles are in radians for calculation.

In this report, the length of the inner mirrors and outer mirrors are denoted as M_i and M_o respectively. The height of each mirror h is approximated according to the width-length ratio of the camera sensor:

$$h = \frac{3024}{4032} * w \quad Eq(2)$$

where w is the total width of the final deliverable. Similarly, l is the total length of the final deliverable, and A is the cross-sectional area of the deliverable (product of width and length) for assessing the compactness of the design. All lengths are recoded in millimeters (mm), and area in square millimeters (mm^2).

Though not specified by Seal *et al.*, two additional parameters are included in our calculation. z denotes the horizontal distance between the virtual pinhole and the end of outer mirror that is closer to the central line, and this end of the outer mirrors are referred as proximal ends hereinafter. Similarly, the end of outer mirrors further away from the central line are referred as distal ends. A positive z value means that the proximal end is to the right of the virtual pinhole, and *vice versa*. Similarly, the vertical distance of the proximal end from the central line is denoted as x .

Assumptions and simplification on calculation

According to calculations from Seal's team, $\phi = \frac{\pi}{3}$ will lead to the most compact design. Therefore, this is set as a constant throughout our calculation.

Calculation for M_i

By similar triangle at the virtual pinhole:

$$\frac{f}{\eta + M_i * \cos(\phi)} = \frac{\epsilon}{2M_i * \sin(\phi)} \quad \text{Eq(3)}$$

$$M_i = \frac{\epsilon\eta}{2f\sin(\phi) - \epsilon \cos(\phi)} \quad \text{Eq(4)}$$

Calculation for θ

Adopted from Seal *et al.*,

$$M_i = \eta \frac{\sin \theta}{\sin(\phi - \theta)} \quad \text{Eq(5)}$$

Expand the sine term with angle difference equation:

$$M_i = \eta \frac{\sin \theta}{\sin \phi \cos \theta - \cos \phi \sin \theta} = \frac{\eta}{\frac{\sin \phi}{\tan \theta} - \cos \phi} \quad \text{Eq(6)}$$

Rearrange and solve for θ :

$$\theta = \tan^{-1} \frac{M_i \sin \phi}{\eta + M_i \cos \phi} \quad \text{Eq(7)}$$

Calculation for M_o

Adopted from Seal *et al.*:

$$M_o = \eta \frac{\sin \theta \sin \phi \sin(4\phi - 2\alpha - \theta)}{\sin(\phi - \theta) \sin(4\phi - 2\alpha) \sin(2\phi - \theta - \alpha)} \quad \text{Eq(8)}$$

Calculation for position of the outer mirrors (x and z)

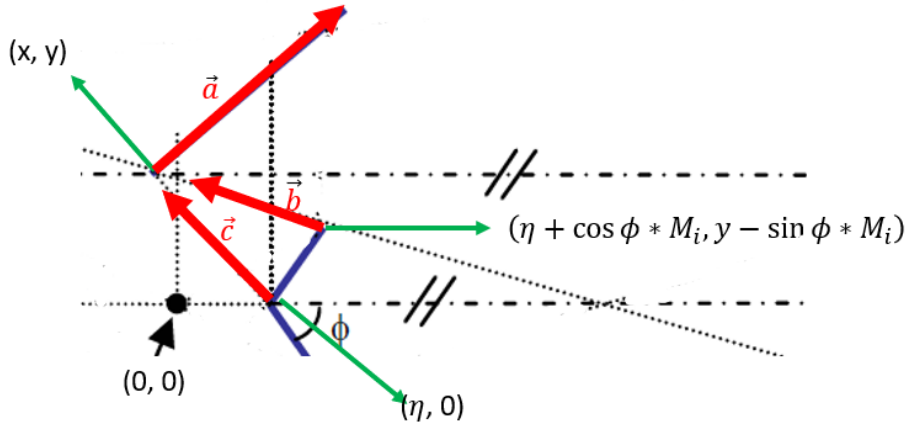


Figure 6: Zoomed view on Figure 5 about the top outer mirror. A coordinate system is set up with the virtual pinhole as the origin, positive y-direction upright and positive x-direction rightward. Note that the (x, y) coordinate is only temporarily used here due to convention of the x-y coordinate system, which are reported as (z, x) in the final results.

As is shown in the figure above, a coordinate system is setup to calculate the value for the position of outer mirror. Note that the (x', y') coordinates are used here due to convention of the

x-y coordinate system, which shall not be confused as the reported position of the proximal end (z, x).

Three vectors are labeled in the figure. \vec{a} is the outer mirror, \vec{b} is the incident light onto the outer mirror, and \vec{c} is the reflected light with direction being reversed. Three points are also labeled for calculation, the vertex of the inner mirrors ($\eta, 0$), the proximal end of the outer mirror (x', y'), and the distal end of the inner mirror ($\eta + M_i \cos \phi, y - M_i \sin \phi$). Since incident angle and reflected angle on a mirror are the same, the vectors can be related with the dot products of the vectors, where the cosine of the angle γ between vectors are the same:

$$\cos \gamma = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}||\vec{b}|} = \frac{\vec{a} \cdot \vec{c}}{|\vec{a}||\vec{a}|} \quad Eq(9)$$

To simplify the calculation, the outer mirror is reduced to a unit vector ($\cos \alpha, \sin \alpha$), and thus Eq (9) is written as:

$$\frac{(x - \eta)\cos \alpha + y \sin \alpha}{\sqrt{(x - \eta)^2 + y^2}} = \frac{(M_i \cos \phi + \eta - x)\cos \alpha + (M_i \sin \phi - y) \sin \alpha}{\sqrt{(M_i \cos \phi + \eta - x)^2 + (M_i \sin \phi - y)^2}} \quad Eq(10)$$

According to Seal's team and since ϕ is assumed to be much greater than θ ,

$$x = \eta - \frac{y}{\tan(\pi - 2\phi)} \quad Eq(11)$$

Substituting Eq (11) into Eq (10) for x and simplify:

$$\begin{aligned} & M_i \cos(\alpha - \phi) (\sqrt{m}) + (\sqrt{m})(n)y \\ & = -(n)M_i^2 - 2M_i \left(\frac{\cos \phi}{\tan(\pi - 2\phi)} - \sin \phi \right) (n)y - (m)(n)y^2 \end{aligned} \quad Eq(12)$$

where $m = \left(\frac{1}{\tan^2(\pi - 2\phi)} + 1 \right)$ and $n = \left(\frac{\cos \alpha}{\tan(\pi - 2\phi)} - \sin \alpha \right)$ to simplify the equation.

Overall size of the final deliverable (width, length, and cross-sectional area)

Observe from the Figure 5,

$$w = 2M_o \sin \alpha + 2M_i \sin \phi \quad Eq(13)$$

$$l = \begin{cases} M_o \cos \phi, & \text{if } M_o \cos \alpha \geq \eta + M_i \cos \phi \\ \eta + M_i \cos \phi, & \text{otherwise} \end{cases} \quad Eq(14)$$

Thus, the cross-sectional area of the design is:

$$A = w * l \quad Eq(15)$$

Baseline (B) of the design

Though not being a design parameter, baseline is calculated with equation provided by Seal's team for future referential purpose:

$$B = \frac{\lambda D}{fd} (D - d) \quad Eq(16)$$

5.2.2 Implementation of MATLAB Code

The MATLAB code consists of five sections. The first two sections are reserved for setting up the workspace, defining constants and initializing arrays. Two independent variables are of primary focus in the calculation: η , initialized from 0 to 100 mm with 0.5 mm increments, and α , initialized from 0 to $\frac{\pi}{2}$ radians with $\frac{\pi}{12}$ radians increment. It is worth noting that $\alpha = 0$ and $\alpha = \frac{\pi}{2}$ are unachievable angles of the design that are kept to provide comparison among different values of α . Then the relationship between the baseline size (B) and the depth resolution (d) is investigated. This section serves as a reference to decide a feasible depth resolution with reasonable size of the virtual camera system. The fourth section calculates the inner and outer mirror lengths with Eq (5) and Eq (8), and the following section calculates the overall size of the attachment, which are used to find the parameters for the most compact design.

The η and α values for the most compact possible design are determined via plots, and unrealistic values are eliminated via examination on the M_o , B and x values.

5.2.3 MATLAB Results

Baseline and Target Depth Resolution

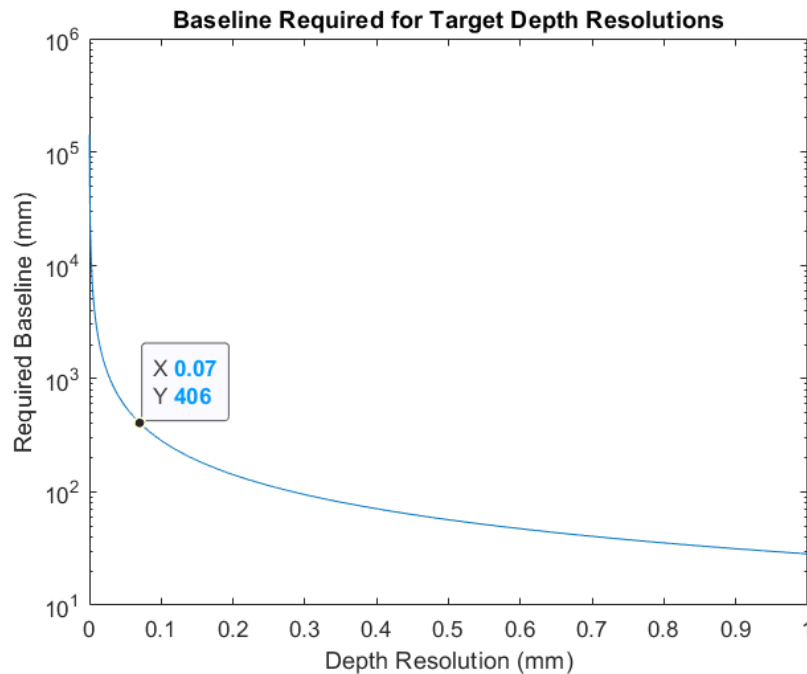


Figure 7: Baseline (B , mm) required for specified depth resolution (mm). The baseline required to have a depth resolution equivalent to diameter of the suture ($d = 0.070$ mm) is labeled on the figure.

As is shown in Figure 7, a depth resolution of $d = 0.070$ mm, which is the diameter of the 6-0 sutures, requires a baseline (B) of 406 mm. Improving depth resolution from this value will drastically increase the baseline size, and the baseline reaches plateau after the specified value for d . Therefore, setting 0.070 mm as the target depth resolution is feasible, and will thus become the value intended to achieve in the final prototype.

Distance between the Inner Mirror Vertex and the Camera Length

The distance between the inner mirror vertex and the camera length, η , is one of the independent variables in the MATLAB code. Figure 8 shows that for all angles of α except $\frac{\pi}{12}$, $\eta = 5 \text{ mm}$ is a reasonable choice of the value. Larger value significantly increases the cross-sectional area of the design, which increases the bulkiness. On the other hand, lower value of η is more likely to involve occlusion between the inner and outer mirror. Thus, 5 mm is chosen for the distance between inner mirror vertex and the camera lens.

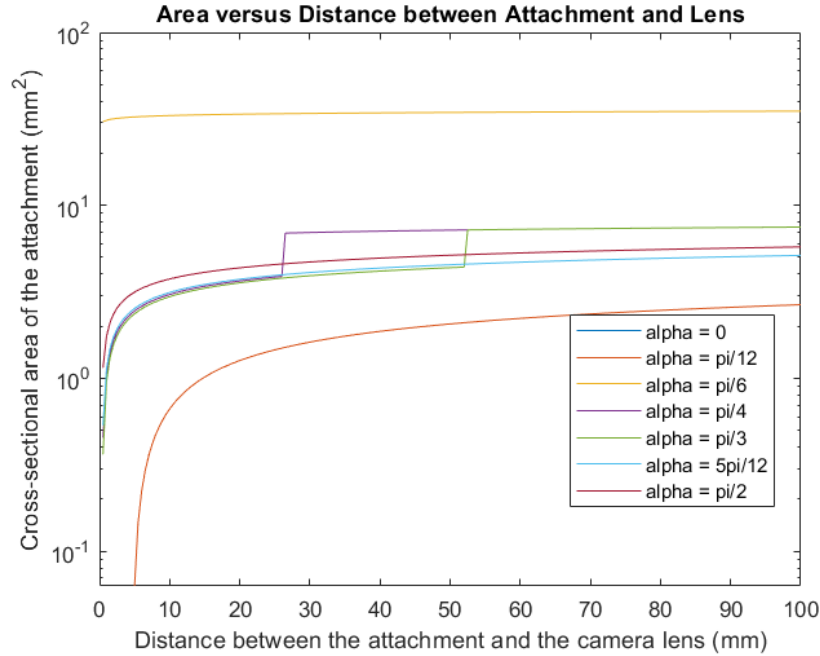


Figure 8: Cross-sectional area with varying angles of outer mirror with respect to the horizon (α , radians) and the distance between the attachment and the camera lens (η , mm). Note that the jumps for $\alpha = \frac{\pi}{4}$ and $\alpha = \frac{\pi}{3}$ result from the outer mirror length becoming more dominant in the overall length of the prototype. See Appendix B for more details. Eq (14) also provides the rationale for the piecewise characteristic.

Angle between the Outer Mirror and the Horizon

Though the angle between outer mirror and the horizon (α) appear to be optimal at $\frac{\pi}{12}$, the value result in a negative value for inner mirror length M_i . All values of α are thus tested for feasibility based on resulting lengths of inner and outer mirror, and the only realistic value is $\alpha = \frac{\pi}{3}$, which is then chosen for the final design.

5.2.4 Final Specifications from MATLAB

According to results from MATLAB calculations, η is chosen to be 5 mm and α at $\frac{\pi}{3}$ (60 degrees) is the only feasible value for the angle. With the two independent variables setup, θ is calculated as 31.65 degrees. The lengths of the inner mirror (M_i) and outer mirror (M_o) are 5.53 mm and 11.63 mm respectively. The proximal end of outer mirror is found to be 2.24 mm

horizontally (z) and 4.79 mm vertically (x) away from the virtual pinhole. The design features a field of view (FOV) for 188 mm wide, and the virtual baseline (B) is expected to be 9.57 mm. Overall, the prototype will be 29.72 mm wide (w), 7.76 mm long (l), 22.29 mm high (h , also the height of the mirrors), and have a cross-sectional area of 230.67 mm² (A).

5.2.5 Testing on the MATLAB Results with Optic Simulation

The parameters determined from MATLAB are used to create a ray tracing diagram on (Ray Optics Simulation, an open-source online simulation website developed by Tu *et al.*). Optic simulation is more advantageous than a physical test with laser pointer, since after converging by the camera lens, laser can create permanent damage on the sensor due to concentrated energy.

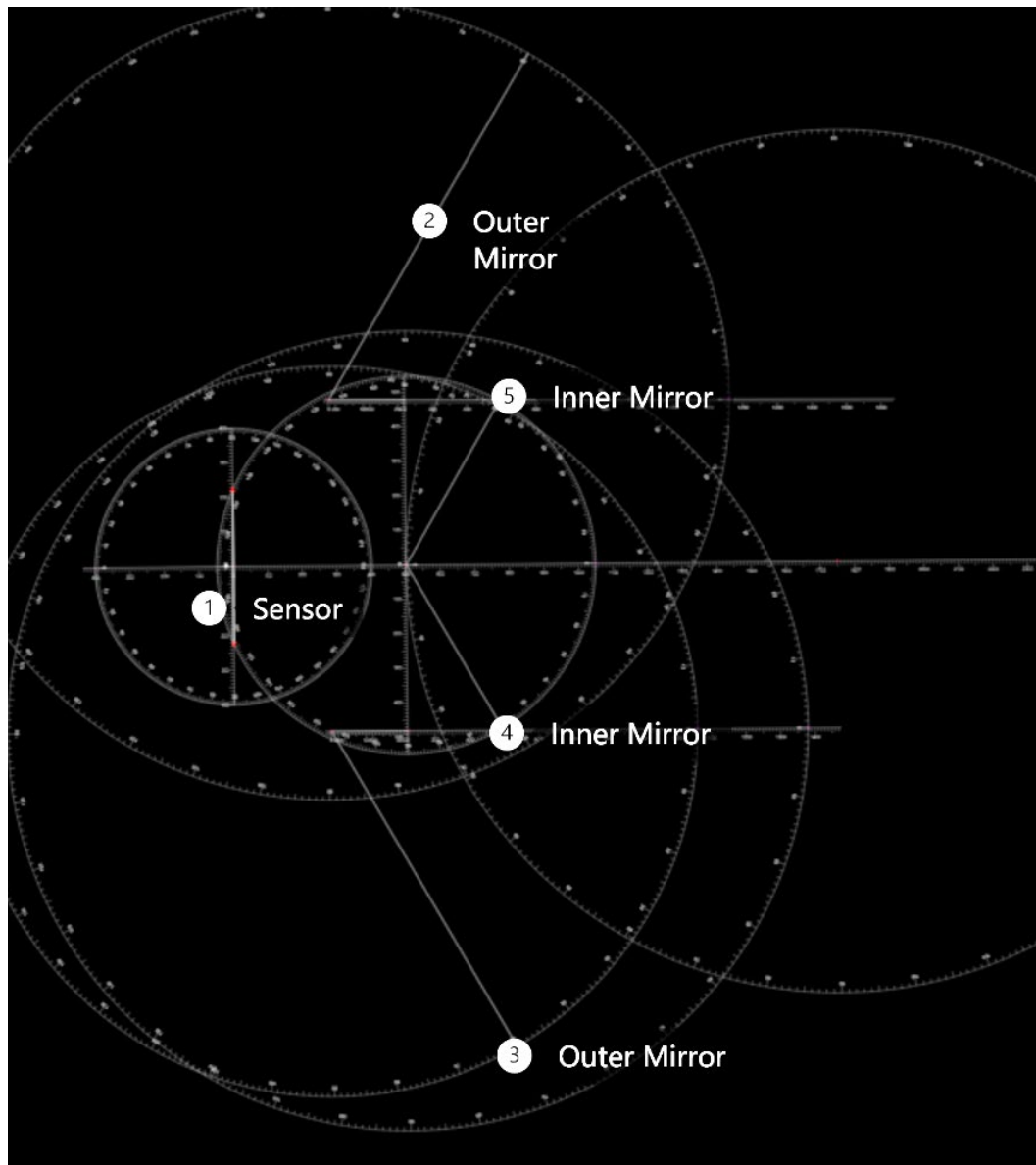


Figure 9: Optic simulation setup with the parameters obtained from MATLAB calculation, including (1) sensor of the iPhone camera, (2, 3) outer mirror, and (4, 5) inner mirror. Auxiliary lines are kept for demonstrating accuracy, with length errors less than 0.1 mm and angles less than 0.5 degrees in the simulation.

Then with the mirrors and sensor positions fixed, as is shown in Figure 10 below, light from the top (4) and bottom (5) of the FOV (left and right ends of the station if in a physical test) will shine on the outer mirror (2), being reflected to the inner mirror (3) and then is expected to form an image on the sensor (1). Since the inner-outer mirror pairs are symmetrical to the central line, only the top pair is used for simulation. However, neither ray passes through the sensor, indicating failure in the parameters determined by MATLAB. The team then decide to set up a physical experiment to test out the feasible angle and position of the mirrors, while keeping the lengths and height of the mirrors to simplify the testing protocols. If time would allow in the future, the mathematical model could be modified with protocols specified in Appendix G.

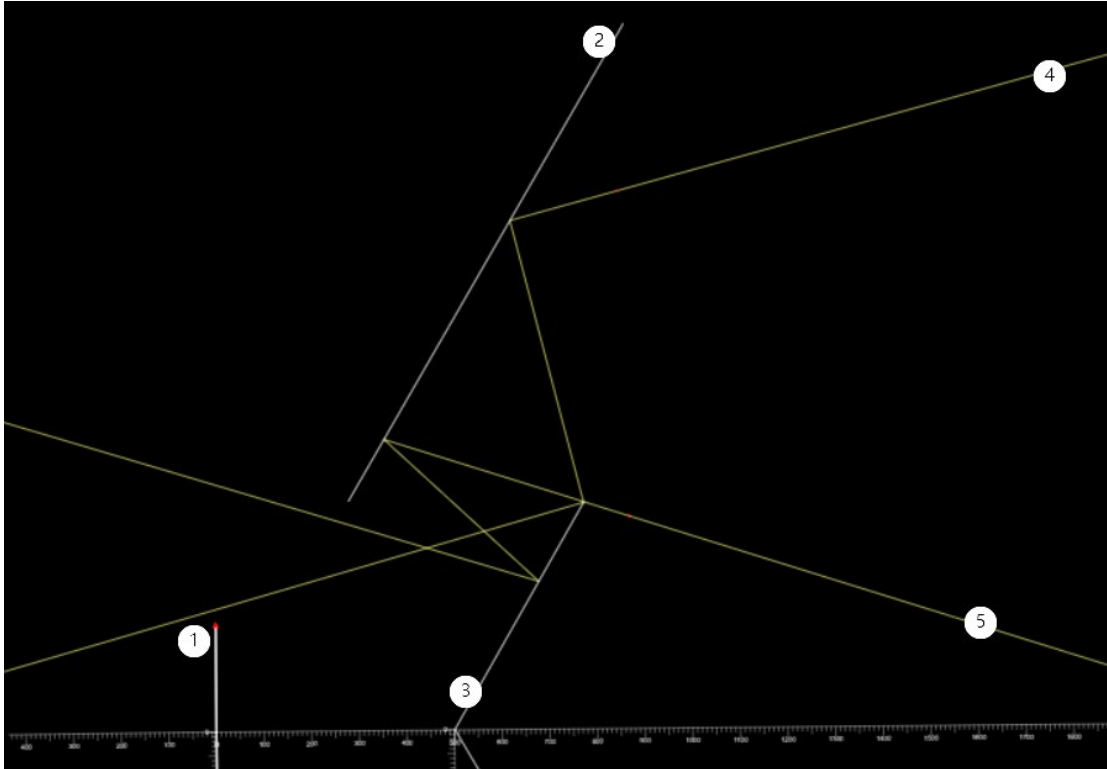


Figure 10: Ray tracing diagram for the top half of the prototype. Light from two ends of the station (4, 5) spacing at $FOV = 188$ mm will first shine on the outer mirror (2), then reflected to inner mirror (3) and is expected to form an image on the sensor (1).

5.2.6 Physical Testing for Feasible Parameters

The testing was performed as the client's lab, with testing protocols attached in Appendix C. Inner and outer mirror pieces were hand-cut from 2.54-cm-sided square mirror adhesive. The mirrors were stuck to T-shaped pins to enable free rotation for angle adjustment. An iPhone 8 was positioned to align with the mirrors horizontally, such that the camera was focused on the inner mirrors. The camera was zoomed in to have the inner mirrors fill up the screen. Image formed on the right half mirror pairs appear upright, while the left half mirror pair formed was tilted. Yet, both views were clear, and the actual FOV was measured to be 60 mm by 75 mm.

A photo was taken above the setup. Position of the smartphone and the mirrors were determined with ImageJ (Fiji package, developed by Schindelin *et al.*) based on pre-measured

paperclip for distance and angle referencing. Figure 11 below shows the photo used to measure distances and angle on ImageJ.

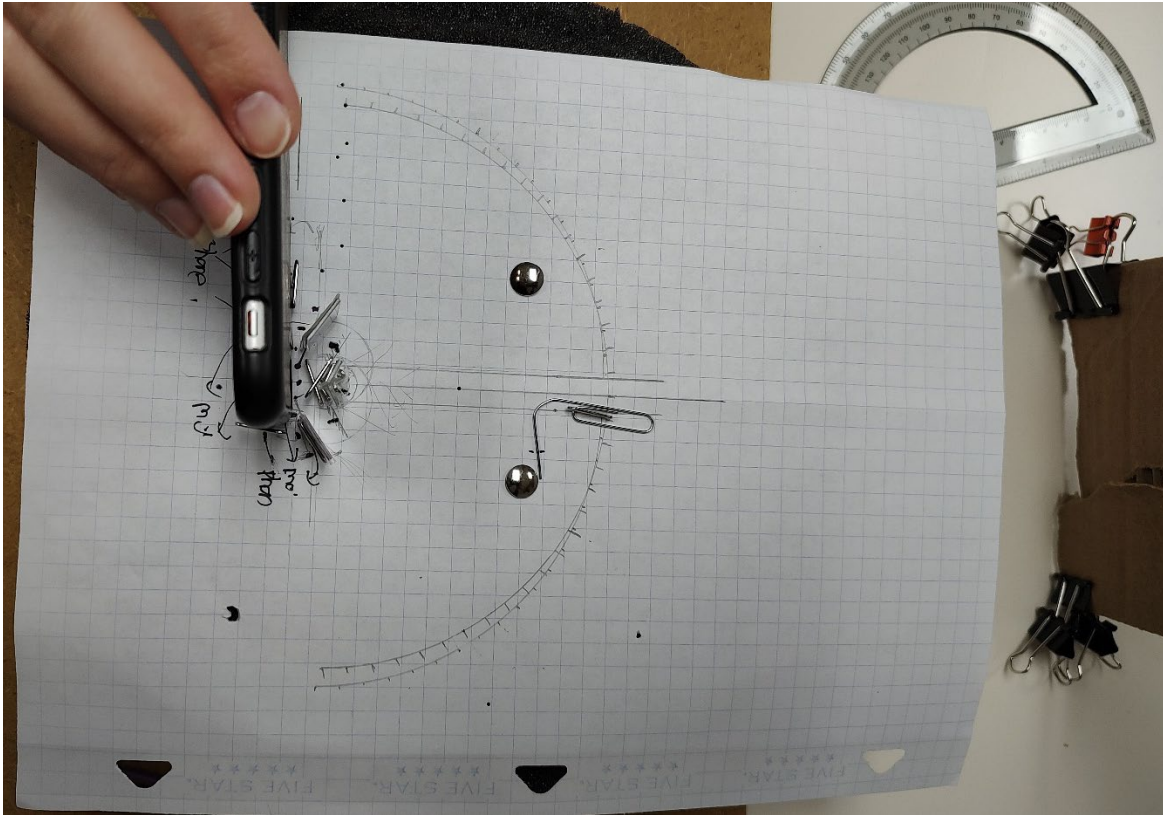


Figure 11: Photo used to measure distances and angles. The phone was positioned to the right of the mirrors, such that the camera was focused on the inner mirrors and could capture two identical views of the cardboard on the right of the photo. The diameter of the paperclip (0.70 mm) was pre-measured with a caliper and used as reference in image processing. Three horizontal lines at the center were auxiliary for angle measurement.

First, the distance between the vertex of inner-mirror-pair and the camera lens (η) was found to be 13 mm, which was much larger than the calculated value. The radius of the camera lens was measured as $r = 6 \text{ mm}$. It was found that the camera was positioned at an angle of $\beta = 94.6^\circ$ relative to the presumed central, horizontal line. As a result, though the proximal vertices of the outer mirrors (x) were both 8.4 mm vertically away from the central line, the horizontal distances and angles were different. For the top (left) outer mirror, $z_1 = 4.1 \text{ mm}$ and $\alpha_1 = 52.8^\circ$, while the bottom (right) outer mirror was $z_2 = 3.4 \text{ mm}$ away from the center of the camera lens, with an angle of $\alpha_2 = 52.1^\circ$ from the horizontal line. Similarly, the top and bottom inner mirrors were $\phi_1 = 61^\circ$ and $\phi_2 = 66^\circ$ from the horizontal line. The following figure shows the definition of updated parameters.

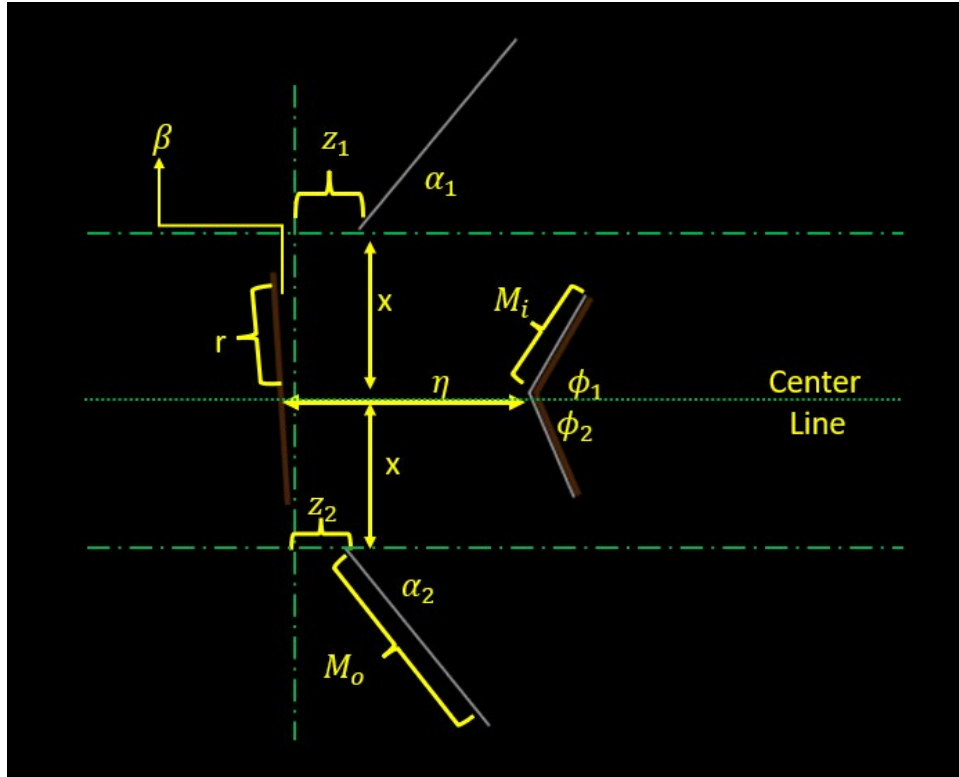


Figure 12: Parameters used for prototyping and their definitions in the final design. Values of the parameters are discussed above.

5.2.7 Fabrication of Prototypes

Two prototypes were hand-made based on the measurements from ImageJ, while adding a cardboard frame to enhance stability and to fix the position of the mirrors. Protocols for fabrication are listed in Appendix D.

The first prototype had a symmetrical design on the top and bottom half of the attachment, adopting the measurements from the right inner and outer mirrors. Sample photo taken with the first prototype is shown below, and tests with several photos showed that the images formed on the inner mirrors were never similar or identical. Thus, the first prototype was considered as a failure, and it was proved that the difference between left and right mirror pairs was indeed necessary.

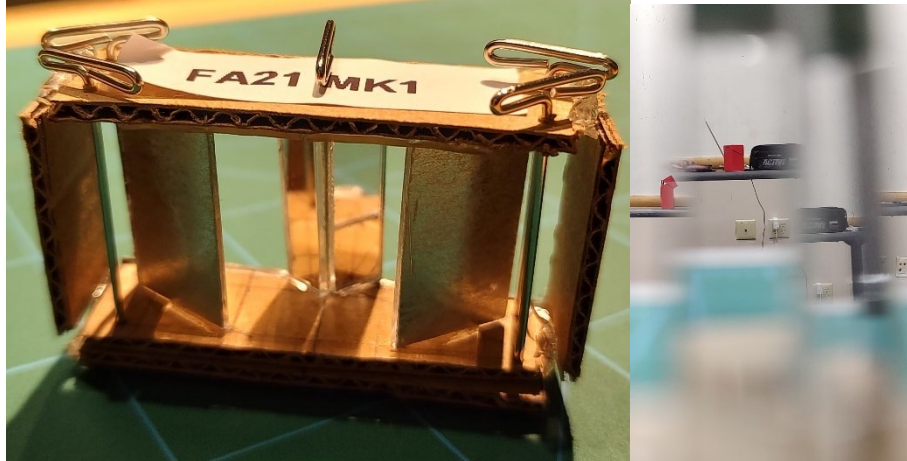


Figure 13: (Left) First prototype, featuring two inner-outer mirror pairs with symmetrical design relative to the center. (Right) Sample image taken with the first prototype, observe that the images formed on the inner mirrors are not identical.

A second prototype was fabricated with the same protocol, except that the position and angles were fully comply with the ImageJ results. A photo of the second prototype, as well as a sample image taken with the prototype, are listed in the section below. Sample photos proved functionality of the second prototype, thus this became the final prototype of the project.

5.2.8 CAD Drawing for the Final Prototype

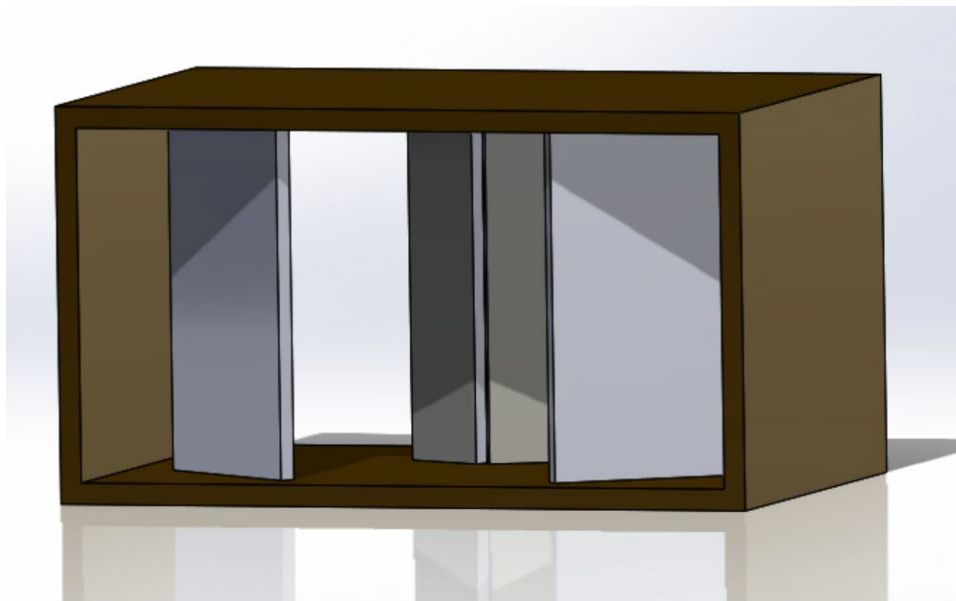


Figure 14: Final CAD assembly of prototype. Made in SolidWorks.

5.3 Final Prototype

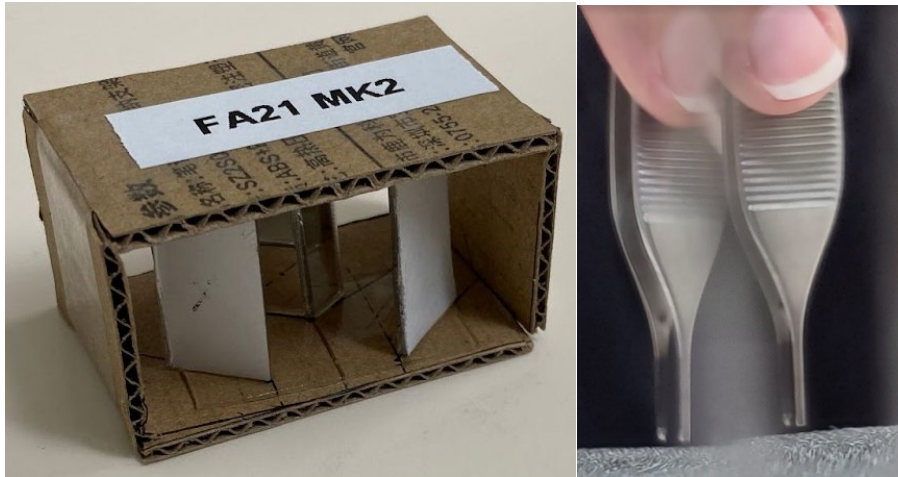


Figure 15: (Left) Second prototype (Right) Sample photo taken with the second prototype, which features slightly different angle and position of the left and right pairs of mirrors. Observe that details of the tweezers are clearly visible, and two identical images are formed on the inner mirror.

Figure above shows the prototype and a sample photo taken with the prototype, which proves the functionality. The prototype contains two pairs of mirrors arranged as follows:

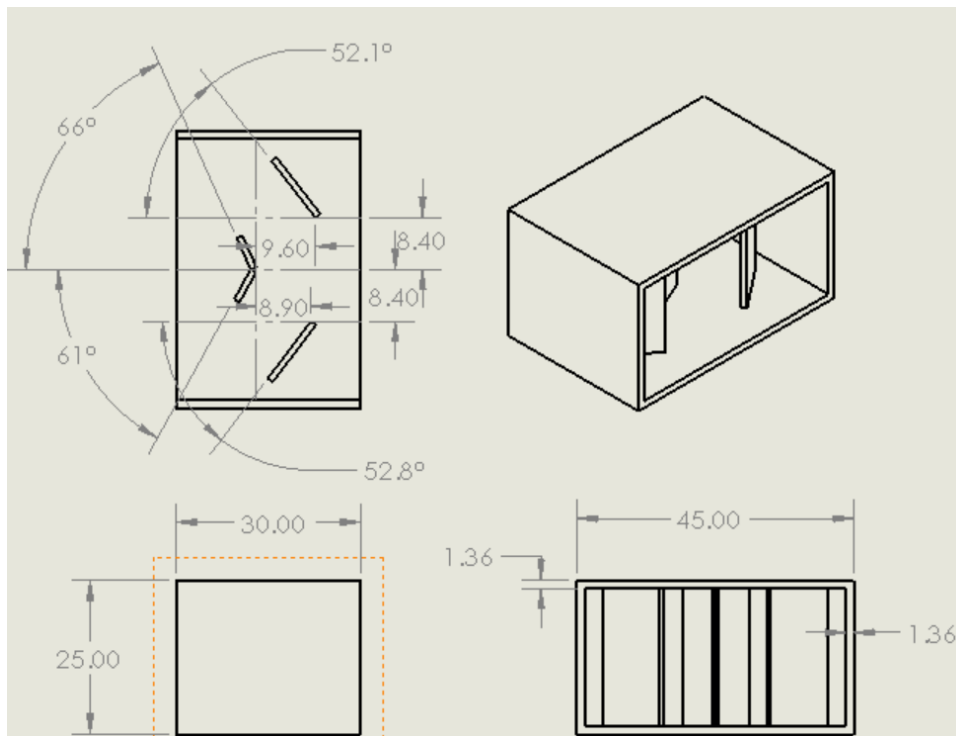


Figure 16: Mechanical drawing of prototype done in SolidWorks. Uses dimensions specified in above Figures.

5.4 Testing

5.4.1 Image Quality and Depth Perception

Resolution of the video can be assessed with image quality. Image quality was tested qualitatively by taking sample photos from the prototype, then the photo quality was determined by whether details such as texture were clearly visible on the photos.

5.4.2 Depth Perception

Being able to perceive depth perception, especially having a depth resolution close to the diameter of sutures, is an important requirement in the PDS. During the test for depth perception, all group members and a client would be tasked to move sutures with tweezers, while viewing the station with video streamed to Google Cardboard (See Appendix E for detailed protocols).

A surgical cloth was placed on a flat surface, and two 2.5-cm squares were drawn apart from each other with sharpie. The client provided 5 pieces of 6-0 sutures (0.070 mm diameter) and placed them onto one of the squares. After positioning the phone stand, the smartphone, and the prototype such that the station was clearly visible on the screen. The view was then streamed to another iPhone via Facetime (developed by Apple Inc.). The second phone, after confirming with a stable connection for the video call, was inserted to Google Cardboard for participants to wear. Each participant would move sutures from one square to another, and the time spent for the task would be recorded and compared with the results with a microscope. If the time spent on moving suture with the final prototype were close to that with a microscope, then the depth resolution from the final prototype could be considered as comparable to the microscope. Data for testing with the microscope was collected during the first client meeting for all group members. The experimental setup is shown in the figure below:



Figure 17: Testing on depth of perception by a team member. With Google Cardboard on, the member is trying to move sutures with a tweezer via the video streamlined from a smartphone with the attachment.

A test video was also created by recording a team member moving a clip from pins that are close to the camera to pins that get progressively further away. This was set up with one phone placed perpendicularly against the table. The lens was taped onto the camera lens after some

adjusting and aimed at the line of consecutive pins. This line of pins was put directly in the center of the split lens so each mirror should see it evenly. Editing the front and back labels purely for clarification of depth onto the video helped decipher between which pins should be seen as close versus far. The output of this video is displayed below, the original view and zoomed with labels.



Figure 18 Left image shows the zoomed in screenshot of a video clip moving with labels of front and back. Right shows a screenshot from the original video with no alterations.

5.4.3 Delay in Streaming

According to the PDS, time lag is defined as the “delay between image capture and streaming to the end user.” Zoom (developed by Zoom Video Communications, version 5.7.8) was chosen as the streaming software, since it was assessable by the clients and their trainees. Experimental setup included a smartphone for capturing music video playing on a monitor, which was connected to a laptop. The smartphone and the laptop joined the same Zoom video call, and an iPad pro was used for recording the monitor playing the music video, the smartphone capturing the video, and a monitor streaming the captured video. The experimental setup is shown as follows:

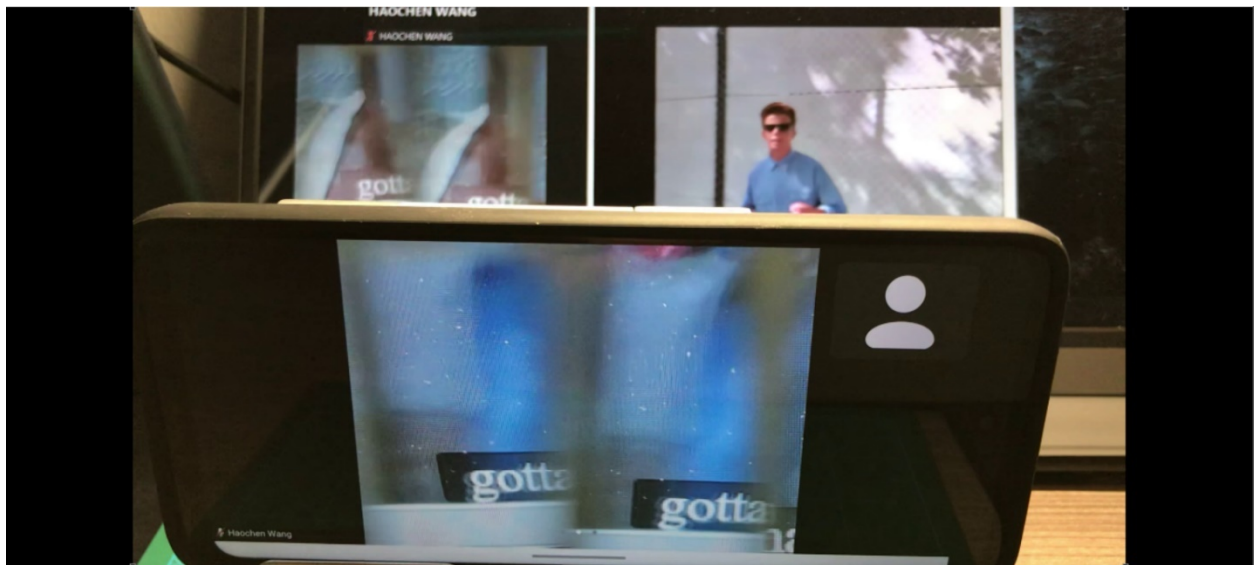


Figure 19: Measurement on the time delay between video recorded with the attachment and the streamed monitor via zoom. (Top left) Streamed video on a monitor via zoom (Top right) Music video being captured by the design (Bottom) Smartphone capturing the music video.

The recorded video was then analyzed with Kinovea (developed by Joan Charmant, version 0.9.5). Three incidences of event on the music video were chosen, and the time difference between

recorded view and the projected view would be measured and reported as an average. In this experiment, the disappearance of the first two verses of the lyrics and the emergence of the third were selected as incidences. Detailed protocol can be found in Appendix F.

5.4.4 Optic Simulation

To better evaluate the compactness and functionality of the design, the optic simulation discussed in Section 5.2.5 was performed for the final prototype. Positions of the mirrors and the camera were the same as the final prototype.

6. Results

All sample images showed texture of the material, notably for memory foams, the porous structure could be clearly captured in the photos. A blind strip was observed for all sample images, and the width was greater in the following tests for depth perception and delay measurement, which was possibly due to movement of the mirrors during transportation.

The final prototype though enabled perception on relative position of hands, the sutures were indistinguishable from the surgical cloth. There were also difficulties in having two identical views projected to the Google Cardboard, and video streamed to the left and right eyes could barely fuse into one. Thus, only two participants performed the test for depth perception, and no numerical data was obtainable from the trials. However, playback for video recorded in Figure 18 demonstrated depth difference for the front and back pins. This proved the ability to form depth perception with the final prototype, though the resolution was not high enough for the clients' intended use of microsurgery training.

Average time delay in streaming was measured as 0.21 ± 0.01 s. This was within the acceptable range required by the clients. Though the delay was greater than value reported by the previous team (0.15 s), real time video was not used for their testing. While the primary limiting factor from the measuring procedure was the external network communication from Zoom video call, using wired connection or local wireless network communication is expected to significantly reduce the time delay in the final prototype. Since raw data from last year was not available, statistical analysis was not performed on the time delay measurements.

Optical simulation below revealed that the surface area of the outer mirrors (2) and (3) was not fully utilized. The void area on inner mirror (5) explained the reason for the blind strip observed in the other tests. Though overall size of the final prototype was 2.5 cm x 2.5 cm x 5 cm, and the cost was primarily on the mirror adhesives only, there was room for improvement by decreasing the surface area of the outer mirror.

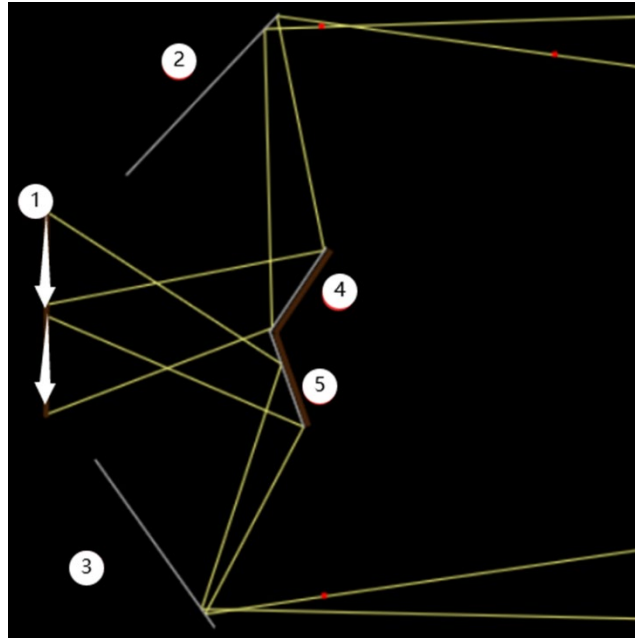


Figure 20: Optic simulation for the final prototype. Light from the subject gets reflected by the outer mirrors (2), (3) onto the inner mirrors (4), (5). Then, light will be directed through the camera lens (1), forming two identical views of the subject (represented by two upside-down arrows). Arrows will be converted upright by the camera lens. Note that surface area of mirror (2), (3) and (5) are not fully utilized.

7. Discussion

The most important goal of the design process was to create a device that creates a percept of stereoscopic/binocular vision, which allows the user to detect depth perception while viewing through the lens. This was the most important achievement obtained during the semester and a breakthrough for the team. The selling points for the prototype include its small, compact size and how inexpensive it is to produce. These differentiate it from the large microscope that is currently used for training medical students in microsurgery. By creating a small and portable device, students can practice microsurgery with a mentor from virtually anywhere in the world where there is internet access. A smartphone along with a cheap cardboard VR headset are the only materials needed in addition to the prototype (however, a stand to hold the phone is useful as well). The compactness, the cost, the minimal latency, and the depth perception aspect are the important goals that the team was able to meet this semester that move this prototype on to a step of future testing and revisions.

While the team was able to meet many important goals over the span of the semester, future work and revisions must be completed to make the prototype more marketable. The flimsy structure of the prototype makes it difficult to use without accidentally moving a mirror out of place or possibly destroying the frame altogether. A 3D printed frame for the mirrors would be ideal for keeping the prototype sturdy and easier to maintain. Another point of work includes a more ergonomic approach than wearing a headset, where a screen may be used at about the height

of a normal microscope that users can view without the need of bending over or wearing a headset. This would allow students to practice for long periods of time without becoming uncomfortable while using the device. Additionally, a shortcoming of the design was determined when the iPhone camera autofocused while using the prototype. This caused the incorrect items to become focused on the screen of the VR goggles, making it difficult to work in a continuous manner. A workaround approach that the team devised includes knobs that can rotate the mirrors on the top of the device, allowing for manual focusing and readjusting of the viewing area. This would allow people to view from different distances and angles to the workbench and would make it much easier to quickly focus on the items that the student is working with. These are all adjustments that the team has considered and are planning to work on in coming semesters.

Testing is a vital part of the design process and needs to be implemented in a manner that shows statistical inference about the device. A testing protocol was designed to give statistical evidence for the efficacy of the prototype and requires 100 medical students who practice microsurgery. Once this protocol is worked through, adjustments can be made if the efficacy of the prototype is not at the level the team is hoping. The team hopes that the efficacy of the prototype is similar to that of the alternative microscope, within a degree of the $p < 0.05$ significance level of statistical analysis. This ensures that the design is a viable alternative for practicing microsurgery and can be marketed to medical training facilities. Testing would make the overall validity of the design much more significant as well as highlight areas that the team can adjust in order to increase its efficacy.

8. Conclusions

The team's goal was to develop a device that allows microsurgery students to practice surgery without needing access to a large microscope. The client wanted the device to work using a smartphone camera because it has adequate magnification capabilities and is readily available to many students. The device would also be a lot more portable and affordable than large surgical microscopes. The client also wanted the device to allow the user to perceive depth in the image. To accomplish this, the team designed a series of mirrors mounted in front of the iPhone camera that provide two slightly different views of the subject. On the iPhone camera app, this appears as two images of the subject right next to one another. With this, the phone was put into a VR headset to allow the eyes to combine the images and perceive stereoscopic vision.

The team was able to meet many specifications that were in place for the design. A few important goals that the team achieved include the device being very small and portable, providing stereoscopic vision, compatibility with a smartphone, and a significant cost reduction from current surgical microscopes. The team also ran into issues when fabricating the design. It was difficult to make sure the mirrors were lined up according to the calculated specifications during the fabrication process. After first trying to pin the mirrors into a piece of foam, a housing was made out of cardboard which helped stabilize the mirrors slightly, leading to increased accuracy. Although the topics regarding optics and ray patterns exceeded the education of the team, and the small scale of the design made it difficult to fabricate, these challenges were overcome, and depth perception was achieved. The device may also have implications outside of the medical field as a portable and affordable way to record virtual reality video with only one sensor.

Future Work

There are many options for future work on the project. The first of these would be to increase the stability of the mirrors and the ease of fabrication. This could be done by using precise machining tools or 3D printing to create a housing for the mirrors that is fabricated to the exact dimensions needed. The mirrors would be able to fit snugly in premade slots, fixing them in place.

Devising a more natural way to view the subject is also a good option for future work. The VR headset we used to test for depth perception is not the best way to perform microsurgery. Integrating our device with an already existing stereoscopic screen or creating a new set of optics that better mimic a microscope would be the best options to improve on this.

Another option for future work is the implementation of low latency software to clean up the image that's received by the phone camera before it is sent to a stereoscopic display. This could be done by cropping or rotating the left and right images so the subject overlaps better in the VR headset or stereoscopic display. Implementing manual focus would also be important because currently the autofocus would focus on to the forceps instead of the sutures.

Testing with surgical trainees to assess the device's performance would also need to be done in the future, but the device should be better optimized before this occurs. Detailed testing protocols can be found in Appendix H.

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10. Appendix

A. Product Design Specification

Product Design Specification (PDS)

Title: iPhone Virtual Reality Training Model for Microsurgical Practice.

Henry Plamondon, Nicholas Jacobson, Mitchell Benyukhis, Haochen Wang, Kenzie Germanson, Cameron Dimino

September 24th, 2021

Updated December 14th, 2021

Function:

This training model will make microsurgical training less expensive and more accessible to a wide range of users. It eliminates the need for an expensive surgical microscope by replacing it with a smartphone. The prototype will utilize the zoom functionality of the smartphone for the surgeon to clearly see sutures and tissues up close. By using a smartphone, it is also possible to stream the training to Zoom or a similar platform so training can occur virtually. The design will minimize lag time between the recording phone and projecting device for simultaneous viewing of both the trainee and observers, while increasing spatial awareness and depth perception via binocular live video.

Client requirements:

- Must allow for depth perception with regard to where the forceps are in relation to the work site.
- Must create an image with high enough zoom and resolution to see sutures (0.070 mm in diameter) clearly [1]
- Must remain inexpensive so it is widely accessible to training surgeons.
- Must produce a streaming resolution of at least 10.2 megapixels.
- Must have a stream delay of no more than 0.5 seconds.
- Should utilize full magnification power of the smartphone.

Design requirements:

1) Physical and Operational Characteristics

a) Performance requirements:

- i) The device must be able to provide a clear image of the subject with depth perception. The device must be able to handle daily use and must be able

to handle a load of at least 400g, the weight of the heaviest available smartphones.

b) Safety:

- i) The device should be out of the way of the surgeon to prevent interference during practice. In order to achieve this, the device should be made to allow for 305mm of distance between the working site and the housing. The device also needs to be able to be sterilized in an efficient manner before and after each use.

c) Accuracy and Reliability:

- i) The device should be able to consistently maintain a magnification of 2x and the displayed magnification should be accurate with repeated trials. The device should display an accurate and clear image of the surgery area with minimal latency.

d) Life in Service:

- i) The device should withstand continued use over the duration of the training process, the longest of which can last up to 12 hours. The device's lifespan should be at least 5 years. The device should be able to withstand this use every day over its lifespan, as many different trainees may use the device.

e) Shelf Life:

- i) The device should be stored in normal interior conditions. After six months without use, a lithium-ion battery may begin to degrade. With continued use, the team would expect the smartphone to be the limiting factor for the whole design. Thus, the final deliverable should have at least one year of lifespan, which matches the lithium battery warranty provided by Apple. [2]

f) Operating Environment:

- i) The product will most likely be used in a domestic or indoor environment, so the device will not be exposed to extreme conditions.
- ii) 0-35 ° C operating temperature, - 20-45 ° C nonoperating temperature, 5-95% non-condensing, relative humidity (the specification of iPhone 8, and more restriction may be applied as other hardware is introduced to the final deliverable) [3]
- iii) The person who will use this will be the trainee, which is the person who is practicing surgery using the iPhone, and the trainer(s) who is/are watching the trainee on the headset.
- iv) Potential splash of food dye, blood, in vitro tissues, etc. [4]
- v) Components that are exposed to the operation station shall not be malfunctioned upon such splash.
- vi) Potential scratches from the surgical equipment, such as tweezers or needles.
- vii) The final deliverable should at least endure accidental damage from the aforementioned scenarios, while maintaining the resolution to recognize the suture.

g) Ergonomics:

- i) The product can involve somewhat delicate technology, such as smart phones and laptops, so the same restrictions of force that cause those devices not to be damaged or break apply here.
 - ii) For the iPhone 8, do not submerge in water greater than 1 meter and for longer than 30 minutes. [3]
 - h) Size:**
 - i) Should be able to be set up in an indoor living space (i.e. 10 x 10 sqft, approximately 3 x 3 meters)
 - i) Weight:**
 - i) Optimum weight: < 10lbs (approximately 4.5 kg). Must be easily transportable
 - j) Materials:**
 - i) No restrictions on material mechanics
 - ii) Cannot be toxic upon skin contact or inhalation
 - iii) Shall have minimal degradation resistance, such as from sunlight
 - k) Aesthetics, Appearance, and Finish:**
 - i) The color of the product should be dull so that it doesn't distract from the microsurgical practice it is intended for. The shape and form should be adjustable so that each user/consumer can place it into alternate positions to get a better and more comfortable practice for themselves. The texture of the finish should be flat and soft in order for it to be comfortable for the user and in order for it to not be a distraction.
 - ii) Should simulate the working condition of an operating room with microscopes.
 - iii) Must not interfere with the operation and training performance of the user.
- 2) Production Characteristics:**
 - a) Quantity:**
 - i) Many units will be needed so that the device can replace expensive training mechanisms for microsurgical practice for medical residents.
 - b) Target Product Cost:**
 - i) The target cost of the product is about \$100, given that the total cost of materials is about \$25. There are existing products whose costs are at least \$100,000 [5] which is drastically greater than the target cost. The prototype is a cheap alternative for medical students to use for remote training, using materials that are commonly owned.
- 3) Miscellaneous:**
 - a) Standards and Specifications:**
 - i) ISO 10936-1:2017
 - (1) Specifies the requirements for microscopes used during surgical procedures, so the team must adhere to these specifications when creating a design. However, since this prototype will be used for practice purposes, the requirements may not all apply. [6]
 - ii) Code of Federal Regulations Title 21, Volume 8, Sec. 882.4525
Microsurgical instrument [7]

- (1) The final deliverable will fall into the Class I medical device category, which is exempt from the premarket notification procedures 510(k).
- iii) Code of Federal Regulations Title 21, Volume 8, Sec. 878.4700 Surgical microscope and accessories [8]
 - (1) The final deliverable, under definition of this section, will be a Class I device. However, since the recording device in this design will be a DC powered smartphone, no more actions shall be made upon this regulation.
- b) Customer:**
 - i) The customer would prefer the delay of relaying the image to the headset to be minimized (less than 0.5 seconds).
 - ii) The quality of the camera while zooming should be clear enough to clearly see the material being worked upon. 2x zoom using an iPhone 11 Pro was tested to be the most practical. The requirement is that the trainee is able to see the suture, which is 0.070 mm [1]
 - iii) The camera should be able to show the depth of the workspace in order to help determine the distance between the instruments being utilized and the suture on the workbench. This may require the use of two lenses to allow for a binocular view.
 - iv) The device should be comfortable to wear for extended periods of time
- c) Patient-related concerns:**
 - i) As this is a device used for practice, there will be no requirements for patient confidentiality.
 - ii) Sterilization should not be an issue with regard to the camera setup. However, it may be practical to clean the headset with a wipe between uses.
- d) Competition:**
 - i) Augmented Reality (Mixed Reality):
 - (1) The Microsoft HoloLens is a very complex device which allows for similar types of practice. However, the HoloLens is much less accessible and much more expensive. This will be an alternative that is possible to use from many different remote locations. Meanwhile, mixed reality provided by HoloLens is rather redundant for the purpose of the clients. [9]
 - ii) Exoscopic Platforms:
 - (1) Zeiss, Olympus and Mitaka are well known medical device providers for exoscopes, featuring high-definition images of the field with 8x to 30x magnifying capability. However, the price varies from 0.2 to 1.5 million dollars, resulting in limited access for trainees from less developed regions [5].

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B. MATLAB Code for Investigating Optimal Baseline Value

Equations derived in Section 5.2.1 are implemented to MATLAB for calculation. Results and analysis are discussed in Sections 5.2.3 and 5.2.4.

Investigation on Optimal Specifications of the Splitting Lens Design

Haochen Wang

Version: 1.4

Date of Last Update: 12/14/2021

Update Notes:

1.4 Fixed figure labels and reset the scales

1.3: Added horizontal position of the outer mirror relative to the virtual pinhole

1.2: Fixed an error in calculating position of the outer mirror (the edge of the mirror that is closest to the camera lens). Added new algorithm discarding negative values of mirror length(s). Determined the proposed final specifications.

1.1: Fixed an error in constant definition (θ), rearranged equations to get correct values of the design. Added a new plot for $\log(\text{area})$ versus η to determine the α value resulting in the most compact design.

```
close all;
clear;
clc;
```

Initialize Constants

```
lambda = 1.22E-03; %% Width of one pixel on the sensor of iPhone8
f = 3.99; %% iPhone 8 physical focal length
D = 305; %% Target working distance, 1 foot
epsilon = 4032 * lambda; %% Width of the camera sensor
eta = 35; %% Value chosen from Seal et al.
phi = 1/3*pi; %% Value chosen from Seal et al.
theta = atan(epsilon / 2 / f);
FOV = D * tan(theta);
```

Initialize Arrays

```
alpha = 0:(pi/12):(pi/2);
% D_matrix = 0:1000;
d_matrix = linspace(0,1,5000); %% Depth resolution in mm
eta_matrix = 0:0.5:100; %% unit: mm
Mo = zeros(7,length(eta_matrix));
w = zeros(7,length(eta_matrix));
l = zeros(7,length(eta_matrix));
B_matrix = zeros(7,length(eta_matrix));
x = zeros(7,length(eta_matrix));
Mi = eta_matrix * sin(theta) / sin(phi-theta);
```

Investigation on Optimal Baseline

```
z = D - d_matrix;
B = lambda*D./f./d_matrix.*z;
log_B = log10(B);
y1 = round(B,3,'decimals');
x1 = round(d_matrix,3,'significant');
figure(1);
plot (x1,y1)
title('Baseline Required for Target Depth Resolutions')
xlabel('Depth Resolution (mm)')
ylabel('Required Baseline (mm)')
ax = gca;
chart = ax.Children(1);
datatip(chart,0.070,406.17,'Location','northeast');
set(gca, 'YScale', 'log')
```

Investigate on Outer Mirror Angle and Mirror Lengths

```
d = 0.070;
for i = 1:length(alpha)
    B_matrix(i,:) = 2*sin(2*phi-2*alpha(i))*eta_matrix ...
        *(1+sin(theta)/sin(phi-theta)*(sin(phi)/sin(2*phi-2*alpha(i)) ...
            +sin(3*phi-2*alpha(i)+sin(phi))/sin(4*phi-2*alpha(i))));
    Mo(i,:) = eta_matrix * sin(theta) * sin(phi) * sin(4*phi-2*alpha(i)-theta)...
        /sin(phi-theta)/sin(4*phi-2*alpha(i))/sin(2*phi-theta-alpha(i));
end
```

Calculate Overall Length and Width of the Attachment

```
for i = 1:length(alpha)
%   x = (eta_matrix*tan(pi-2*phi)-y)/tan(pi-2*phi);
    for j = 1:length(eta_matrix)
        syms y positive
        eqn = (cos(alpha(i))*(cos(phi)*Mi(j)+eta_matrix(j)-(eta_matrix(j) ...
            *tan(pi-2*phi)-y)/tan(pi-2*phi))+sin(alpha(i))*(sin(phi)*Mi(j)-
y)) ...
            ./ sqrt(((cos(phi)*Mi(j)+eta_matrix(j)-(eta_matrix(j)*tan(pi-2*phi)-
y) ...
                /tan(pi-2*phi)).^2 + (sin(phi)*Mi(j)-y).^2) - (cos(alpha(i)) ...
                *((eta_matrix(j)*tan(pi-2*phi)-y)/tan(pi-2*phi)-eta_matrix(j)) ...
                + sin(alpha(i))*y) ./ sqrt(((eta_matrix(j)*tan(pi-2*phi)-y) ...
                /tan(pi-2*phi)-eta_matrix(j)).^2 + y.^2) ==0;
        temp = double(subs(solve(eqn,y)));
        for k = 1:length(temp)
            if (temp(k) > 0) && (temp(k) < 50)
                x(i,j) = temp(k);
            else
                x(i,j) = -99999;
            end
        end
    end

    end
    w(i,:) = 2*Mo(i,)*sin(alpha(i)) + 2*x(i,);
    l(i,:) = max(Mo(i,)*cos(phi), eta_matrix + Mi*cos(phi));
    A(i,:) = w(i,).*l(i,);
end
```

Plot eta versus area

```
x0 = eta_matrix;
y1 = log10(A(1,));
y2 = log10(A(2,));
y3 = log10(A(3,));
```

```

y4 = log10(A(4,:));
y5 = log10(A(5,:));
y6 = log10(A(6,:));
y7 = log10(A(7,:));
figure(2);
% Jump in the plot occurs when the acutal width of the desgin becomes eta +
% Mi*cos(phi), since eta becomes larger and thus the dominating parameter
% in the width.
plot(x0,y1,x0,y2,x0,y3,x0,y4,x0,y5,x0,y6,x0,y7)

legend('show')
title('Area versus Distance between Attachment and Lens')
xlabel('Distance between the attachment and the camera lens (mm)')
ylabel('Cross-sectional area of the attachment (mm^2)')

legend({'alpha = 0','alpha = pi/12','alpha = pi/6','alpha = pi/4',...
        'alpha = pi/3','alpha = 5pi/12','alpha = pi/2'})
set(legend,...
    'Position',[0.64988094914527 0.23317459713467 ...
    0.226785717521395 0.270000006039939])
set(gca, 'YScale', 'log')

```

Further determination on the most compact design

```

figure(3);
% Jump in the plot occurs when the acutal width of the desgin becomes eta +
% Mi*cos(phi), since eta becomes larger and thus the dominating parameter
% in the width.
plot(x0,y2,x0,y3,x0,y4,x0,y5,x0,y6)
legend('show')
title('Area versus Distance between Attachment and Lens')
xlabel('Distance between the attachment and the camera lens (mm)')
ylabel('Cross-sectional area of the attachment (mm^2)')

legend({'alpha = pi/12','alpha = pi/6','alpha = pi/4',...
        'alpha = pi/3','alpha = 5pi/12'})
set(legend,...
    'Position',[0.649880949145271 0.428412692372764 ...
    0.226785717521395 0.270000006039938]);
set(gca, 'YScale', 'log')

```

Examination on calculated values

```

figure(4)
plot(x0,Mi)
xlim([0.0 100.0])
ylim([0 120])
title('Length of Inner Mirror versus Eta Values at alpha = 60 deg')
xlabel('Distance between the attachment and the camera lens (eta, mm)')
ylabel('Inner Mirror Length (Mi, mm)')

```

```

figure(5)
plot(x0,Mo(2,:),x0,Mo(4,:),x0,Mo(5,:),x0,Mo(6,:))
legend({'alpha = pi/12','alpha = pi/4','alpha = pi/3','alpha = 5pi/12'})
title('Outer Mirror Length versus eta values')
xlabel('Distance between the attachment and the camera lens (eta, mm)')
ylabel('Outer Mirror Length (Mo, mm)')
set(legend,...
    'Position',[0.652023805649549 0.258650754743244 ...
    0.226785717521395 0.157857146308536])

```

```

figure(6)
plot(x0,x(5,:))
xlim([0.0 100.0])
ylim([-100000 20000])
xlabel('Distance between camera lens and the attachment (eta, mm)')
ylabel(['Vertical distance between the outer mirror '; ...
    'and the lens(x, mm) ']);
title(['Distance between outer mirror and ']; ...
    'the lens versus eta for alpha = 60 deg']);

```

```

figure(7)
% All angles were tested, yet only alpha = 60 deg can provide a positive
% baseline value based on the restrictions
plot(x0,B_matrix(5,:))
title('Baseline versus eta for alpha = 60 deg')
xlabel('Distance between the camera lens and the attachment (eta, mm)')
ylabel('Baseline from the configuration (B, mm)')

```

Finalized Specifications

```

final_eta = eta_matrix(11) % in mm
final_lambda = lambda % in mm
final_f = f % in mm
final_D = D % in mm
final_epsilon = epsilon % in mm
final_theta = rad2deg(theta) % theta in degrees
final_FOV = FOV % in mm
final_phi = rad2deg(phi) % phi in degrees
final_d = d % in mm
final_alpha = rad2deg(alpha(5)) % alpha in degrees
final_Mi = Mi(11) % in mm

```

```

final_Mo = Mo(5,11) % in mm
final_x = x(5,11) % in mm
final_B = B_matrix(5,11) % in mm
final_w = w(5,11) % in mm
final_l = l(5,11) % in mm
final_A = A(5,11) % in mm^2
final_h = 3024/4032*final_w % in mm, height of each mirror
final_z = (final_eta*tan(pi-2*deg2rad(final_phi))-final_x) ...
        /tan(pi-2*deg2rad(final_phi))
% z: horizontal distance of the outer mirror lower edge relative to the
% virtual pinhole (negative means to the left of the pinhole)

```

C. Protocol and Observations for Testing on Most Feasible Parameters

<p>I. Purpose</p> <p>A. The protocol aims to find the most feasible parameter based on the proposed final design and the calculations</p> <p>B. While the optic simulation with software demonstrated failure in the mathematical model, the team decided to directly investigate the most optical parameters with the smartphone, with trial-and-error tests</p> <p>II. Materials and equipment</p> <p>A. Mini size square mirror adhesive (1 in by 1 in, x 50 pieces)</p> <p>B. Memory foam (x1)</p> <p>1. Size may vary, as long as it is large enough to mount the mirrors</p> <p>2. Serve as the fixation for the mirrors</p> <p>C. Ruled index cards</p> <p>D. iPhone 8 (x1)</p> <p>E. Smartphone stand (x1)</p> <p>F. Caliper (x1)</p> <p>G. Paper Clip (x1)</p> <p>1. Served for calibration in ImageJ</p> <p>H. Sharpie (x1)</p> <p>I. Protractor (x1)</p> <p>J. T-shaped/drawing pins</p> <p>K. Thumbtacks (at least 4)</p> <p>L. Graph paper with grids</p>	<p>11/19/2021</p> <p>Observations:</p> <p>II.b.: Used a larger one provided by the clients</p> <p>II.e.: not accessible during the testing, used pins to secure the smartphone</p> <p>II.j.: obtained a box of T-shaped pins</p>
--	--

<p>M. Glue and clear tape N. Scissors/knives</p> <p>III. Procedure</p> <p>A. On a piece of graph paper, draw out desired locations of mirrors based on the calculation (use the caliper and the protractor to get more accurate measurement)</p> <ol style="list-style-type: none"> 1. Also mark the horizontal center line and the horizontal lines at the proximal edge of the mirrors <p>B. Use protractor, beginning with the mirror edge proximal to the camera lens, draw rays centered at the edge with 5 degrees of increments</p> <ol style="list-style-type: none"> 1. Draw the angle references for all four mirrors <p>C. Pin the graph paper onto the memory foam</p> <p>D. Stroke the edge of mirror with the size as calculated on the notecards</p> <ol style="list-style-type: none"> 1. 5.53 mm x 22.29 mm for the inner mirrors, and 11.63 mm x 22.29 mm for the outer mirrors 2. Repeat for all four mirrors 3. Leave some extra space vertically on the notecards, such that the mirrors can be pinned onto the memory foam upon the extra space 4. Cut off the pieces <p>E. Stick the mirror adhesives to the notecard pieces prepared in D</p> <ol style="list-style-type: none"> 1. Then cut the mirrors to fit the shape of the notecards 2. CAUTION: be careful with splashing of the mirror pieces and potential cut due to sharp edges <p>F. Pin the mirrors at the desired locations with thumbtacks</p>	<p>Lower half of the Mi(2) is cracked off, thus the imaged formed on it should be trimmed for better visibility</p> <p>Measurements:</p> <table border="1" data-bbox="868 520 1230 1041"> <thead> <tr> <th>Mirror/ Position</th> <th>Width (mm)</th> <th>Length (mm)</th> </tr> </thead> <tbody> <tr> <td rowspan="3">Mi(1)/ Left</td> <td>6.38</td> <td>24.73</td> </tr> <tr> <td>6.51</td> <td>24.69</td> </tr> <tr> <td>6.61</td> <td>24.68</td> </tr> <tr> <td rowspan="3">Mi(2)/ Right</td> <td>5.51</td> <td>24.81</td> </tr> <tr> <td>5.31</td> <td>24.77</td> </tr> <tr> <td>5.63</td> <td>24.78</td> </tr> <tr> <td rowspan="3">Mo(1)/ Right</td> <td>12.62</td> <td>24.72</td> </tr> <tr> <td>12.54</td> <td>24.74</td> </tr> <tr> <td>12.57</td> <td>24.71</td> </tr> <tr> <td rowspan="3">Mo(2)/ Left</td> <td>13.09</td> <td>25.01</td> </tr> <tr> <td>13.99</td> <td>24.81</td> </tr> <tr> <td>13.08</td> <td>24.79</td> </tr> </tbody> </table> <p>Discarded the original plan, used 2-T-pins and magnet to hold the mirror stable</p> <p>Cut with scalpels (2 blades used)</p> <p>0.70 mm (flat, with marks on both sides to the measured position) 0.85 mm (vertical)</p>	Mirror/ Position	Width (mm)	Length (mm)	Mi(1)/ Left	6.38	24.73	6.51	24.69	6.61	24.68	Mi(2)/ Right	5.51	24.81	5.31	24.77	5.63	24.78	Mo(1)/ Right	12.62	24.72	12.54	24.74	12.57	24.71	Mo(2)/ Left	13.09	25.01	13.99	24.81	13.08	24.79
Mirror/ Position	Width (mm)	Length (mm)																														
Mi(1)/ Left	6.38	24.73																														
	6.51	24.69																														
	6.61	24.68																														
Mi(2)/ Right	5.51	24.81																														
	5.31	24.77																														
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Mo(1)/ Right	12.62	24.72																														
	12.54	24.74																														
	12.57	24.71																														
Mo(2)/ Left	13.09	25.01																														
	13.99	24.81																														
	13.08	24.79																														

<p>G. Fold the notecard pieces such that the extra part is on the reflective side, then pin on these white spaces</p> <p>H. Place drawing/T-shape pins on the non-reflective side to hold the mirrors upright</p> <p>I. On a stable platform, mount the phone stand such that the smartphone and the attachment are aligned horizontally</p> <p>J. Secure the smartphone to the stand</p> <p>K. Draw a line with sharpie on the paper clip, then measure the diameter (thickness) with the caliper</p> <p>L. Secure the paperclip on the memory foam, making the marked part visible from above</p> <p>M. Adhere several pieces of graph paper to simulate the desired workspace (141 mm x 188 mm)</p> <p>N. Stick the workspace to a wall</p> <p>O. Adjust the position of the memory foam, such that it is 305 mm (the desired working distance) away from the workspace</p> <p>P. Turn on the smartphone camera, adjust distance of the mirrors from the camera lens and their angles, such that two views of the same portion of the workspace present on the smartphone at x1 magnification</p> <p>Q. If the desired outcome cannot be achieved, adjust the mirror lengths by covering/lengthening the mirrors</p> <p>R. Take a picture from the iPhone 8</p> <p>S. Take a picture from the top of the setting with another phone 1. Make sure to include marked paperclip</p> <p>T. Repeat steps F-N for x2 optical zoom then for additional x5 digital zoom (total x10 magnification)</p> <p>U. Clean up the testing station</p>	<p>Working distance is estimated, not accurate. It is observed better image quality and duplication is achieved with further working distance.</p> <p>Observed working space width: Left: 3-11 cm marks Right: 6-14 cm marks Observe that the left view and right view are not perfectly aligned. Use the right half as the reference for prototyping. Measured FOV: 6 cm wide by 7.5 cm high The images appear blurry on the side and edges</p> <p>Did not adjust the zooming capability during the tests</p> <p style="text-align: center;">$\eta = 13 \text{ mm}$ (Distance between the camera lens and the inner mirror vertex)</p> <p style="text-align: center;">$r = 6 \text{ mm}$ (Radius of the camera lens)</p> <p style="text-align: center;">$x = 8.4 \text{ mm}$</p>
--	---

<p>IV. Data processing</p> <p>A. Take notes of the precision of the measuring equipment</p> <p>B. Export photos taken above the station to ImageJ</p> <p>C. Using diameter of the paper clip as reference, measure the lengths and parameters (distances) specified in the mathematical model</p> <p>D. Measure angle of the mirrors relative to the horizontal lines</p> <p>E. From the pictures taken by iPhone 8, evaluate distortion, effective area of workspace and image quality</p> <p>F. Calculate error margin in component preparation and measurements</p>	<p>(Vertical distance between the proximal edge of outer mirror and the assumed center line)</p> $z_1 = 4.1 \text{ mm}, \alpha_1 = 52.8^\circ$ <p>(Horizontal distance between the proximal edge and the assumed 0-distance base perpendicular to the center line, and the angle between the outer mirror with respect to the center line. Both values are for the left/first outer mirror)</p> $z_2 = 3.4 \text{ mm}, \alpha_2 = 52.1^\circ$ <p>(Same parameters as above, for the right/second outer mirror)</p> $\phi_1 = 61^\circ, \phi_2 = 66^\circ$ <p>(Angle between the first/left and second/right inner mirror and the central line)</p> $\beta = 94.6^\circ$ <p>(It was found that the smartphone lens is in fact tilted at this angle from the center line)</p> $Mi = 6 \text{ mm}, Mo = 13 \text{ mm}$ <p>(The length of the inner and outer mirrors)</p> <p>Caliper: +/- 1 mm Protractor: +/- 0.5 deg Ruler: +/- 0.5 mm</p>
--	---

D. Prototyping Protocols

<p>I. Purpose</p> <p>A. To specify the protocol for prototyping</p> <p>II. Material and equipment</p> <p>A. Mini size square mirror adhesive (1 in by 1 in, x 50 pieces)</p> <p>B. Cardboard box (size may vary)</p> <p>C. Smartphone</p> <p>D. Caliper (x1)</p> <p>E. Sharpie (x1)</p> <p>F. Protractor (x1)</p> <p>G. T-shaped/drawing pins</p> <p>H. Thumbtacks (at least 4)</p> <p>I. Glue and clear tape</p> <p>J. Scissors/knives</p> <p>III. Procedure</p> <p>A. Disassemble the cardboard box into several large, flat pieces</p>	<p>12/02/2021</p> <p>Observations:</p>
---	--

<p>B. On the disassembled cardboard, stroke out the position of mirrors obtained from ImageJ</p> <ul style="list-style-type: none"> • Also stroke the frame of the attachment <p>C. Cut out the cardboard pieces</p> <ul style="list-style-type: none"> • Prepare 2 side pieces and 2 base pieces in total <p>D. Prepare the inner outer mirrors</p> <ul style="list-style-type: none"> • Mark out the cutting line with a sharpie that are 6 mm (for inner mirrors) or 13 mm (for outer mirrors) away from a side • Cutoff the mirrors with a knife • BE CAUTIOUS FOR risk of being cut by sharp pieces <p>E. Attach glue pads onto the base cardboard pieces</p> <p>F. Mount the mirrors onto the glue pads, then assemble the attachment frame with tape</p> <p>G. Adjust the position of the mirrors such that the edges of the mirrors align with the reference lines</p> <p>H. Check the result with a smartphone aligned with the attachment, adjust the mirrors as necessary until two identical views can be observed from the camera</p>	<p>Prototype 1 failed: Prototype 1 adopted the right half pieces (right inner mirror and right outer mirror) and assumed symmetry in the attachment design. No identical views can be formed on the camera through camera position, camera magnification and mirror position were adjusted.</p> <p>A second prototype was made based on all measurements from ImageJ, fully adopting the camera position, angle, left and right halves of the mirror system.</p> <p>The second prototype was successful in forming two identical images, thus becoming the final model used for further testing.</p>
---	---

E. Protocols for Testing on Image Quality and Depth Perception

<p>I. Purpose To assess the image quality and depth perception from the final design</p>	<p>Day 1: 12/03/2021 Day 2: 12/06/2021 Observations:</p>
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<p>II. Material and equipment</p> <p>A. Provided by the client</p> <ul style="list-style-type: none"> • Surgical cloth • Sutures (5 pieces) • Tweezers (2 pairs) • Google Cardboard • Phone stand • Memory foams <p>B. Prototype</p> <p>C. Tapes/adhesives</p> <p>D. Retractable knife</p> <p>E. Smartphone</p> <p>F. Sharpie</p> <p>G. Software</p> <ul style="list-style-type: none"> • Zoom <p>III. Procedure</p> <p>A. Mount the smartphone onto the phone stand</p> <ul style="list-style-type: none"> • The lens should point down toward the station • The phone should be placed at approximately 305 mm away from the desk <p>B. Align the attachment with the smartphone camera lens</p> <ul style="list-style-type: none"> • Then secure the attachment onto the smartphone with adhesives <p>C. Adjust the magnification such that the inner mirrors fill up the screen</p> <ul style="list-style-type: none"> • Take sample image of an object to ensure that two identical views are formed on the inner mirrors <p>D. Draw two squares on the surgical cloth</p> <p>E. Put 5 sutures in one of the squares</p> <p>F. Use Zoom to project the view from the recording smartphone onto another receiving smartphone</p> <p>G. Insert the receiving smartphone into Google Cardboard</p> <p>H. Have each team member and the client wear Google Cardboard, using tweezers to move sutures from one square to another.</p>	<p><u>First day notes:</u></p> <p>Phone stand is not prepared Photo was taken horizontally for a tweezer, the visual quality was acceptable, all carved lines on the tweezer were captured. Hard to form two identical views from the inner mirrors, took a sample video for demo during poster presentation.</p> <p><u>Second day notes:</u></p> <p>Nicholas and Dr. Zeng tried to perform the test, yet not enough depth perception formed. Though relative distance can be determined, it is impossible to distinguish the sutures or to move them from one place to another. Due to instability of the prototype, the position and the angle of the mirrors appear to be moved. Failed to adjust them to fuse the views together when projecting to Google Cardboard.</p>
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<ul style="list-style-type: none"> a. Find the corresponding frame when the same effect is observed on the streamed video b. Subtract the time and record as time delay <p>G. Take the average</p>	<p>disappears, and the frame when the third verse emerges</p> <p>Results:</p> <p>First lyrics disappearing: 6.59 s Projected disappearing: 6.81 s Second lyrics disappearing: 11.60s Projected disappearing: 11.80s Third lyrics appearing: 12.03s Projected appearing: 12.24s</p> <ol style="list-style-type: none"> 1. 0.22s 2. 0.20s 3. 0.21s <p>Average: 0.21s</p>
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G. Protocol for Modifying Mathematical Model Used for MATLAB Codes

Note that this protocol was never performed in this semester, and it is listed for future reference.

<ul style="list-style-type: none"> I. Purpose <ul style="list-style-type: none"> A. To modify the mathematical model for parameter calculation such that the outcome fits observation B. To develop a MATLAB script such that the parameters can be customized to fit various models of smartphones II. Materials and equipment <ul style="list-style-type: none"> A. Personal computer (model may vary) B. MATLAB C. Procedure D. Import data collected from testing E. Ray Optics Simulation, a web-based simulation app developed by Tu <i>et al.</i> III. Disclaimer <ul style="list-style-type: none"> A. Mathematical model and equations are adapted from Seal <i>et al.</i> (2005) B. MATLAB code used to make initial calculation on desired parameters are developed by a team member IV. Procedure <ul style="list-style-type: none"> A. Use obtained distance data and plug back to the equations used in the MATLAB code B. Find coefficients such that the angles (α, ϕ, θ) match the observed values 	<p>Due to time limits of the project, this portion of the testing protocol will not be executed in this semester.</p> <p>The final parameters are close to the calculated results, so minor change are expected to be made in the future.</p>
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<p>C. Alter the parameters initialized in the MATLAB code, then perform a ray simulation based on the parameters to confirm feasibility of the mathematical model</p>	
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H. Protocol for Consumer Testing

Note that this protocol was never performed in this semester, and it is listed for future reference.

<p>Overall Test:</p> <ol style="list-style-type: none"> A. Draw two 2' x 2' boxes side by side on a surgical sheet B. Place 8, 1mm long, sutures in left box C. Students will use tweezers to move sutures from left box to right box D. Time will start when student picks up tweezer E. Time will conclude when student puts down tweezer <p>Test Simulations 1:</p> <ol style="list-style-type: none"> a. Collect a simple random sample of 100 first year medical students who are practicing microsurgery and split randomly into groups A and B, 50 students in each b. Both groups can practice the testing procedure using the microscope during normal training hours c. Group A is allowed to use the mirror prototype at home after normal training hours and during the weekend d. Group B is allowed to use no prototype after normal training hours, prior to the test e. After five days of training, the students will return the following week and be tested in the lab f. Allow both groups 3 attempts at the test and take average completion time and number of movements. <p>Analysis 1:</p> <ol style="list-style-type: none"> a. Record Total time to complete the task b. Record Total hand movements c. Total grade 0-100 	<p>Due to time limits of the project, this portion of the testing protocol will not be executed in this semester.</p>
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- i. Time points start at 50, and 1 point is subtracted for every second over 25 seconds
- ii. Hand movement points start at 50, and 1 point is subtracted for every movement over 16 base movements

Conclusion 1:

- a. Evaluate the scores using a Student's t-test for population means using a significance value of 0.05.
- b. H_0 : Mean value of each student's three scores in group A = mean value of each student's three scores in group B
- c. H_A : Mean value of each student's three scores in group A \neq mean value of each student's three scores in group B
- d. If our p-value for the Student's t-test using the means of each students' three scores is less than or equal to .05, we reject the null hypothesis and can conclude that there is significant statistical evidence that the means of the means of groups A and B are not the same. If the p-value is greater than .05, we have insufficient evidence to reject the null hypothesis and we can conclude that the values of the means of each group are similar.

Test Simulations 2:

- a. Collect a simple random sample of 100 first year medical students and split randomly into groups A and B, 50 students in each
- b. Group A is allowed to use mirror prototype during normal training hours
- c. Group B is allowed to use currently-used microscope during normal training hours
- d. After five days of normal training, both groups will return the following week and be evaluated using the testing method

- e. Allow both groups 3 attempts at the test and take average completion time and number of movements.

Analysis 2:

- a. Record Total time to complete the task
- b. Record Total hand movements
- c. Total grade 0-100
 - i. Time points start at 50, and 1 point is subtracted for every second over 25 seconds
 - ii. Hand movement points start at 50, and 1 point is subtracted for every movement over 16 base movements

Conclusion 2:

- f. Evaluate the scores using a Student's t-test for population means using a significance value of 0.05.
- g. H_0 : Mean value of each student's three scores in group A = mean value of each student's three scores in group B
- h. H_A : Mean value of each student's three scores in group A \neq mean value of each student's three scores in group B
- i. If our p-value for the Student's t-test using the means of each students' three scores is less than or equal to .05, we reject the null hypothesis and can conclude that there is significant statistical evidence that the means of the means of groups A and B are not the same. If the p-value is greater than .05, we have insufficient evidence to reject the null hypothesis and we can conclude that the values of the means of each group are similar.