iPhone Virtual Reality Training Model for Microsurgical Practice

BME 200/300
University of Wisconsin-Madison
Department of Biomedical Engineering
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Abstract

Microsurgery training can be expensive and it can be hard for students to access microscopes in the operating room to practice surgical techniques. The team has been tasked with creating a microsurgery training tool that works using a smartphone in order 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 able to be livestreamed so instructors can view and give feedback in real time. Also, the device should be able to produce stereoscopic video in order 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 which utilizes mirrors to achieve two different viewing angles on the subject. These two different viewing angles, when output through a stereoscopic display or VR headset, will allow the user to have 3D vision of the operating environment. The team will produce a prototype of this design and test it in the future.

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1. Introduction

1.1 Motivation

There is an ever growing need for microsurgeons, but resources available for training can be hard to access or expensive. It can be hard to get a student and teacher's schedules to line up with when a microscope is available. Especially during the COVID-19 pandemic, it is proved that virtual training is advantageous and preferred for medical students [Wang 3].

1.2 Problem statement

The team has been tasked with making it easier for microsurgery students to practice by designing a training tool that uses a smartphone lens, is capable of creating depth, and has a high quality resolution comparable to a surgical microscope.

2. Background

2.1 Surgical Microscopes

Surgical microscopes provide a view of the surgical site that has both depth and high resolution. They obtain this stereoscopic image through a series of prisms and lenses to enlarge the image while maintaining the quality [1]. These microscopes, however, are very expensive and can range anywhere from $200,000 to $1 million [2]. 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 depending on how much storage it has [3]. Although the resolution and zoom is not the exact same as that of microscopes, it is comparable enough to be used for training purposes.

2.2 Smartphone Cameras

Smartphones are widely accessible and provide flexibility for a trainee to practice anywhere they would like and therefore aren't restricted only to the location and time availability of surgical microscopes. The issue iPhones present is that they lack the depth perception that microscopes provide.

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[4].

2.4 Clients

The team's clients are Dr. Ellen Shaffrey and Dr. Samuel Poore. They are both 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, in order 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. Photo provided by clients.

2.6 Product Design Specifications

The clients specified that the final product should allow for depth perception in regard to where the trainee's hands are in the work space. Additionally the zoom capacity and resolution needs 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 professional microscopes used in the surgery room but at a fraction of the cost. Two surgical microscopes that are currently used for microsurgeries 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 [5]. 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 [6]. 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

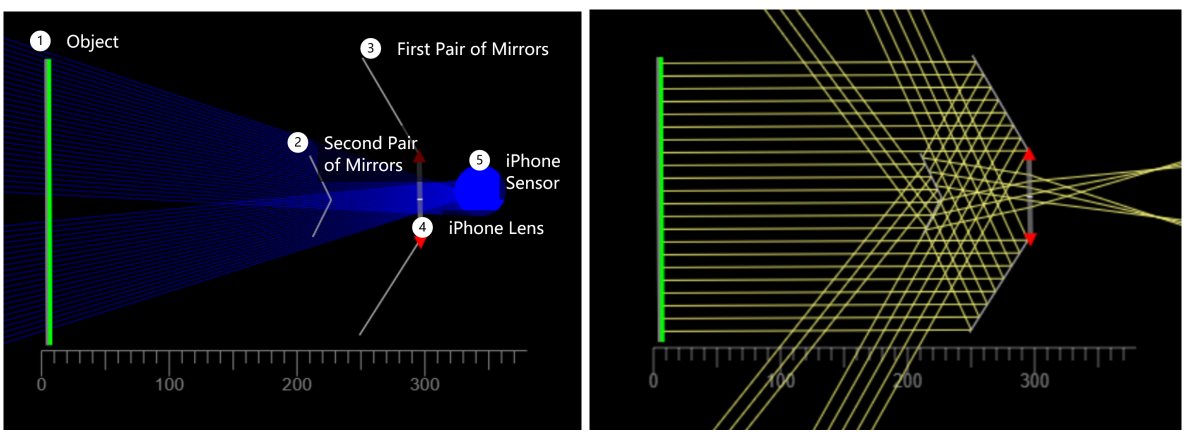

Figure 2. *(Left) Imaging tracing diagram. The light will reach (3) the first pair of mirrors then to the second pair (2), and be reflected to the smartphone lens (4). The position and dimensions of the components are not in scale and are subject to change. (Right) Ray tracing diagram from the same set 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 in order to utilize the full field of view (FOV) from the smartphone. The mirrors are a cheaper alternative to using two separate lenses/cameras as it allows the viewer to get the same 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). 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.

3.2 Complimentary Multi-Bandpass Filter

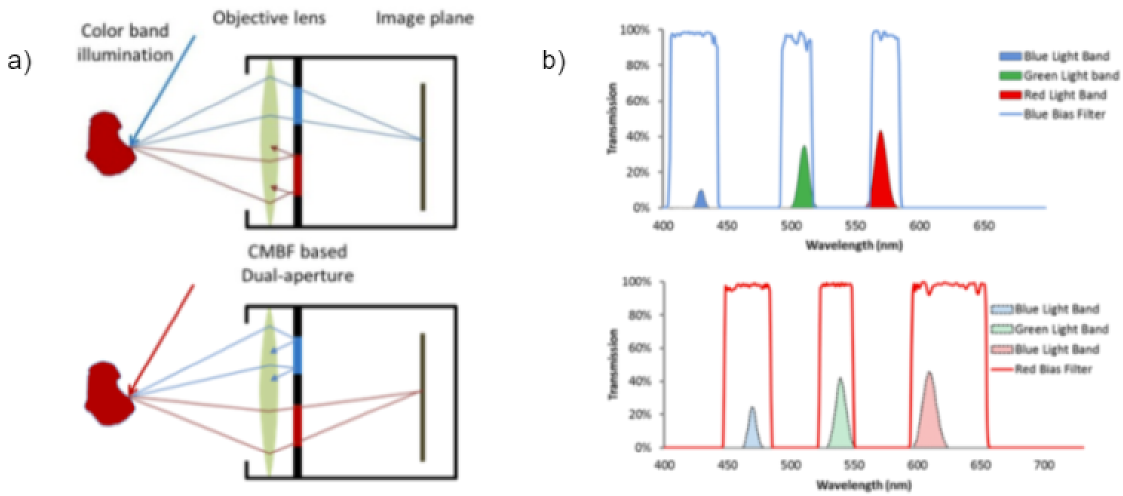

Figure 3. (a) A pair of complementary bandpass filters placed at the dual-aperture single objective lens. The scheme describes the two viewpoints made by the complementary bandpass filters. (b) An actual spectral plot of a pair of complementary triple-band bandpass filters [Wang 2]

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 [Wang 2].

3.3 Efficient Algorithm

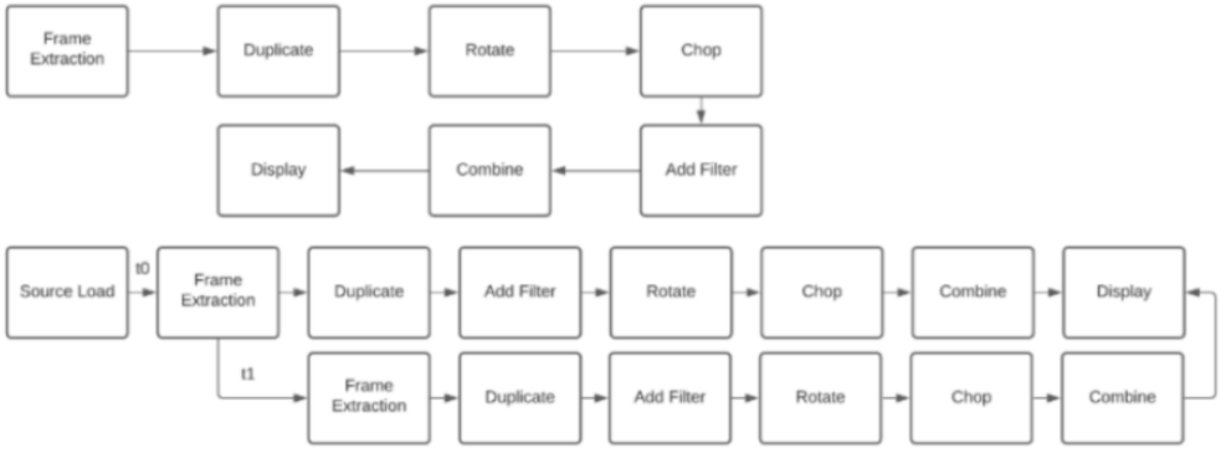

Figure 4. (Top) Original algorithm developed by the previous team. (Bottom) Proposed algorithm to enhance efficiency

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 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 criteria. 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. 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 a 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 criteria. Though all three designs utilize full resolution of the smartphone, Seal *et al.* concluded that the Splitting Lens Design resulted in image distortion [Wang 1]. 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 none distortion, which leads to the highest score assigned for the criteria [Wang 2].

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 minal interference on the trainee's practice during a 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 a 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 [Wang 2].

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 covers 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. Though cost can be reduced via mass production, the Splitting Lens Design and CMBF design consist of customized optic glasswares, 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 the majority of the risk during microsurgery practice comes from the surgical equipment (scalpers, tweezers, etc.), and since there is little to none 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, manufacture and assembly. Since cost is listed as an individual criteria, 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

The materials required for the design include an iPhone 8 and an iPhone 10 with WiFi access, a computer with WiFi access, printing paper and ink, a metal or plastic stand, and application for live viewing between the iPhone and the computer/screen. The team already possesses the iPhones necessary and the computer. The remaining materials to purchase include the stand to hold the iPhone and the paper that will be overlaid on the computer screen.

5.2 Determination on the parameters

Adopting mathematical description from Seal *et al*, the relationship between resolution and baseline magnitude is investigated [Wang 1]. Observe from figure below, that when depth resolution is smaller than the suture diameter (0.070 mm), the baseline required between two virtual cameras is exponentially increasing with a higher rate. Since higher baseline values indicate larger attachment to the smartphone, it is not worth achieving higher resolution than the 0.070 mm that is stated in the PDS.

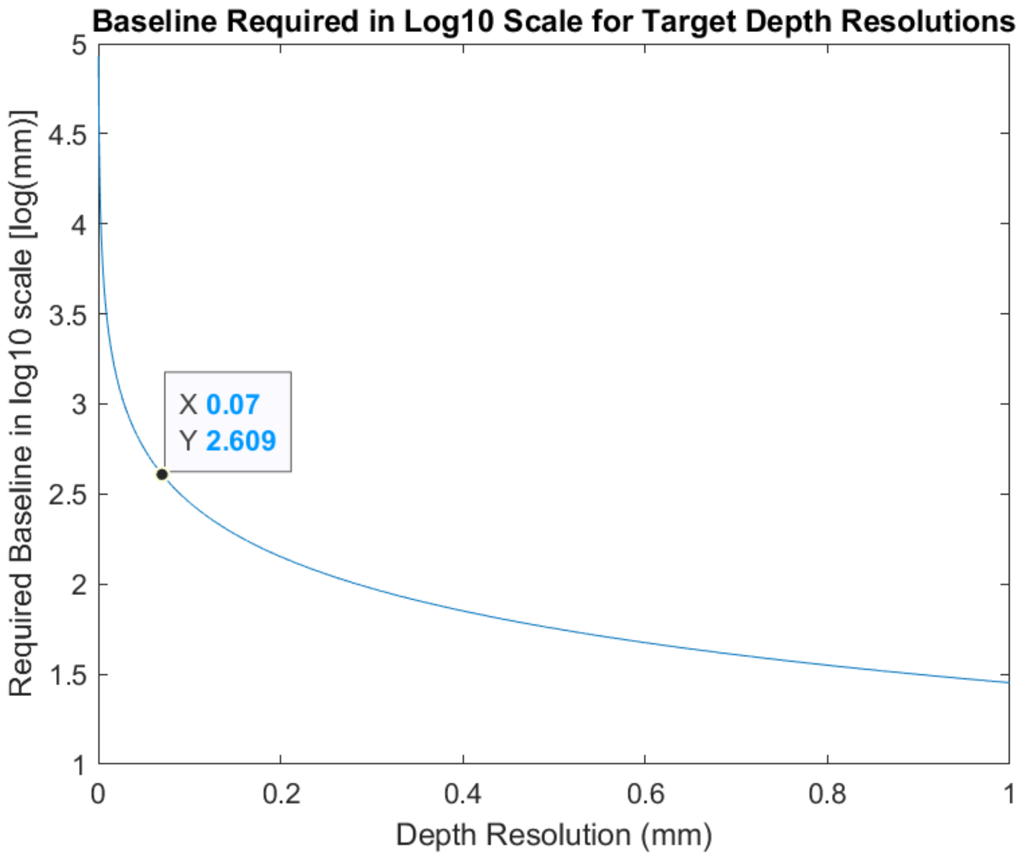

Figure 5: The baseline required (in a log10 scale) for target depth resolution. The diameter of the suture (minimal detectable size) is marked on the graph. The resulting baseline is 406 mm for the configuration Mathematical model adapted from Seal et al. [Wang 1].

Similarly, the angle and lens of the mirrors are investigated to decide on the optimal values with the most compact design possible. The equations are first derived based on results from Seal's team, and steps for derivation are shown in Appendix C. Equations are then coded in MATLAB, and the cross-sectional area of the attachment (A, mm^2) is plotted against the distance from the convex of the second pair of mirrors to the camera lens (η, mm). Several parameters are set as constant according to Seal's team, while the angle between the first pair of length and the horizontal line (α, rads) cannot be determined with the assumptions. Thus, the resulting cross-sectional area for an α set between 0 and π/2 rad is also investigated to determine the optimal angle for the first pair mirror. According to the results (Figure 5), α value of π/12 results in the most compact attachment for the proposed final design. Thus, this will be the value used for CAD drawing and fabrication. Also note that when the distance (η) is larger than 20 mm, the cross-sectional area approaches its maximum at a log10 scale. Therefore, an ideal distance between the lens and the mirror shall be less than 20 mm, and further investigation shall prove that the chosen distance does not result in occonlution. MATLAB code, assumptions for the constants and definitions on the parameters are available in Appendix B and C.

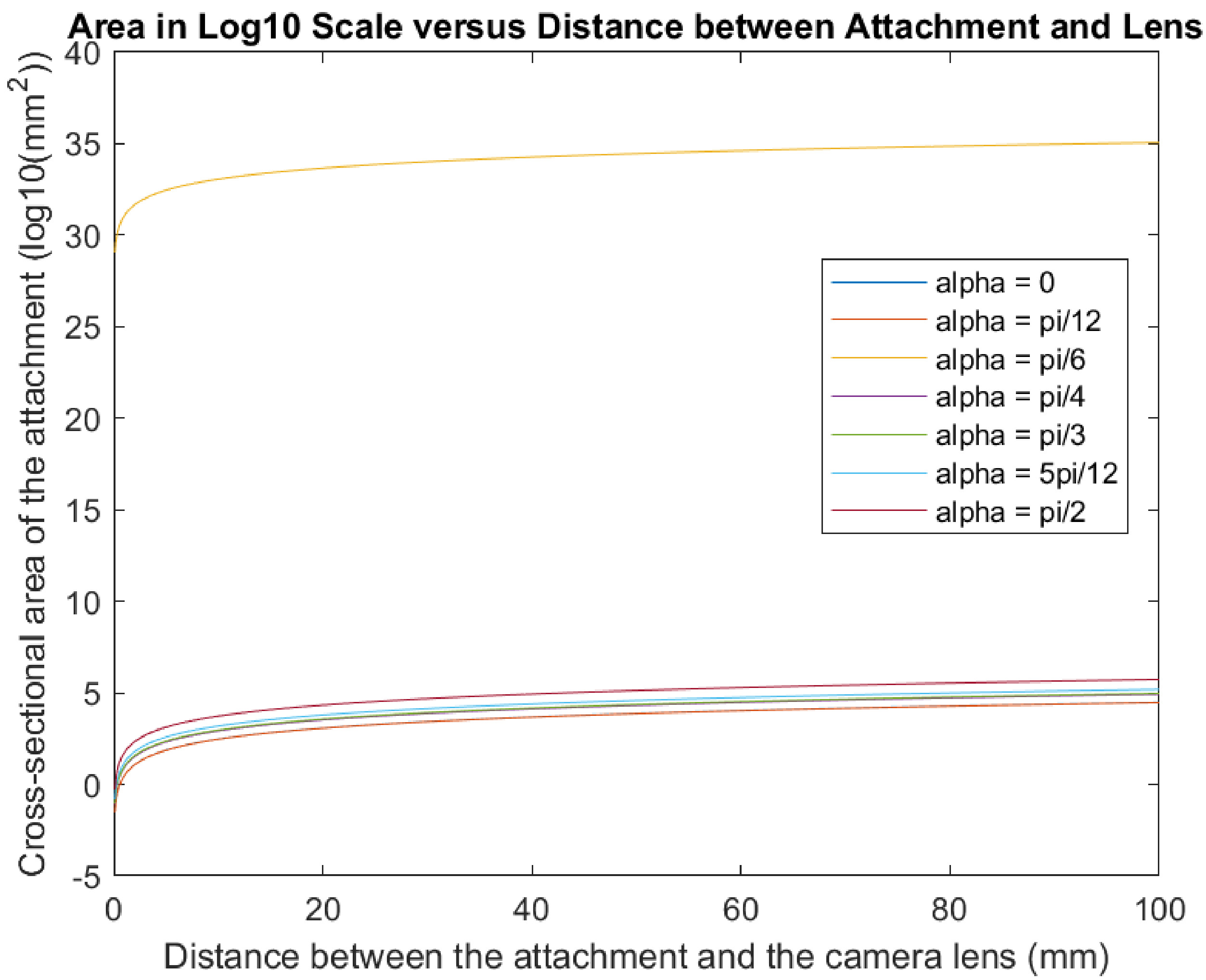

Figure 6: The cross-sectional area (horizontal plane) of the proposed final design with varying distance between the attachment from the smartphone lens. Alpha is the angle between the first pair of mirrors and the horizontal line, which is indeterminate based on current assumptions made. The figure shows that pi/12 results in most compact design, and the distance shall be kept within 20 mm from the camera lens. Mathematical model adapted from Seal et al. [Wang 1].

5.3 Methods

The team will determine the correct color pattern to print onto the printer paper in order to achieve the depth perception necessary when overlaid on the computer screen. An application will be downloaded onto the iPhone in order to share the camera view in live time with the computer screen. The stand will be used to correctly align the iPhone to view the sutures on the workbench at the correct level of zoom. The image shown from the iPhone camera will be relayed to the computer using the application that the operator previously downloaded, and the paper will be overlaid onto the screen of the computer to give depth perception.

5.4 Testing
In order to test, the team will meet back with our clients, including a microsurgeon teacher, Dr. Weifeng Zeng, at the UW hospital in the Neurology Department. The team will set up the prototype and align the camera on the workbench. The team has previously attempted a practice activity with Dr. Zeng using the microscope that is currently used for microsurgery practice. Team members will attempt this practice activity again using the prototype and will compare the amount of time taken to complete it with the original attempted practice. The activity involves moving sutures from one box drawn onto a piece of fabric to another drawn-on box using two sets of medical forceps.

Discussion

Future Work

The team will continue with the splitting lens design, which is the most feasible for the timeframe given. The materials should be relatively inexpensive and should be easy to obtain. The team will work on calculating distances, angles, etc. moving forward and will hopefully be able to soon begin purchasing materials. Following the purchase of materials, fabrication will ideally take less than two weeks and testing can begin. After comparing the results of the prototype with the results of the professional grade microscope, the team will be able to make alterations and continue to refine the prototype before the end of the semester.

Conclusions

The team has made significant progress in understanding the necessary components of binocular vision in order to successfully teach microsurgery to students. The current design has a promising outlook and the purchasing of materials, fabrication, and testing will ideally be completed within six weeks.

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Appendix

A. Product Design Specification

Product Design Specification (PDS)

Title: iPhone Virtual Reality Training Model for Microsurgical Practice.

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September 24th, 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 view 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 trainee's hands 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 in a clinical environment. 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. 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 should be able to withstand this use everyday 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 being 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 operation room with microscopes
iii. Must not interfere with the operation and training performance of the user

1. Production Characteristics

a. **Quantity:**

i. Tens of Thousands of units will be needed so that this can replace all current expensive training mechanisms for microsurgical practice for medical residents.

b. **Target Product Cost:**

i. The target cost of the product is undetermined thus far until clients discuss but it will need to allow for an iPhone, a stand, and any attachment that is necessary to put over the camera to replicate microsurgery practice as best as possible. 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.

2. **Miscellaneous**

a. **Standards and Specifications:**

   i. ISO 10936-1:2017
      - 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 many not all apply [6]

   ii. Code of Federal Regulations Title 21, Volume 8, Sec. 882.4525 Microsurgical instrument [7]
      - 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]
      - 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 for enhance practicing technique (less than 0.5 s)

   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)
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
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*

Investigation on Optimal Specifications of the Splitting Lens Design
Haochen Wang
Version: 1.0
Date of Last Update: 10/19/2021

```
close all;
clear;
Clc;
```

Initialization

```
d_matrix = linspace(0,1,5000); %% Depth resolution in mm
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
D_matrix = 0:1000;
eta = 35; %% Value chosen from Seal et al.
phi = 1/3*pi; %% Value chosen from Seal et al.
epsilon = 4032 * lambda; %% Width of the camera sensor
alpha = 0:(pi/12):(pi/2);
eta_matrix = 0:0.1:100; %% unit: mm
Mo = zeros(7,length(eta_matrix));
w = zeros(7,length(eta_matrix));
l = zeros(7,length(eta_matrix));
A = zeros(7,length(eta_matrix));
```

Investigation on Optimal Baseline

```
z = D - d_matrix;
B = lambda*D./f./d_matrix.*z;
log_B = log10(B);
y1 = round(log_B,3,'decimals');
x1 = round(d_matrix,3,'significant');
plot (x1,y1)
title('Baseline Required in Log10 Scale for Target Depth Resolutions')
xlabel('Depth Resolution (mm)')
ylabel('Required Baseline in log10 scale [log(mm)]')
ax = gca;
chart = ax.Children(1);
datatip(chart,0.070,2.609,'Location','northeast');
```

Investigate on Outer Mirror Angle and Mirror Lengths

```
Mi = epsilon * eta_matrix / (2 * f * sin(phi) - epsilon * cos(phi));
theta = atan(Mi * sin(phi) / (eta_matrix + Mi * cos(phi)));
for i = 1:length(alpha)
   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)
   w(i,:) = 2*Mo(i,:)*sin(alpha(i)) + 2*Mi*sin(phi);
   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,:));
plot(x0,y1,x0,y2,x0,y3,x0,y4,x0,y5,x0,y6,x0,y7)

legend('show')
title('Area in Log10 Scale versus Distance between Attachment and Lens')
xlabel('Distance between the attachment and the camera lens (mm)')
ylabel('Cross-sectional area of the attachment (log10(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',[0.654880949145271 0.450317454277525 0.226785717521395
0.270000006039937])
```

C. *Calculations for the parameters in the proposed final design*

C.1 Assumptions and constants set for the calculations

- f = 3.99 mm, this is the actual focal length (not the equivalent focal length) of the iPhone camera [Wang 4]
- epsilon = 4032 x 3.99 mm = 16087 mm, this is the width of the camera sensor [Wang 4]
- Lamba = 1.22E-03 mm, which is the size of one pixel in the sensor [Wang 4]. This determines the minimum depth perception in the video.
- D = 305 mm, this is the working distance (1 foot) claimed by the clients.
- Phi = pi/3 (60 degrees), this is the angle between the first pair of mirrors and the horizontal line. The value is concluded by Seal *et al*. that produces least amount of occlusion [Wang 1]

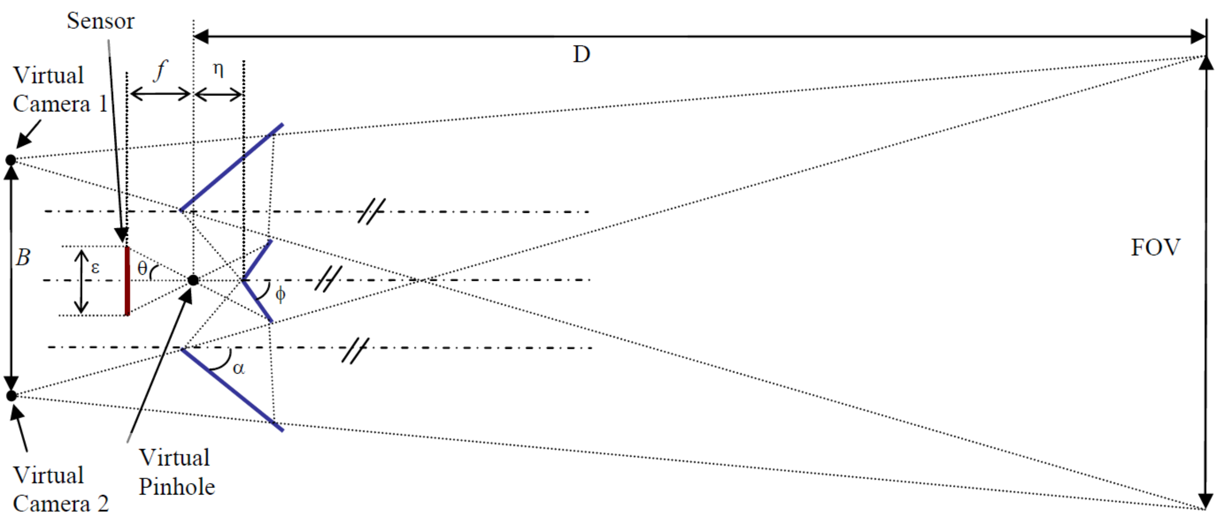

Figure x: The catadioptric system showing the position of mirrors, sensor, lens and definitions of the parameters. Adapted from Seal et al *[Wang 1].*

C.2 Formula for the Length of Second Pair of Mirrors (Mi) in Figure x

By similar triangles,

$$\frac{f}{\eta + Mi * \cos(\phi)} = \frac{\epsilon}{2Mi * \sin(\phi)} \qquad Eq(1)$$

$$Mi = \frac{\epsilon\eta}{2f\sin(\phi) - \epsilon\cos(\phi)} \qquad Eq(2)$$

Where Mi is the length of each mirror in the second pair of mirrors in mm. All other parameters are shown in the figure above. f is the actual focal length of iPhone 8 (3.99 mm) [Wang 4]. Epsilon is calculated by multiplying 4032 pixels to the length of each pixel (1.22E-03 mm) [Wang 4]. Eta is the distance between the vertex of the second pair of mirrors and the camera lens (varying from 0 mm to 100 mm with 0.1 mm increment). Phi is the angle formed between the horizontal line and one of the second-pair mirrors (pi/3 radians). These two values are adopted from Seal *et al.* for the most compact settings that have some flexibility to compensate fabrication errors [Wang 1].

C.3 Calculation on angle (theta) formed by the extended ray from the sensor that passes through the pinhole (center of the smartphone camera lens)

$$Mi = \eta \frac{sin\theta}{\sin(\phi - \theta)} = \eta \frac{sin\theta}{sin\phi \, cos\theta - cos\phi \, sin\theta} = \frac{\eta}{\frac{sin\phi}{tan\theta} - cos\phi} \qquad Eq(3)$$

$$\theta = \tan^{-1} \frac{Mi \, sin\phi}{\eta + Mi \, cos\phi} \qquad Eq(4)$$

Where theta is the tangential angle formed by the extended ray from the sensor that passes through the pinhole (center of the smartphone camera lens) in radians.

C.4 Length of the second pair of mirrors (Mo, in mm) with varying angles between the horizontal line

Adopted from Seal *et al.* [Wang 1]

$$Mo = \eta \frac{sin\theta \, sin\phi \, \sin(4\phi - 2\alpha - \theta)}{\sin(\phi - \theta)\sin(4\phi - 2\alpha)\sin(2\phi - \theta - \alpha)} \qquad Eq(5)$$

Where Mo is the length of the second pair of mirrors in mm. Alpha (in radians) is the angle formed between the horizontal line and each of the mirrors in radians. Alpha is unable to calculate directly from previous assumptions, thus is set as varying angle from 0 to pi/2 with increments of pi/12,

C.5 Overall size (length and width in mm) of the attachment from proposed final design

$$w = 2Mo\sin(\alpha) + 2Mi\sin(\phi) \qquad Eq(6)$$

$$l = \begin{cases} Mo \, cos\phi \; (Mo \, cos\alpha \geq \eta + Mi \, cos\phi) \\ \eta + Mi \, cos\phi \; (otherwise) \end{cases} \qquad Eq(7)$$

Where w is the width of the attachment in mm, and l is the length of the attachment in mm.
Thus, the area occupied in the x-y plane (horizontal plane) is:

$$A = wl \qquad Eq(8)$$

C.6 Investigation on feasible baseline size

Baseline is the distance between two virtual According to Seal *et al.*, the baseline size can be calculated as

$$B = \frac{\lambda D}{fd}(D - d) \qquad Eq(9)$$

D is the targeting working distance specified by the clients (305 mm, 1 foot), lambda is the width of one pixel (1.22 microns) on the sensor of iPhone8, f is the actual focal length (2.99 mm) of iPhone 8 [Wang 4]. d is the independent variable, which is the expected depth perception that a user can detect.