iPhone Virtual Reality Training Model for Microsurgical Practice

BME 301
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Abstract

The current method utilized to train microsurgical students entails students travelling to hospitals with access to expensive microsurgical microscopes and expert microsurgical trainers. While this is a very standard method for training medical students, it has limitations that were especially evident during the COVID-19 pandemic. While students and professors alike were quarantined, students around the globe were unable to make trips to the hospital to practice microsurgery during their medical education. Even with the uplifting of COVID-19 restrictions, travel is still expensive and time-consuming for students and can be difficult to arrange. The microscopes necessary for training are not locally available in all locations of the world and are not portable. The iPhone Virtual Reality team was tasked with creating a prototype that would allow students to practice microsurgery from their homes without the need for travelling to a location with the large and expensive microscopes currently available. This would enable students to train more often, more easily, and without the necessity for travel. The final design consists of a 3D printed housing, using Grey Pro Resin material, with small mirrors meticulously placed inside. This housing is attachable to any camera phones' lens, which makes this prototype accessible to almost all medical students globally, as most students have access to a phone with a camera in some capacity. The mirrors project two images onto the single phone lens, allowing the user to utilize depth perception, a characteristic that is not possessed by the camera lens alone. This prototype is much cheaper and more portable than the currently used microscopes with a cost of less than $15 and a size small enough to fit over a phone lens.

Table of Contents

1. Introduction

1.1 Motivation

Microsurgery is a necessary aspect of the medical field that helps to improve the quality of and extend the length of lives globally. Students practicing microsurgery must access locations where large and expensive microscopes are available, which causes problems for students in remote locations. By creating a small, portable, and inexpensive attachment to a phone's camera lens, the iPhone Virtual Reality team can provide access to microsurgical practice from any location. This will allow any student in need of training to practice microsurgery at any time that is most convenient from any location that has Wi-Fi access. This prototype can simultaneously feed the field of view to a trainer in any other location for immediate feedback and tips while practicing. This will allow teachers of microsurgery to give a similar training experience as if the student were in the same room using the current microscopes.

1.2 Problem statement

Microsurgical microscopes are difficult to access due to their large size and expensive costs. In addition, these microscopes are even more difficult to access in less developed regions. This makes it difficult for medical students to train in microsurgery from locations that are far from hospitals that have these microscopes available. Medical students are busy with many different classes and training exercises that they must complete and planning a trip to a location with these microscopes consumes a large portion of time. Creating a portable alternative to microsurgery that allows immediate feedback from teachers and other students has the capability of saving hours of students' valuable time and reduces travel costs.

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 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 are not the exact same as that of microscopes, it is comparable enough to be used for training purposes.

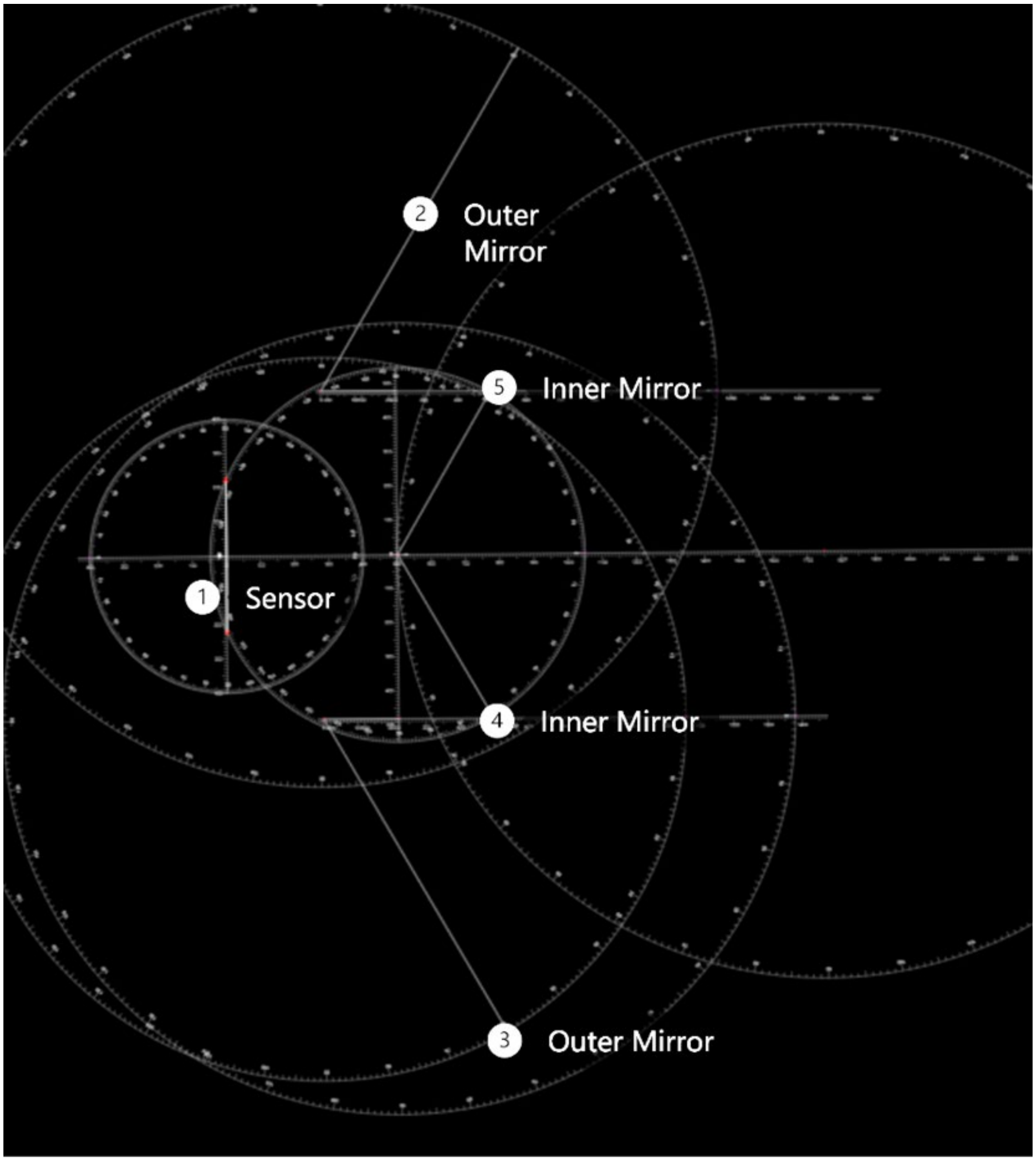

Figure 1: Optic simulation setup with the parameters obtained from MATLAB calculation, including (1) sensor of the iPhone camera, (2, 3) outer mirror, and (4, 5) inner mirror. Auxiliary lines are kept for demonstrating accuracy, with length errors less than 0.1 mm and angles less than 0.5 degrees in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

3. Preliminary Designs

3.1 Grey Pro Resin

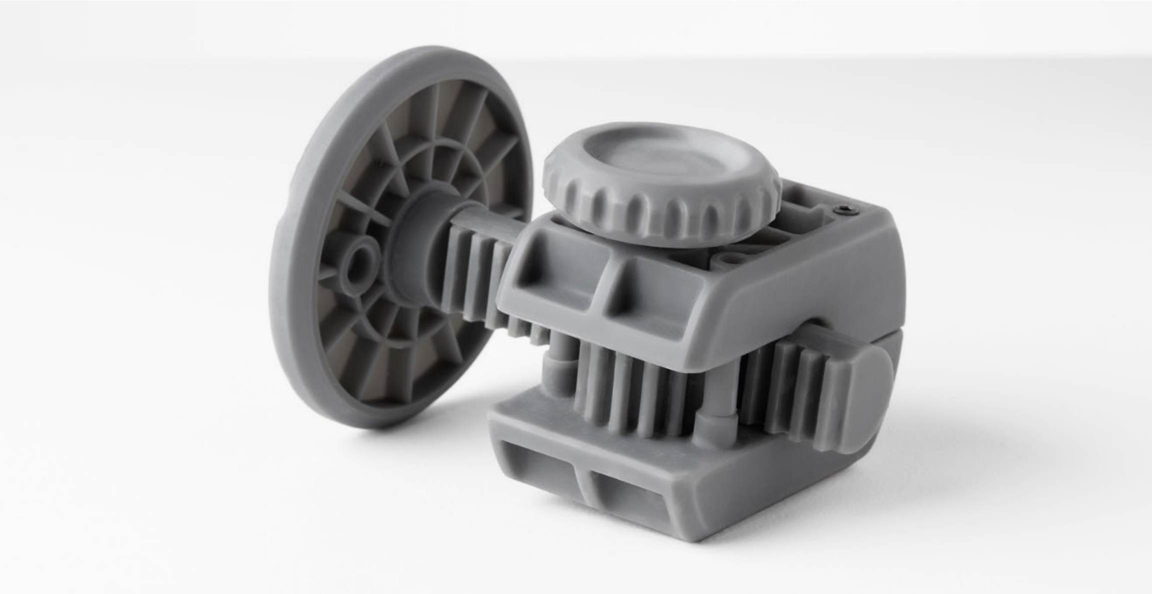

Figure 2: Example of 3D printed material, Grey Pro Resin from Formlabs[4]

The first material option for the housing of the device is the Grey Pro Resin from Formlabs. This material is available for being 3D printed at the UW Madison Makerspace. The Grey Pro Resin has a precision of 50 micrometers. It also offers a tensile modulus of 2.6GPa [4]. This strength is needed to ensure the lens does not move when in use. This material is also very inexpensive, being only \$0.26/mL especially since the attachment that will be printed is only 2.5x2.5x5cm. [5]. The Grey Pro Resin is lightweight with a density of 1.08g/cm^3 which is essential to the design as it will be used as an attachment to the iPhone [6]. A dense material could make the device difficult to use. This option is also intended for repeated use and handling and aesthetic [4]. This is ideal for the product as the attachment is intended to be used for students to practice microsurgery.

3.2 Tough 1500 Resin

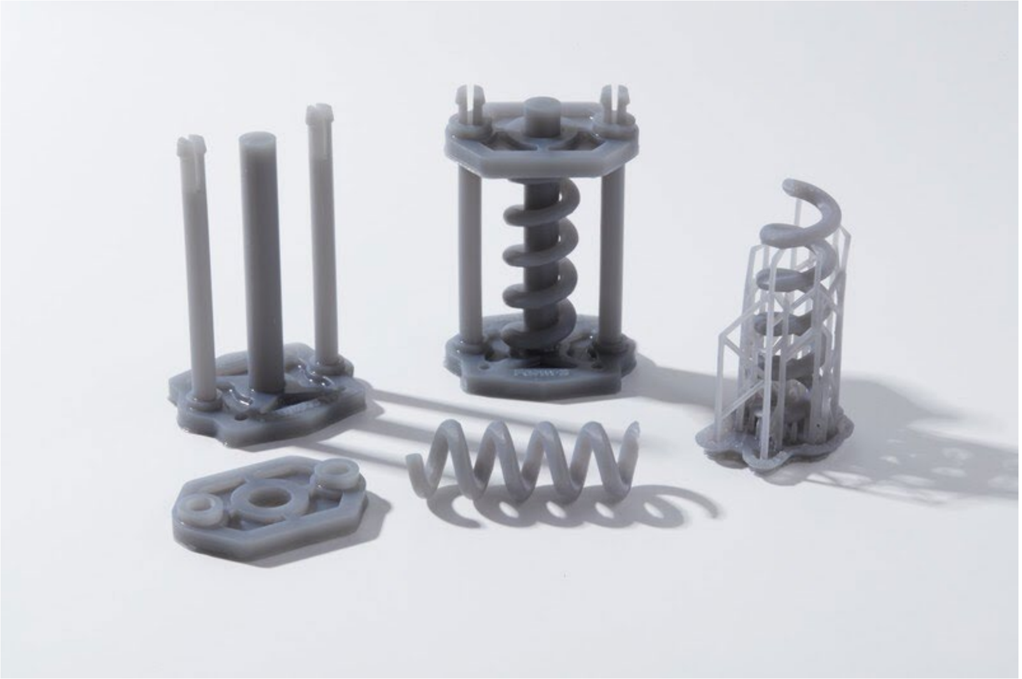

Figure 3: Example of 3D printed material, Tough 1500 Resin from Formlabs[6]

The second option for materials in the final design is also available for 3D printing at the UW Madison Makerspace. It is called the Tough 1500 Resin. This material offers the same precision as the Grey Pro Resin with 50 micrometers. However, this option has a lower tensile modulus of 1.5GPa. The Tough 1500 resin is then a pliable material and is not recommended for fine features[6]. Although Tough 1500 is not an ideal replacement to Grey Pro, the most optimal replacement being Tough 2000 with better mechanical strength, it is currently available at UW Madison Makerspace unlike the Tough 2000. This material has a similar density to the Grey Pro Resin with 1.07g/cm^3 [7]. It also has the same cost as the Grey Pro Resin.[5]

3.3 Laser Cut Acrylic

The last option is acrylic. In this option, a laser cutter would be used on a sheet of acrylic into pieces that would be attached together to create the housing of the product. The laser cutter involved is the universal laser system ILS95.150D that is available at the UW Madison Makerspace. This option gives more precision with 10.5 micrometers as this uses a laser cutter and the other materials use a 3D printer. [8] The acrylic is more expensive than the previous materials being $10.75 for a 18x25x1/8 inch sheet [9]. This material is slightly denser than the previous options, being 1.19g/cm^3. [10] The acrylic does have the largest tensile modulus with 2.8GPa which again is important to prevent the movement of the lens causing errors in the microsurgery training. [11] The biggest problem that arises with this option is that the pieces of acrylic would have to be manually attached together which gives the possibility of human error. This could alter the lens placement and in turn affect the accuracy of the training.

4. Preliminary Design Evaluation

4.1 Design Matrix

The table below shows the design matrix to select a material for prototyping. The matrix evaluates Grey Pro Resin, Tough 1500 Resin, and Acrylic according to their quality, durability, ease of fabrication, cost, stability, and safety. In Table 1, all points of analysis that receive a full score are heighted in yellow, with the highest total score in green.

Criteria		**Grey Pro Resin (Foamlab)**		**Tough 1500 Resin (Foamlab)**		**Acrylic (Laser Cut)**	
	Weight	**Raw Score**	**Score**	**Raw Score**	**Score**	**Raw Score**	**Score**
Quality (Precision)	30	4/5	24	4/5	24	1/5	6
Durability (Strength)	25	5/5	25	3/5	15	5/5	25
Ease of Fabrication	20	3/5	12	3/5	12	5/5	20
Cost	15	4/5	12	4/5	12	2/5	6
Stability	5	5/5	5	5/5	5	1/5	1
Safety	5	4/5	4	4/5	4	5/5	5
Total	100	25/30	82	23/30	72	19/30	63

Table 1: Design matrix of proposed materials. 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 Quality

Quality is determined by the precision in fabrication and assembly processes. The former refers to the printing or cutting resolution of the material, and the latter accounts for human error that may involve when assembling the prototypes. It is given the highest weight, since prototype from the previous semester was not precise enough to be tested for microsurgery training. The imprecision occurred due to errors in the location and angles of the mirrors. As material with higher precision can better achieve the goal of fixing optic parts, a higher score will be given for more precise fabrication and assembly processes. Though Grey Pro and Tough 1500 are processed at lower resolution than acrylic, the laser-cut acrylic parts must be manually assembled, which leads to more error and misalignment of the optic parts. Therefore, 4 out of 5 is given for Grey Pro and Tough 1500, and 1 is given for acrylic.

4.2.2 Durability

Durability is determined by the Young's moduli and ultimate stress of the materials. More durable material can provide better protection to the optic parts, avoiding fractures that undermine the performance of the prototype. While device performance is crucial for this project, safety concerns for the users shall also be emphasized by avoiding formation of sharp pieces from broken glassware. Therefore, durability is given the second highest weight. Grey Pro and acrylic have similar material properties, and they are given a 5 out of 5 for this category. A score of 3 is given for Tough 1500 for its lower material strength.

4.2.3 Ease of fabrication

Ease of fabrication is determined by the processing (3D-print or laser-cut) and assembling time of each material. The team is expecting to have multiple iterations of prototypes over the semester, so faster processing speed enables more prompt testing and re-design cycles. The team acknowledges that there are other factors that may be considered in this category, for example, the access of the processing equipment. However, since both 3D printers and laser cutters are less accessible in less-developed regions, access to the equipment is equally scarce for all the materials. Meanwhile, the inside of the design is hollow, and compared to manual assembly of the acrylic parts, pulling out supporting structures in 3D-printed models leads to a similar level of inconvenience during assembly. Therefore, the team only considers the processing time by 3D-printers and laser cutters in this category, and acrylic is given the highest score for the highest processing speed.

4.2.4 Cost

Cost is an important factor for the project, since as is stated in the PDS, the project aims to provide an affordable solution compared to the expensive exoscopes. Cost is not weighted as much as the first three categories, as the cost to produce our current design is similar for all three materials. Yet, cutting parts from a large acrylic board will result in more waste of the material. Thus, in consideration of cost-efficiency and sustainability, acrylic receives the lowest score for the category.

4.2.5 Stability

Stability is determined by how well the material could fix the optical parts in place upon shaking or moving. The category is weighted less, since ideally high precision processing will maximize the fixation of the optic parts. However, because optic parts will be inserted to a frame made of the materials in the design matrix, the parts will not be perfectly held at their desired locations, and movement of optic parts in the design is almost inevitable. Thus, stability is listed as an independent category of quality. It is expected that the extra space for movement of optic components will be reduced with less handcrafting during assembly. Grey Pro and Tough 1500 are given the highest score, since only one component will be made with the material; acrylic is expected to have the lowest level of stability, since more parts for the housing introduce more error in assembly, which then leads to less stability.

4.2.6 Safety

Though safety is an important factor for engineering ethics concern, all materials have similar but non-lethal health hazards during fabrication. Grey Pro and Tough 1500 are in their liquid form prior to printing, which also requires UV light to cure the material to make them tougher. Though it may be less harmful in a closed working environment, liquid irritation and UV damage are still considerably more hazardous than a truly enclosed environment for laser cutting. Therefore, 4 out of 5 is given for Grey Pro and Rough 1500.

4.3 Final Design

After evaluating the materials against PDS and proposed criteria, Grey Pro receives the highest score, which thus becomes the choice of material for fabrication.

The final design involves one pair of mirrors in an attachment for the smartphone. Light emitted from the object forms a direct capture and a reflective capture of the same object. For the direct capture, light emitted from the top and the bottom of the object passes through the space between the mirrors, forming a right (top) view of the object on the sensor. For the reflective view, light emitted from the object will first arrive at the outer mirror, then being reflected to the sensor by the inner mirror. These two captures form two images of the same object, each from a slightly different viewing angle with respect to the original object. This difference in angle of view enables the depth perception of the user.

The images formed on the sensor will be then projected to another display device. For this semester, we use Zoom to display the view captured by our design onto a second smartphone, which is inserted in Google Cardboard. Google Cardboard has converging lens that can merge these two captures into one.

Figure below shows a ray-tracing diagram from optic simulation.

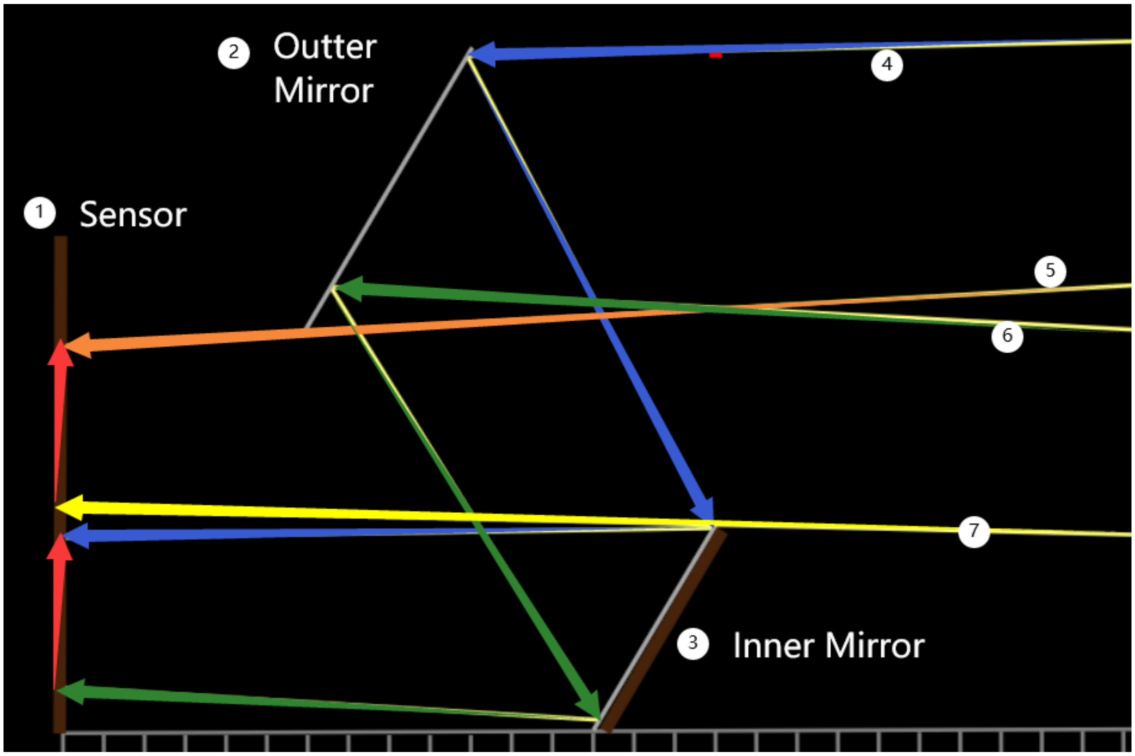

Figure 4: Ray tracing diagram of the final design. The top half of the camera sensor ① receives light emitted from the original object- an upright red arrow (omitted in the figure) at 200 mm away from the sensor, and the bottom half receives reflected light from the inner mirror ②. Light reflected onto the inner mirror comes from the outer mirror ③. Rays ④(blue) and ⑤(orange) show light path emitted from the top of the object, while ⑥(green)⑦ (yellow) show light path from the bottom of the object. These paths eventually form two identical images (two upright, red arrows) on the camera sensor.

5. Fabrication/Development Process

5.1 Materials

The materials used in this prototype include the 1x1 mirrors and 3D printed material that was evaluated in the design matrix. The mirrors are used to reflect and split the image into stereoscopic vision. The housing consists of Grey Pro Resin from Formlabs which is a 3D printing material that was determined to be the best for the purposes of this design.

Component	Use	Cost
Grey Pro Resin	Housing	$4
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

Appendix B shows how the final design evolves since the final design in Fall 2021. The team adopts a 2-mirror design as the final design for this semester, and the details for the design are presented in the following sections.

5.2.1 Variables and Definitions

Figure below illustrate the definition of the symbolic representation of the parameters. Based on measurements from previous semester, the approximated radius of camera lens is $r = 6mm$.

The lengths of the outer mirror and the inner mirrors are M_o and M_i respectively. The nomenclature is adopted from last semester, where light emitted from the object first arrives at the outer mirror, then gets reflected to the inner mirror, and finally arrives at the camera sensor. In this 2-mirror system, the outer mirror is the larger one that first receives the light from the object, and the inner mirror is the one which the sensor captures the reflect view from.

The mirrors form an angle with respect to the horizonal central line, which locates at the center of the camera lens and is perpendicular to the plane of the lens. The angles are denoted as α for the outer mirror and ϕ for the inner mirror.

The locations of the mirrors are all labeled with the distance of their tips that are closest to the camera lens. Using the same parameter definitions as in previous semester, the inner mirror has η as the horizontal distance and x^* as the vertical distance from the camera lens. The asteroid stands for x^* being a new parameter for this new final design. As for the outer mirror, the horizonal distance is z, and the vertical distance is denoted by x. All values are positive, and the relative locations with respect to the camera lens are shown in the figure below.

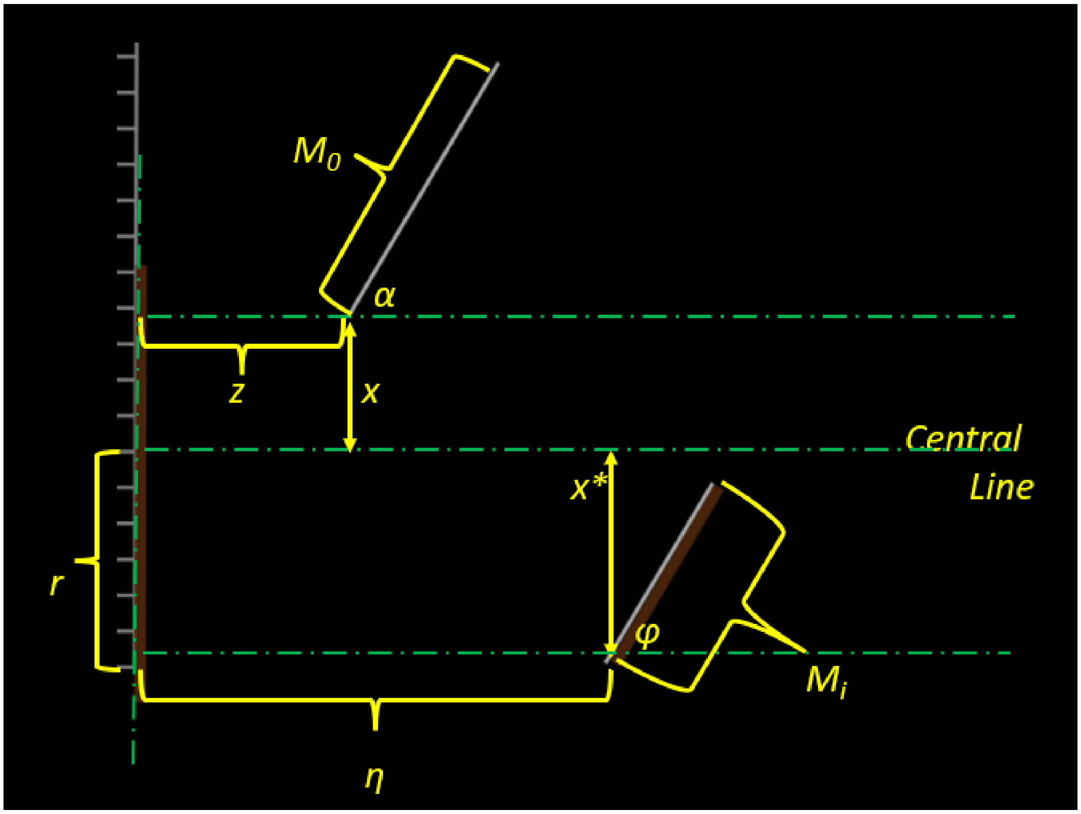

Figure 5: Parameters used for prototyping and their definitions in the final design. Values of the parameters are discussed above. The green dotted lines are horizonal and vertical reference lines.

The height of the mirrors, though now shown in the figure above, are all set to $h = 25\ mm$, which is the size of the unprocessed mirror pieces used and the values are used to simplify the fabrication processes.

The table below summarizes the parameters and their definitions:

Part(s)	Symbol	Verbal definition
Camera Lens	r	Radius of the camera lens
Inner Mirror(s)	M_i	Length of the inner mirror
	ϕ	Angle of the inner mirror with respect to the central line
	η	Horizontal distance from the lens
	x^*	Vertical distance from the centra line
Outer Mirror(s)	M_o	Length of the outer mirror
	α	Angle of the outer mirror with respect to the central line
	z	Horizontal distance from the lens
	x	Vertical distance from the central line
All Mirrors	h	Height of the mirrors

Table 2: Overview of the parameters and their definitions

5.2.2 Optic simulation to determine starting point

The team test out the mirror angles and their positions with Ray Optics Simulation, an online simulation tool developed by Yi-Ting Tu, based on the final design from Fall 2021 shown in Appendix B.1. And here we refer the final design from last semester as “the previous design.”

To simplify the simulation and fabrication process, the team first fix the horizontal position and the length of the inner mirror from the previous design. Since for one, the length (M_i) and horizontal distance (η) are calculated for the previous design and were proved to work. Meanwhile, parameters from both the inner and outer mirrors are independent variables. Fixing one mirror can dramatically reduce the workload. In addition, the team move the sensor position upward as shown in Figure 5

Beginning with 6 mm and 12 mm for the inner and outer mirror lengths (M_i and M_o), the team gradually rotate the mirrors. The rotation is achieved by increments of 5 degrees between 0 and 90 deg, and we find that the area on the sensor is best utilized when both mirrors are at 60 degrees with respect to the central line (α and ϕ). The team then move the outer mirror upward and rightward by steps of 1 mm, until the outer mirror can form a view that fully occupied the inner mirror. The team then reduce the lengths of the mirrors, until the outer mirror is fully utilized. Figure below shows the simulation in progress.

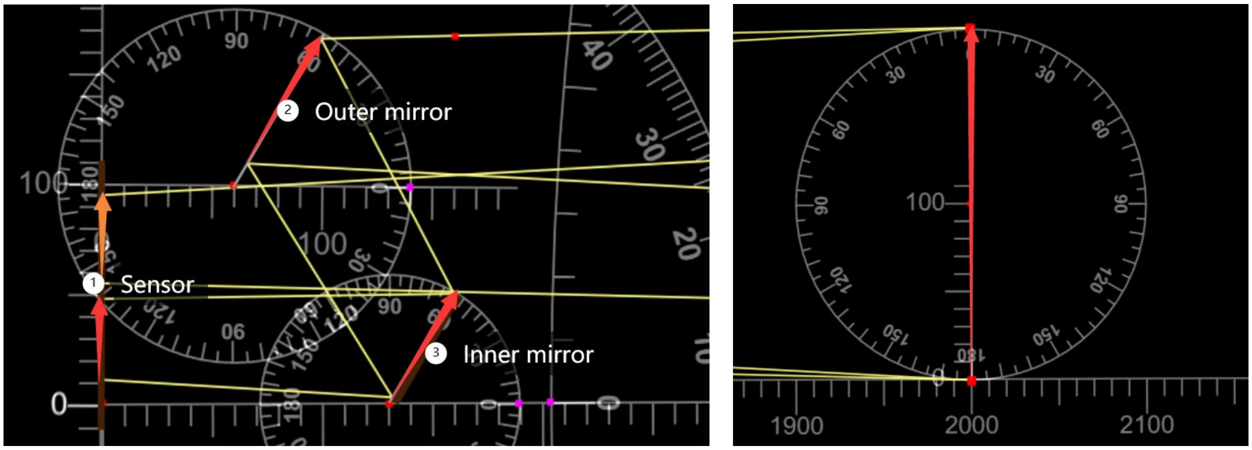

Figure 6: (Left) Light emitted from the red arrow forms an image represented by a red arrow on the left half (bottom half) of the camera sensor ①. The image shall full occupy the inner mirror ② and utilizes most length of the outer mirror ③. The direct capture is represented by an orange arrow on the camera sensor. (Right) The original red arrow project placed at 200 mm away from the sensor. Unit of rulers: 0.1 mm; Unit of protractors: 1 degree.

Simulation results show that the inner mirror was $M_i = 6\,mm$ long, $\eta = 13\,mm$ horizontally away from the lens, and $x^* = 5\,mm$ vertically with respect to the central line. The outer mirror was $M_o = 8\,mm$, with $z = 6\,mm$ being the horizontal distance and $x = 5\,mm$.

The radius of the camera lens was previously measured as $r = 6\,mm$, and the height of the mirrors is kept as $h = 25\,mm$ to simplify the fabrication process. We then convert the simulation results to a prototype that allows free rotation of the mirrors, as shown below, to account for differences in the camera lens among different models of smartphones.

5.2.3 Prototype Based on The Optic Simulation Results

The prototype shown below consists of four holes (d = 1.5 mm) that extrude through the top, while penetrate 1 mm on the base. Therefore, when inserting a T-shape pin to a hole from the top, the base of the prototype can hold the tip of the pin in place. After sticking mirror pieces onto the pins, this design allows free rotation of the mirror about the axis of their midpoint. And two sets of the pins allow shifting between the inner mirrors on the left and on the right. This is the prototype that the team printed for testing.

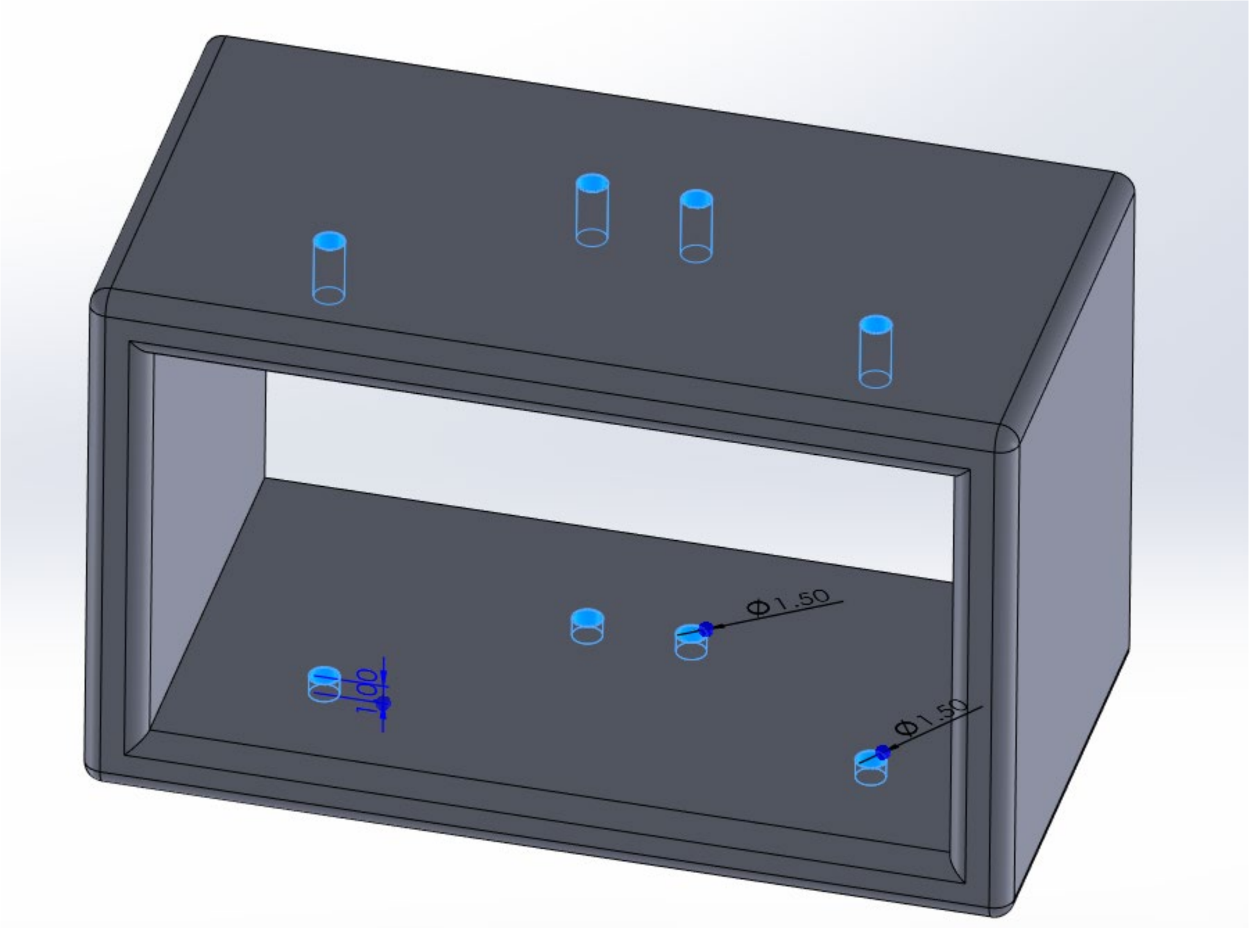

Figure 7: CAD drawing of Prototype 3, showing the extrusion of holes to hold the T-shape pins. The holes are 1.5 mm in diameter, extrude through the top and 1 mm to the bottom (measurement highlighted in blue). Unit in mm.

The overall dimension of 46.4 mm × 23.4 mm × 28.7 mm (Width × Length × Height). With the front surface filleted at 1 mm radius. The thickness of the material is set to 3.2 mm, which is the thickness of the acrylic sheet evaluated in the design matrix. The team believes that such thickness can best balance the material strength and cost, while leaving enough room for the mirrors at the bottom (see Appendix C.1 and C.2, based on which this design is created, that the carving on the bottom allows fixation of the mirrors). Figure below shows the overall dimension of the design.

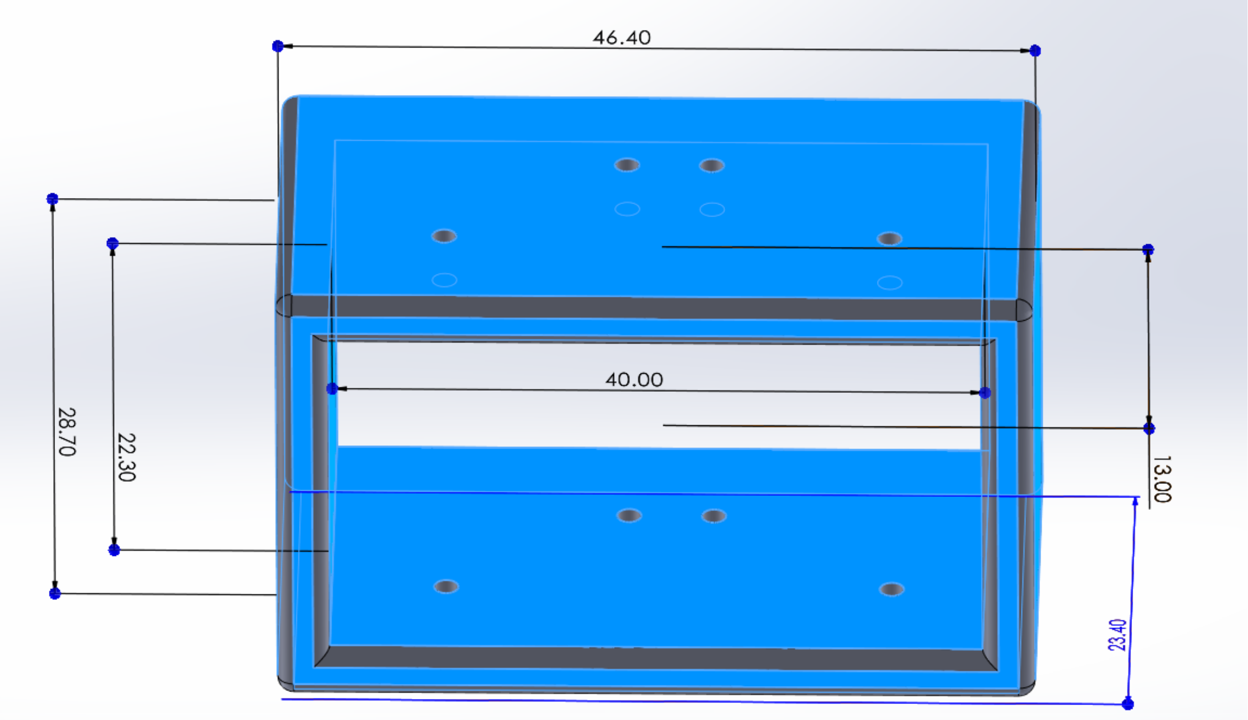

Figure 8: CAD drawing of Prototype 3, showing the overall dimension of the prototype. The outer dimension is 46.4 mm × 23.4 mm × 28.7 mm (Width × Length × Height), and inner cross-sectional area is 40.0 mm × 22.3 mm (Width × Height). Unit in mm.

5.3 Testing

5.3.1 Image Quality and Resolution

According to the PDS, the design must allow the 6-0 sutures being distinguishable from the background. Therefore, the team perform this test to check the image quality from this prototype.

First, two T-shaped pins are inserted through the holes on the left side of the prototype. And a laser-cut inner mirror and a laser-cut outer mirror are glued to the T-shaped pins. Then, the team rotate the pins slowly to approximately 30 degrees with respect to the camera lens (same as 60 degrees with respect to the central line in Section 5.2.2) and attached to the smartphone with two removable 3M strips.

The smartphone is set to 2x magnification, and it is mounted to a smartphone stand focusing on the testing station that is 200 mm below the camera lens. The team then fine-tuned the mirror angle to achieve clear image on the reflected view. Sample images are taken from the smartphone.

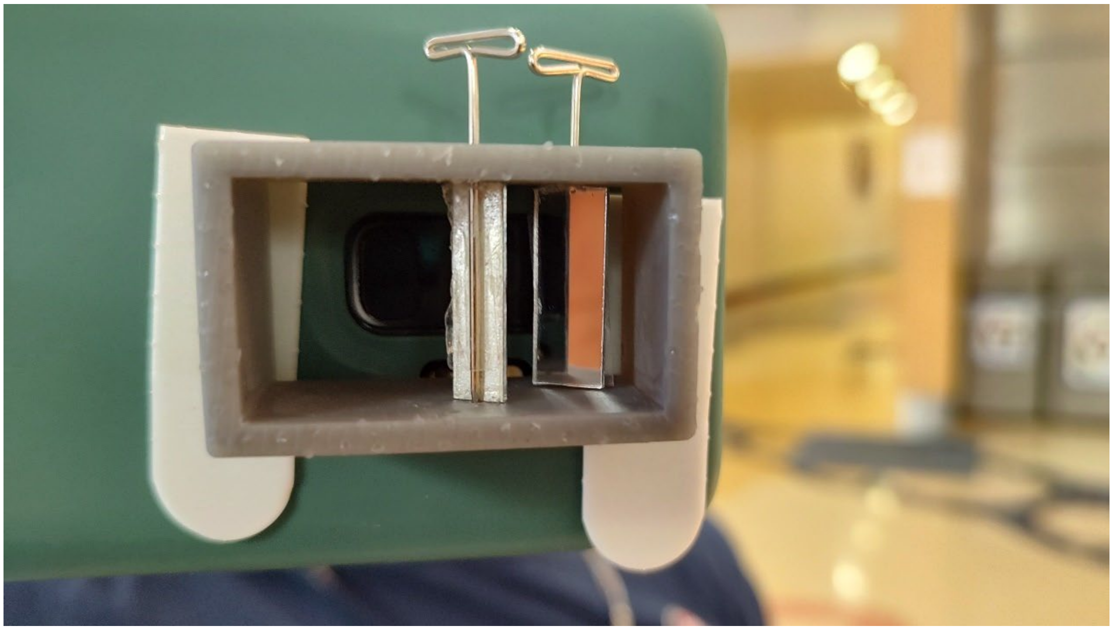

Figure 9: A smartphone with the prototype attached over the camera lens. The mirrors are glued to the T-shaped pins, which are inserted to the left half holes in Figure 7. With 2x magnification, the pins are first adjusted to make the mirrors at 30 degrees with respect to the plane of the plane of the camera lens (same as 60 degrees with respect to the central line in Section 5.2.2). Then the prototype is fixed to the smartphone with removable 3M strips.

Image quality is acceptable if there is no obvious distortion of the suture. Resolution is also qualitative determined by whether the suture is easily distinguishable from the background.

5.3.2 Misalignment and Field of View (FOV)

During the first test, we noticed that there was misalignment between the direct capture and the reflected view, as is shown in figure below. Using this sample image from the test in 5.3.1, the team first calibrated the measurement in ImageJ (Fiji package, developed by Schindelin *et al.*) with the distance between two adjacent lines on the notecard (6.0 mm).

Then we measured the difference in vertical distance of the pinpoint between the left and right half views. Meanwhile, the figure shows that the left and right view are not evenly distributed in the screen. Using the midpoint as the reference, the increase of width on the left (direct capture) and decrease on the right (reflected view) are measured relative to the central red line showing in the figure.

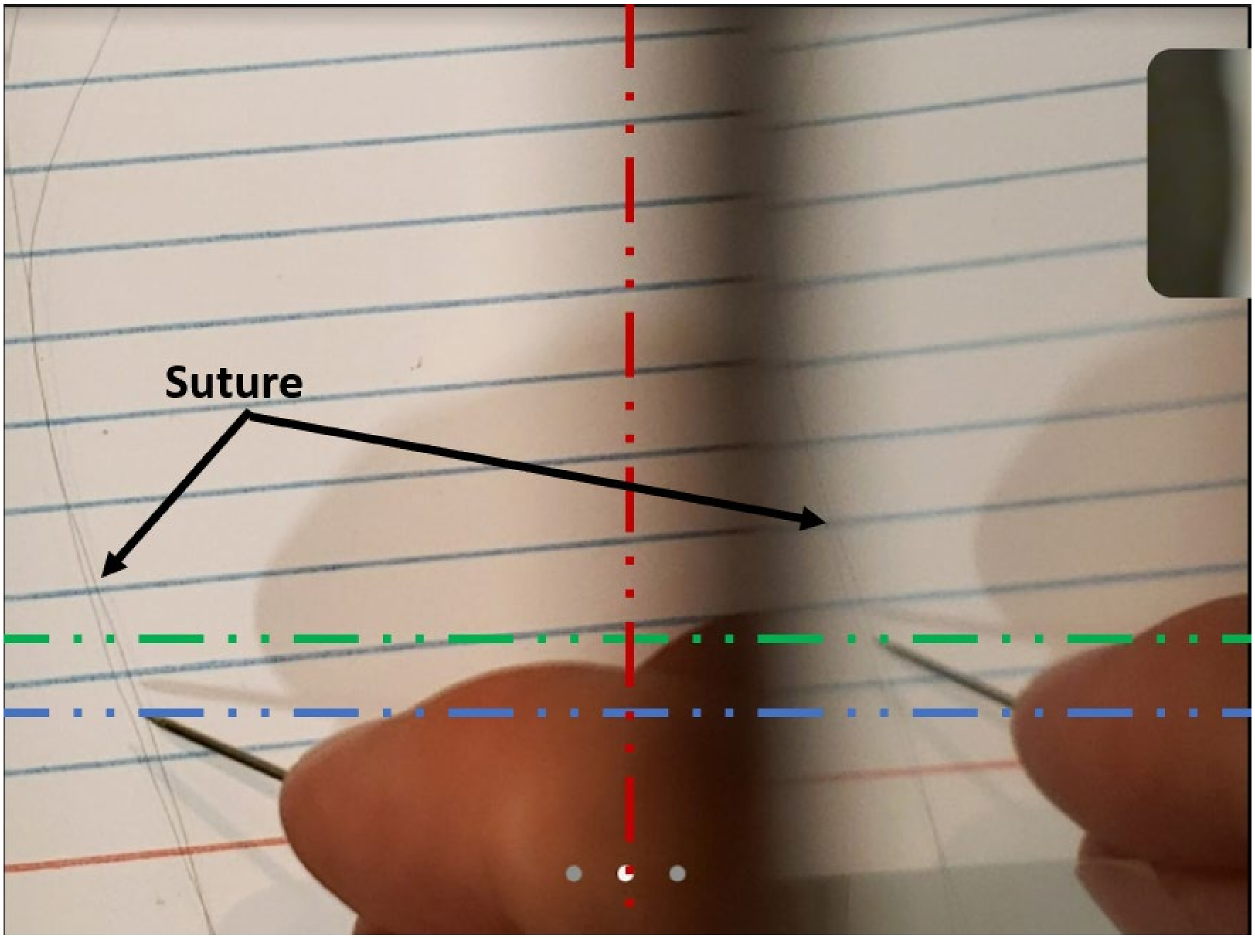

Figure 10: Screenshot from testing on the image quality, resolution, and misalignment. 6-0 suture strings are labeled with the black arrows. Note that there are two 6-0 suture strings on the notecard, and they are distinguishable in both views. The horizontal blue dashed line represents the vertical location of the pin in the direct capture, and green dashed line represents that in the reflected view. The vertical red dashed line shows expected separation between the views, with the actual separation to the right of the right line (the shadowed area).

The height of field of view (FOV) is the actual height being captured in the screenshot, and the width is half of the total width of the two views.

5.3.3 Depth Perception

Enabling depth perception from a single camera lens is the primary goal of this project. Therefore, a client is invited to perform microsurgery practice with the prototype.

In addition to the testing procedures in Section 5.3.1, we streamline the video to a second device via Zoom (Zoom Video Communications, Ver.5.10.4.5757 on Google Play). The second device is inserted to Google Cardboard. As shown in the figure below, while wearing the Google Cardboard, the client performs stitching with 6-0 suture and two tweezers on a piece of sponge. Qualitative analysis on the depth perception is based on the client's comfort level of using the prototype to perform microsurgery training.

Figure 11: A client testing with the prototype. He tries to move two tweezers around to check out the depth perception. The client is wearing Google Cardboard, in which a smartphone displays the view recorded by the other smartphone that is above the station via Zoom. The second device is at 2x magnification, and the mirrors are find-tuned to form clear image on the smartphone screen.

5.3.4 Measurement on the Angle of Mirrors during Testing

To accomplish our goal of having a prototype that can secure the place of the mirrors, we then measure the angle of mirrors after fine-tunes during testing. Using one edge on the housing as reference, the angles are measured via ImageJ, as shown in the figure below. These results are then used to make the CAD drawing of our final prototype.

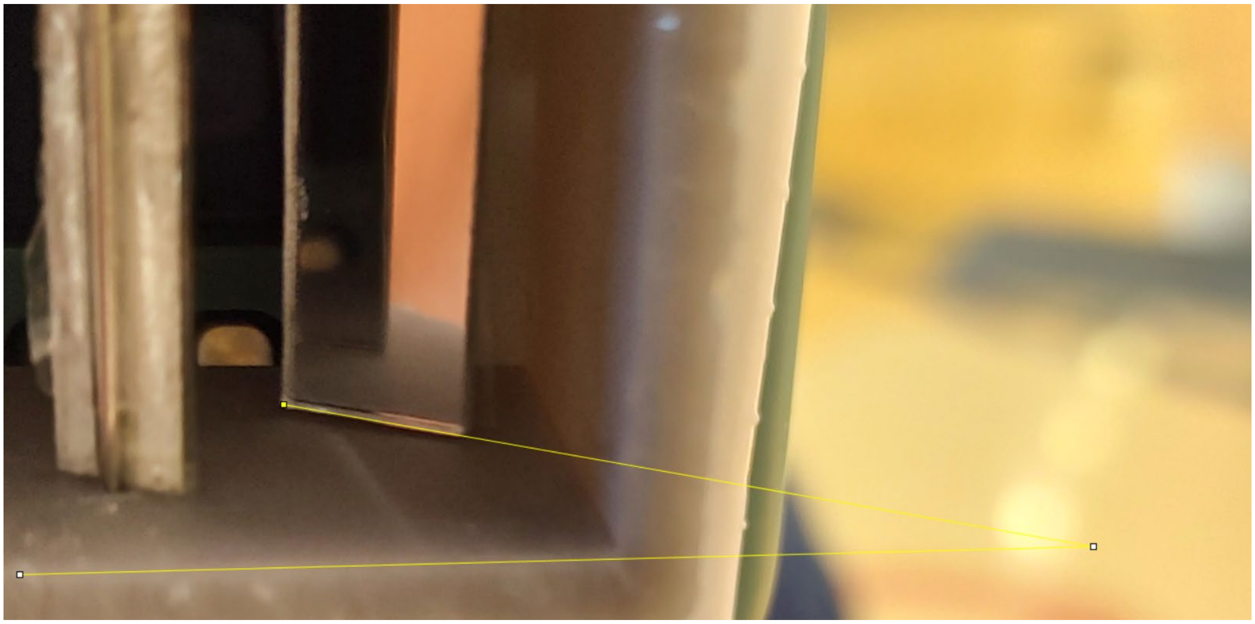

Figure 12: Screenshot of measuring the angle of outer mirror in ImageJ (the angle between thin yellow lines). The angle is measured with respect to the edge of the housing.

5.4 Final Prototype

The following figures show CAD drawing with modification on the prototype used for testing. First, the right set of mirrors and pinholes are removed. And the overall size is thus reduced to 31.4 mm × 23.4 mm × 28.7 mm (Width × Length × Height). Second, the angle of the mirrors (ϕ for inner mirror, α for outer mirror) are fixed based on the measurements in Section 5.3.4 (9 degrees and 11 degrees respectively). The slots reserved to hold the mirrors are 6 mm × 1.5 mm for the inner mirror and 8 mm × 1.5 mm for the outer mirror, both being extruded through the top and 1 mm to the bottom.

Essentially, both designs are considered as the same final design for this semester. Though we demonstrate the more compact one with fixed angle here, due to time restraints, we are not able to 3D-print this design or to further test the feasibility of it. Based on previous tests, we would expect the unprinted Prototype 4 having the same performance as Protype 3 that we test with, at least when being attached to the same smartphone.

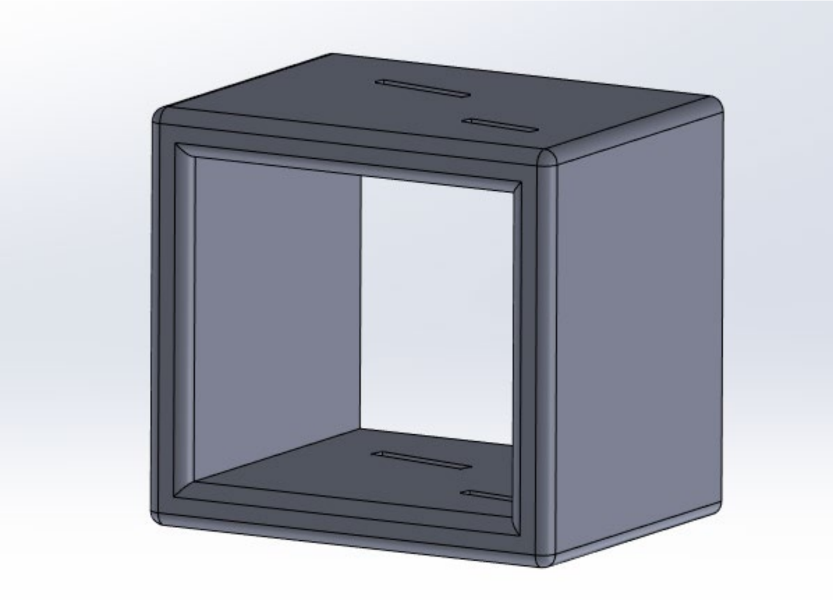

Figure 13: Isometric view of the final prototype. Two slots are created for insertion of the outer mirror (left) and inner mirror (right) respectively. See Appendix C.4 for detailed mechanical drawing.

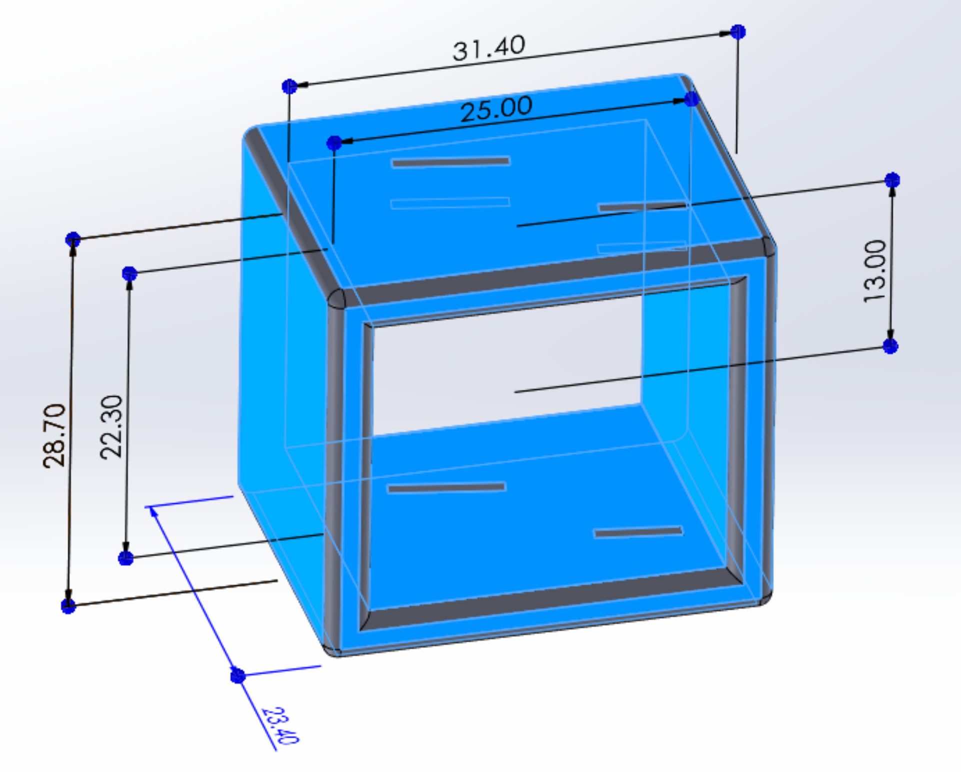

Figure 14: CAD drawing of Prototype 4, the unprinted final prototype, showing the overall dimension of the prototype. The outer dimension is 31.4 mm × 23.4 mm × 28.7 mm (Width × Length × Height), and inner cross-sectional area is 25.0 mm × 22.3 mm (Width × Height). Unit in mm.

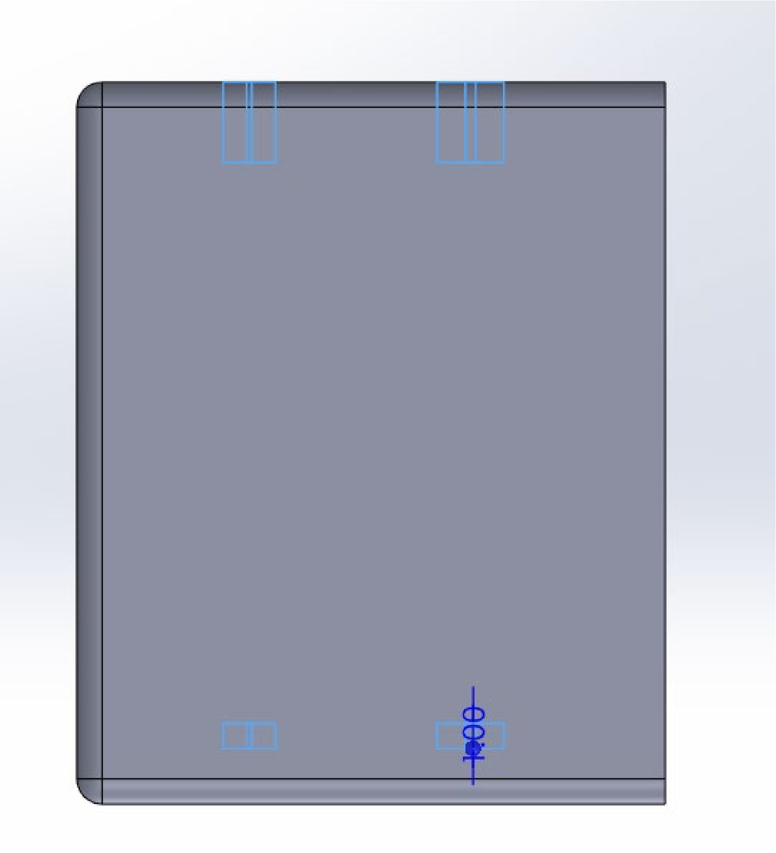

Figure 15: CAD drawing of Prototype 4, the unprinted final prototype, showing the extrusion of slots to hold the mirrors. The slots are 6 mm × 1.5 mm for the inner mirror and 8 mm × 1.5 mm for the outer, extrude through the top and 1 mm to the bottom (measurement highlighted in blue). Unit in mm.

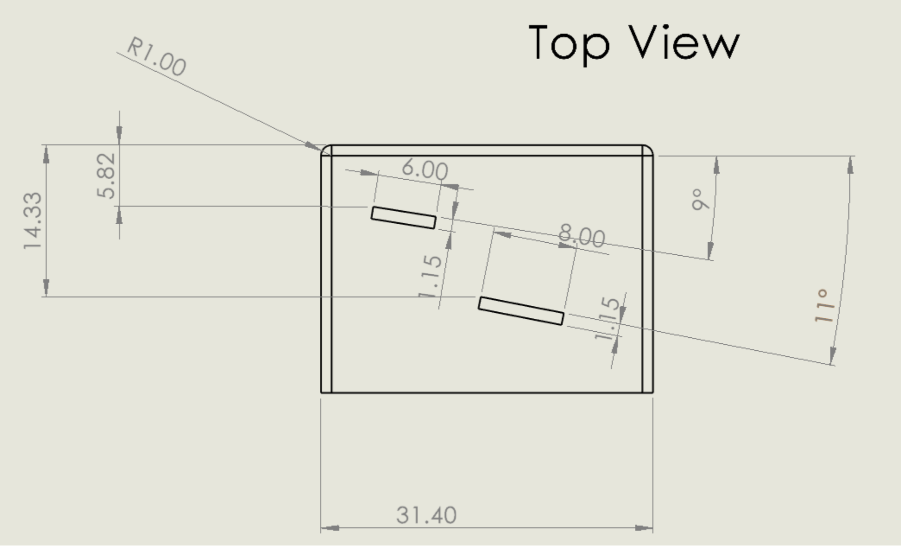

Figure 16: Top view in mechanical drawing of Prototype 4, the unprinted final prototype. Dimensions are labeled, and full mechanical drawing is provided in Appendix C.4.

6. Results

The new final design was able to produce a stereoscopic image like the one created by the prototype made last semester. The stereoscopic vision is then able to give the device depth perception which is one of the main goals of this project. This prototype also improved the image quality and reduced the size of the blind spot in the image. During the testing, the 6-0 sutures were clearly visible in Figure 10 without perceivable image distortion, so the concept behind this project is feasible to accomplish. Yet, we also notice that the reflect view from all testing images are less clear than the direct capture. Though the sutures are still distinguishable from the background, this still raises uncertainty in the image quality.

Also, according to the same figure, the two identical images are not symmetrical in size which is necessary for the virtual reality headset so medical students can simulate microsurgery. ImageJ results show that the FOV is 47 mm by 70 mm (Width × Height). On the horizontal direction, the left view (direct capture) is 8.45 mm wider than the expected FOV, and right view (reflected view) is 9.22 mm narrower. As for the vertical direction, the right view is 5.37 mm higher than the left view. This misalignment in images undermines the performance of the design and depth perception. As the client reports during the testing, though the suture is clearly visible in the headset, he still has a hard time forming spatial awareness of his hands. On the other hand, the client feels that this final design achieves better depth perception than the one from last semester.

In addition, when the image was streamed to another phone in the VR headset, there was a delay present that impairs the ability to accurately perform any sort of task especially microsurgery. The time lag between recording and display to the end user was measured as 0.21 seconds from last semester, yet this is still a significant delay on Zoom. And when comparing sample picture in Figure 10 and the screenshot from Zoom below, the image quality from direct capture is obviously compressed on Zoom meeting. This loss of image clarity further undermines the performance of the attachment.

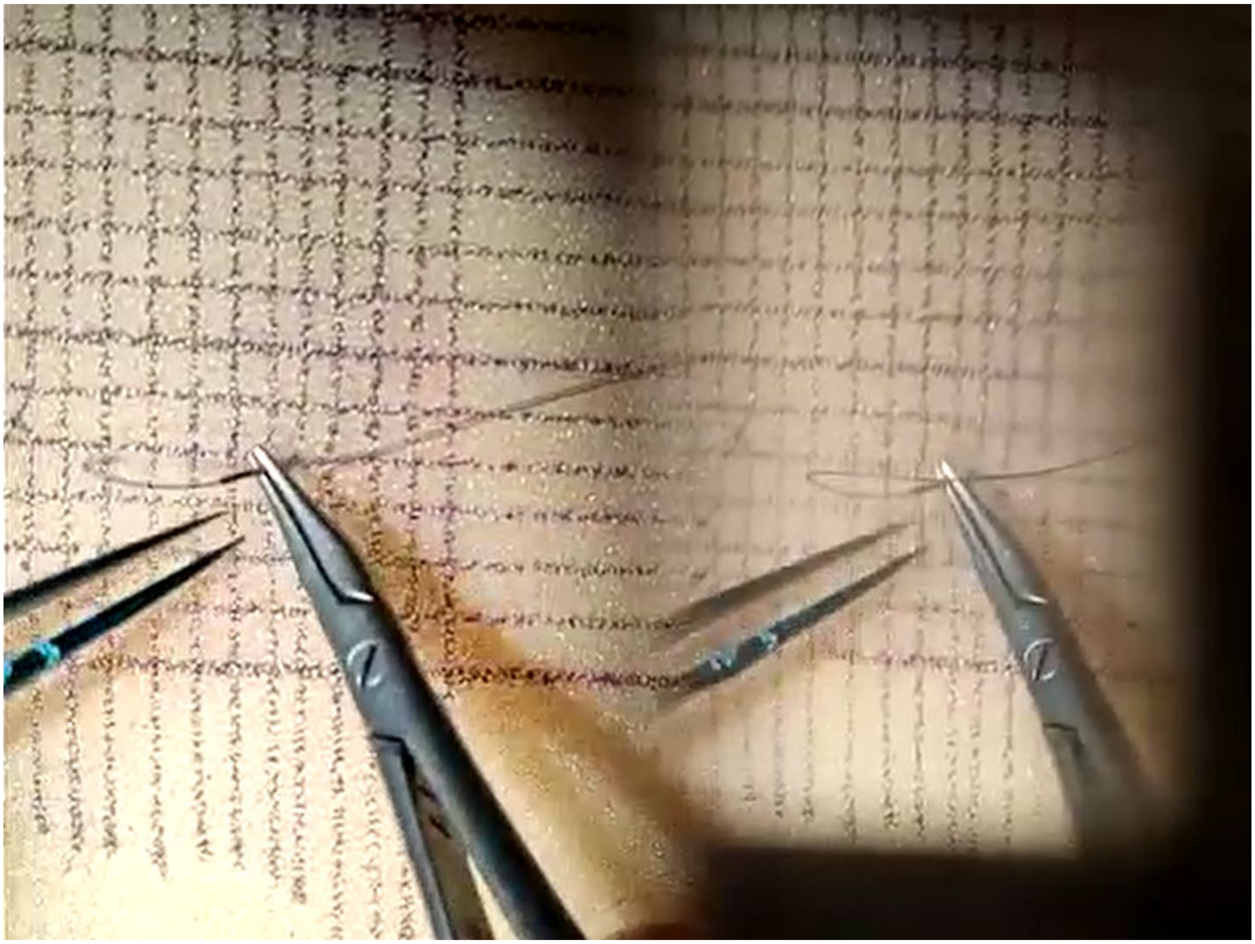

Figure 17: Screenshot of testing during Zoom meeting, from the view of testing participant. A smartphone with the testing protype attached recorded this microsurgery practice station, and the video is streamlined to another device inserted to Google Cardboard. The client, wearing the Google Cardboard over his eyes, was trying to make stitch using 6-0 suture with two tweezers. The test is performed on a piece of sponge with grids. (Left) Direct capture on the station (Right) Reflected view from the mirrors.

7. Discussion

The final design created this semester improved the prototype built last semester. The current design, however, did not accomplish every goal that was set out for this semester. The progress made this semester did give insight on how the prototype can be improved in the future. For example, pins were added in one of the iterations of the design to change the angles of the mirrors during testing to improve the image. While this aspect should eventually be able to fine-tune the angles, the current design is a good place to start. In addition, the prototype should have the mirror in stationary positions where the medical students do not have to recreate the angles when using the device. This semester, a fabrication technique was used that was able to efficiently and accurately stabilize the mirrors in place. This technique is 3D printing. As shown in the results, the low-quality mirrors lead to blur in the reflected view. Thus, future prototypes should use better optic parts.

In addition to the aspects already mentioned, the prototype could be improved in other ways. One of which is the possible implementation of software to help improve image quality and reduce the delay between the two phones. Another aspect is devising a way to easily attach the device onto the phone without having to line up the prototype every time it is used. This attachment should also prevent the device from moving while in use.

Finally, during the testing with the client, we realize that the prototype does not fully mimic the pupil distance of human beings. The difference in view of angle is essentially determined by the distance between the eyes, and the final prototype shall mimic this effect on the sensor. While the client is wearing the headset, the team rotated the smartphone by 6.6 degrees clockwise (shown in Figure 11) and adjusted the mirrors to slightly shift the reflect view rightward. The client reports feeling better, though still not sufficient, depth perception after the adjustment. The results reveal an unconsidered factor in the design – the viewing angles for the left and right views.

8. Conclusion

This semester, the team can achieve better image quality in the design with a 3D printed, stable housing for the mirrors. The final testing with the clients demonstrated promising results with the updated design with one pair of mirrors.

While acknowledging that delay in streaming via Zoom and misalignment are still apparent flaws, future work will focus on adding fine-tuning knob for rotating mirrors, as well as on wired connection between the capturing device and displaying monitors. If times allows, the next iteration should be free from Google Cardboard to enhance user awareness to the surrounding environment. This can be achieved with, for example, polarized glass as for 3D movies in theaters.

Meanwhile, the final testing revealed the importance of viewing angle difference in promoting depth perception. In other words, we have not yet account for pupil distance or viewing angle from real human eyes. Thus, future work should also adjust the viewing angle of the direct capture and reflected view to better simulate the human eyes for stereoscopic views.

9. References

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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, Haochen Wang, Frida Albiter, Emma Kupitz

February 11, 2022

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 equipped with the model. 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:

Physical and Operational Characteristics

Performance requirements:

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.

a. **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.
b. **Accuracy and Reliability:**
    ii. The device should be able to consistently maintain a magnification of 5x 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.
c. **Life in Service:**
    iii. 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.
    iv.
d. **Shelf Life:**
    v. 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 product should have at least one year of lifespan, which matches the lithium battery warranty provided by Apple. [2]
e. **Operating Environment:**
    vi. The product will most likely be used in a domestic or indoor environment, so the device will not be exposed to extreme conditions.
    vii. 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 product) [3]
    viii. 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.
    ix. Potential splash of food dye, blood, in vitro tissues, etc. [4]
    x. Components that are exposed to the operation station shall not be malfunctioned upon such splash

- xi. Potential scratches from the surgical equipment, such as tweezers or needles.
- xii. The final product should at least endure accidental damage from the aforementioned scenarios, while maintaining the resolution to recognize the suture

f. **Ergonomics:**
- xiii. 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.
- xiv. For the iPhone 8, do not submerge in water greater than 1 meter and for longer than 30 minutes. [3]
- xv. The device should be comfortable to use for over 1 hour
- xvi. Should not cause any unnecessary strain to the surgeon

g. **Size:**
- xvii. Should be able to be set up in an indoor living space (i.e. 10 x 10 sqft, approximately 3 x 3 meters)

h. **Weight:**
- xviii. Optimum weight: < 10lbs (approximately 4.5 kg). Must be easily transportable

i. **Materials:**
- xix. No restrictions on material mechanics
- xx. Cannot be toxic upon skin contact or inhalation
- xxi. Shall have minimal degradation resistance, such as from sunlight

j. **Aesthetics, Appearance, and Finish:**
- xxii. 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.
- xxiii. Should simulate the working condition of an operation room with microscopes
- xxiv. Must not interfere with the operation and training performance of the user

Production Characteristics

k. **Quantity:**
- xxv. One final prototype as deliverable
- xxvi. Tens of thousands of units for mass production after approval, replacing all current expensive training mechanisms for microsurgical practice for medical residents.

l. **Target Product Cost:**
- xxvii. The target cost of the product is undetermined, but shall be less than our clients budget of $500
- xxviii. Cost for an iPhone, a stand, and any attachment that is necessary to put over the camera to replicate microsurgery practice are not considered as part of the budget for this project. Since the existing products cost at least $100,000 [5] which is drastically greater than the target cost. The prototype, even considering the cost for the equipment listed above, will be a cheap alternative for medical students to use for remote training, using materials that are commonly owned.

Miscellaneous

m. **Standards and Specifications:**
    xxix. 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]
    xxx. 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)
    xxxi. 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

n. **Customer:**
    xxxii. 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)
    xxxiii. 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]
    xxxiv. 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
    xxxv. The device should be comfortable to wear for extended periods of time

o. **Patient-related concerns:**
    xxxvi. As this is a device used for practice, there will be no requirements for patient confidentiality.
    xxxvii. 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.

p. **Competing designs**:
    xxxviii. 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]

2. 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. Iteration of designs

B.1 Final design from previous semester

Final design from previous semester was determined with a trial-and-error method, in which the positions, distances and angles were measured in figure below with ImageJ. During testing, the length of the outer mirror was set to $M_o = 12\ mm$, and $M_i = 6\ mm$ for the inner mirror. Mirror heights were $h = 25\ mm$ for all pieces.

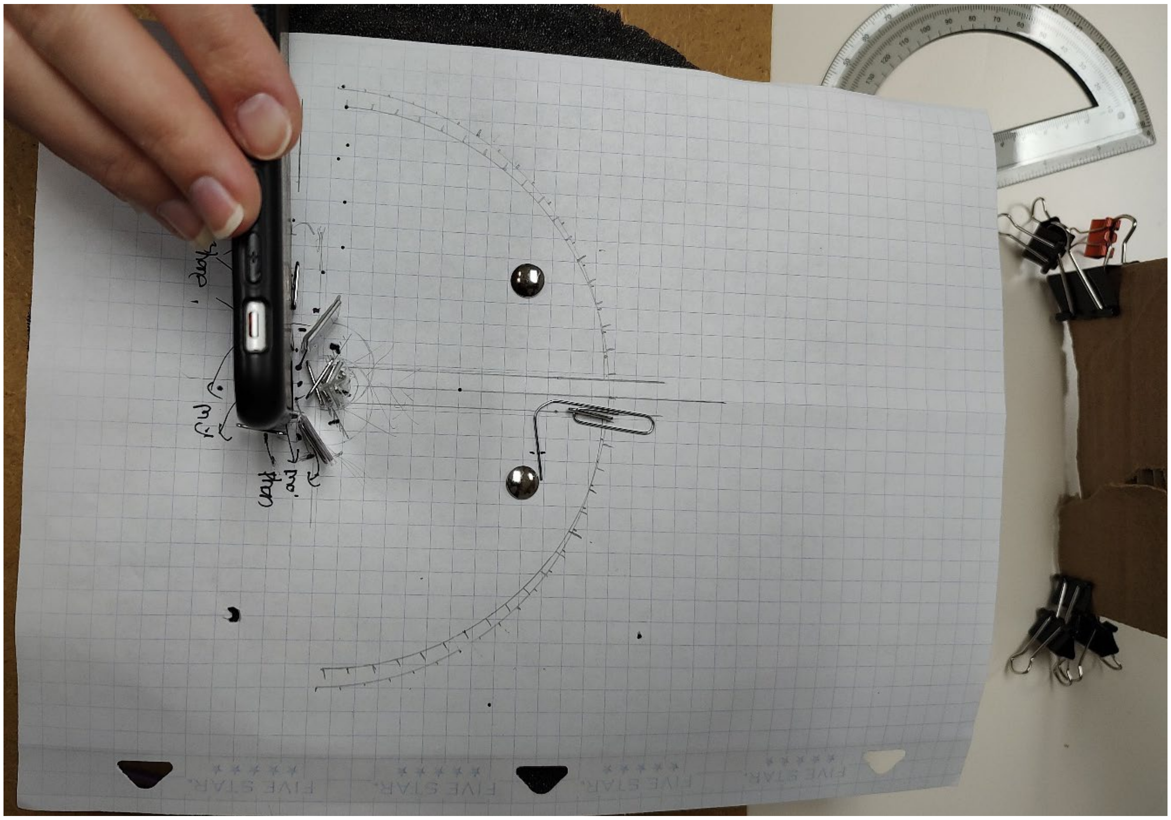


Figure 18: Photo used to measure distances and angles in Fall 2021. The phone was aligned to the mirrors, such that the camera was focused on the inner mirrors and could capture two identical views of the cardboard on the right of the photo. The diameter of the paperclip at the center (0.70 mm) was pre-measured with a caliper and used as reference in image processing. Three horizontal lines at the center were auxiliary for angle measurement.

Using the pre-measured diameter of the paper clip (0.70 mm) and the central line as references for distances and for angles, figure below demonstrate the symbolic representation of theses parameters in this final design.

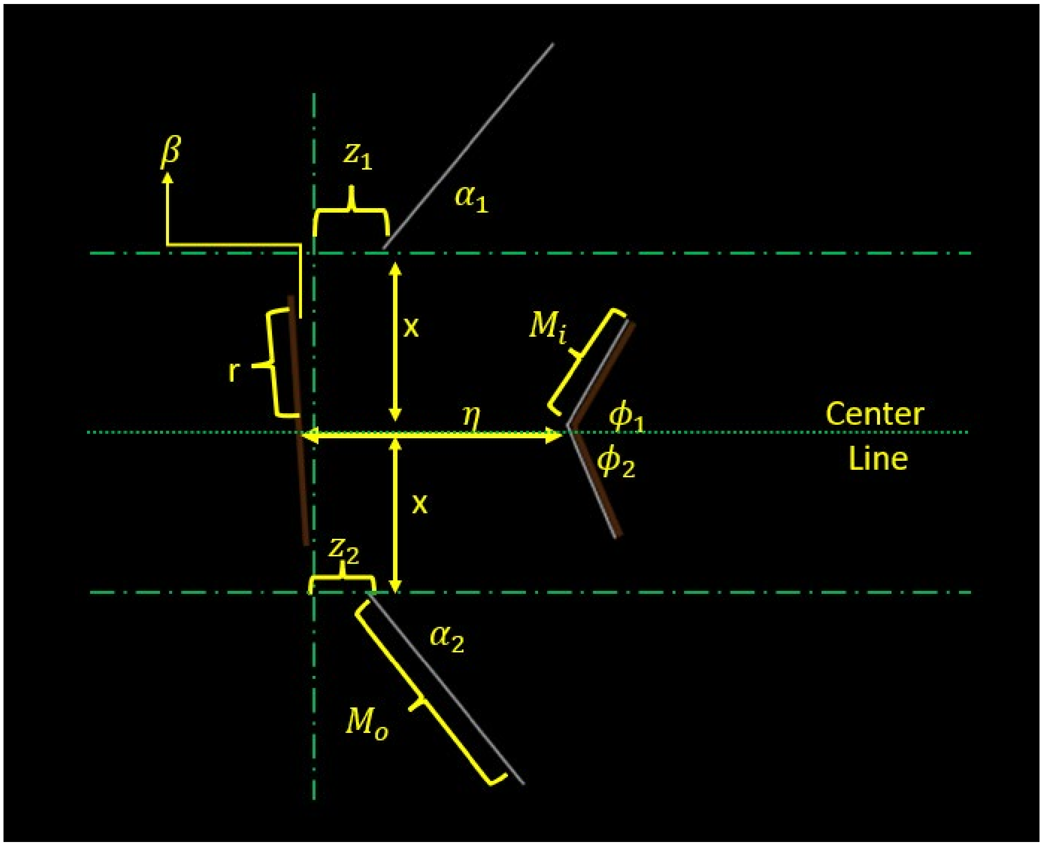


Figure 19: Parameters used for final design in Fall 2021, and their definitions in the final design. Values of the parameters are discussed above.

According to ImageJ analysis, η, the distance between the center of the camera lens and inner-mirror-vertex, was 13 mm. The radius of the camera lens was $r = 6\ mm$. The camera lens was positioned at an angle of $\beta = 94.6°$ relative to the presumed central, horizontal line. The outer mirrors were both $x = 8.4\ mm$ away from the central line in the vertical direction. For the top (left) outer mirror, it was $z_1 = 4.1\ mm$ away from the camera lens and had an angle of $\alpha_1 = 52.8°$ with respect to the horizontal line. The values for the bottom (right) outer mirror were $z_2 = 3.4\ mm$ and $\alpha_2 = 52.1°$. Similarly, the top (left) and bottom (right) inner mirrors were $\phi_1 = 61°$ and $\phi_2 = 66°$ from the horizontal line.

B.2 Symmetrical design

This design is derived from the final design from previous semester. η is kept as 13 mm. Radius of the camera lens r and height of the mirrors h are also remain unchanged. The inner mirrors are both 6 mm long, being placed at $\phi = 60°$ with respect to the central line. The outer mirrors are $M_o = 8\ mm$ long. They are placed at $z = 6\ mm$ horizontally and $x = 10\ mm$ vertically away from the center of the camera lens. The angle α is also 60°. The figure below shows definition of these parameters, with the parts at their expected location.

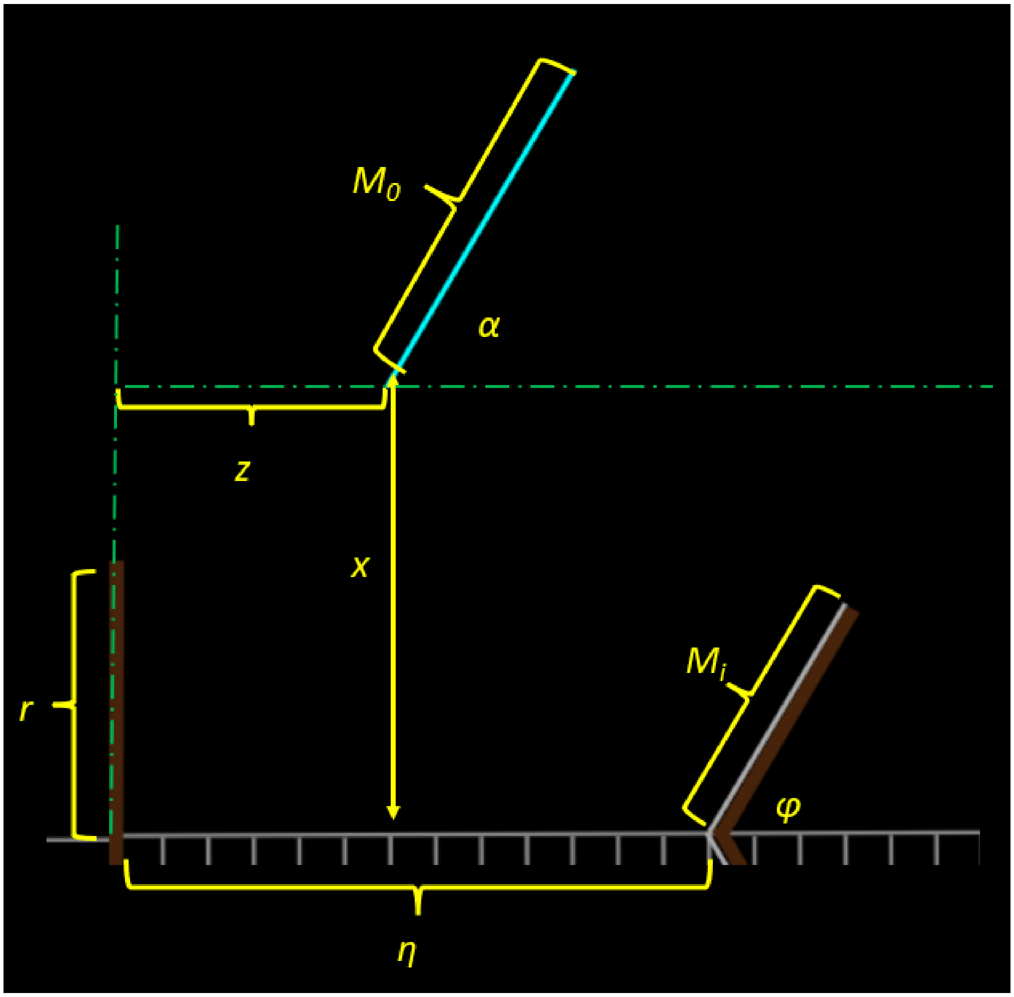


Figure 20: Parameters used for prototyping and their definitions in the second design. Values of the parameters are discussed above. The green dotted lines are horizonal and vertical reference lines.

A ray-tracing diagram below shows the working mechanism of this design. However, since the first testing with the clients shows that the Symmetrical Design leads to combination of the left and right views into a single, blurry image, this design is updated to Prototype 3: Free Rotation Design as is discussed in Section 5.2.3 and Appendix C.3. Testing protocols and notes are provided in Appendix D.

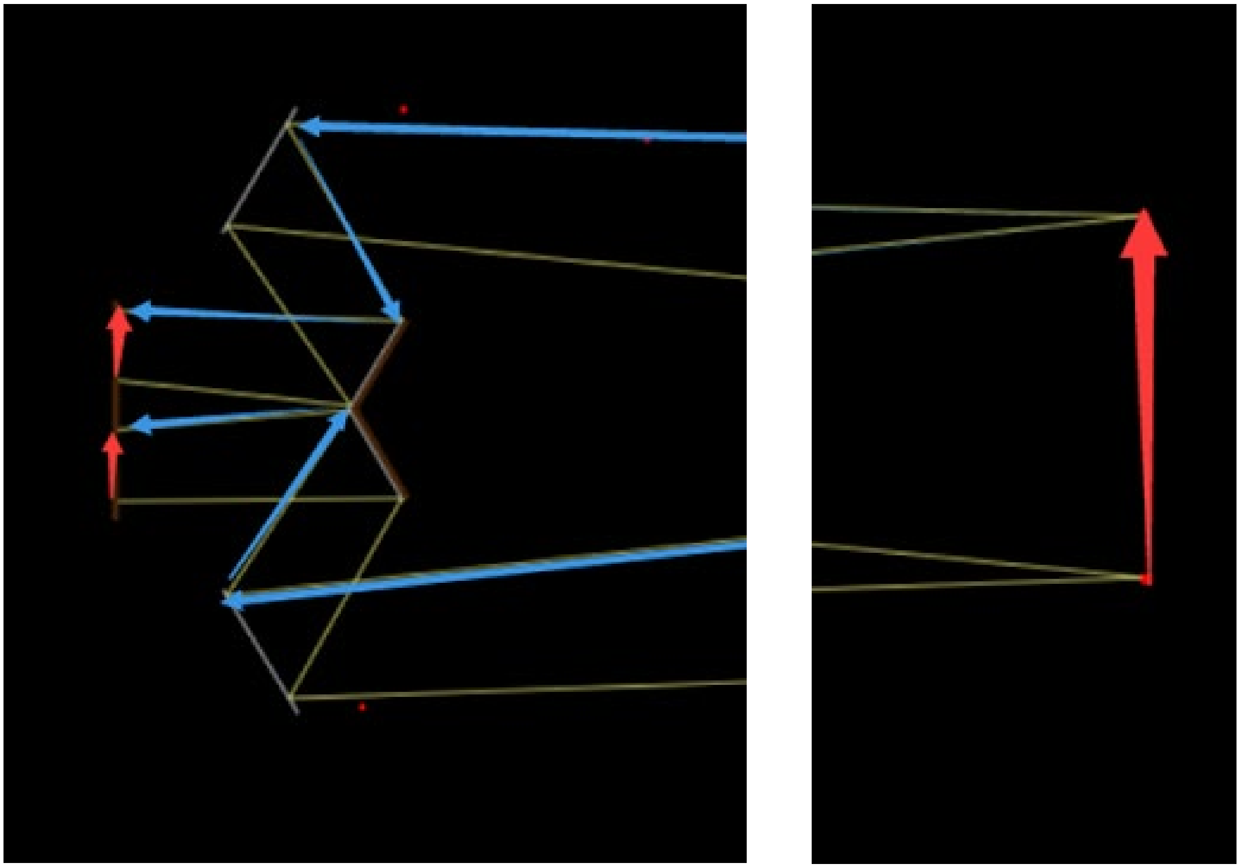
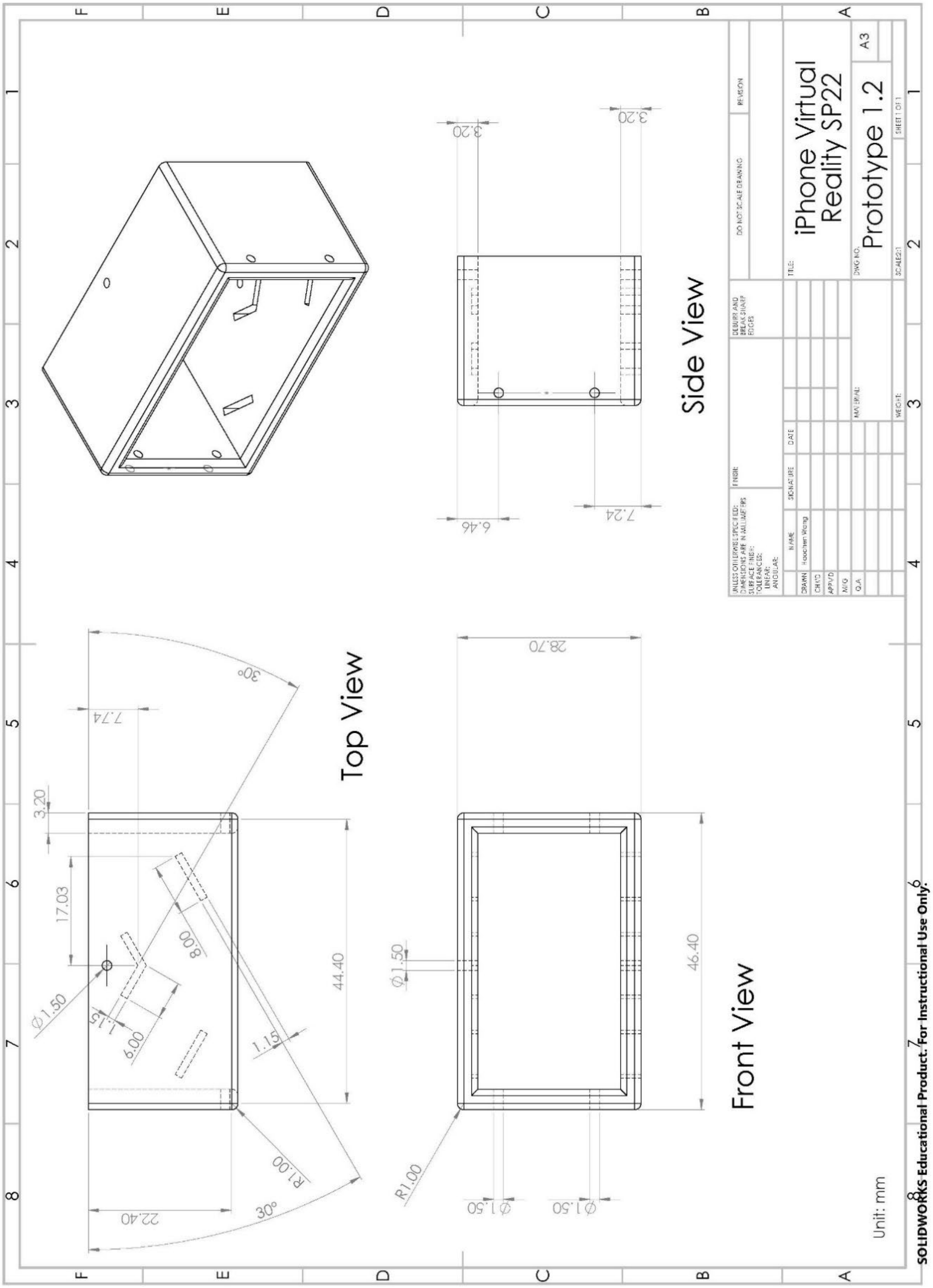


Figure 21: Left - Image forming on the sensor (two red arrows). Right - Light emitted from the object (red arrow). Ray tracing between the images is omitted.

C. Mechanical drawing of all prototypes

C.1 Prototype 1: Symmetrical Design

This design involves two pairs of inner-outer mirrors, and all are placed at 60 degrees with respect to the central line.


Top View
Front View
Side View
Unit: mm
7.74
30°
3.20
17.03
Ø1.50
8.00
1.15
6.00
1.15
44.40
R1.00
22.40
30°
28.70
Ø1.50
46.40
R1.00
Ø1.50
Ø1.50
6.46
7.24
3.20
3.20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
Haochen Wang
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
TITLE:
iPhone Virtual Reality SP22
DWG NO.
Prototype 1.2
A3
WEIGHT:
SCALE:2:1
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.
A
B
C
D
E
F
1
2
3
4
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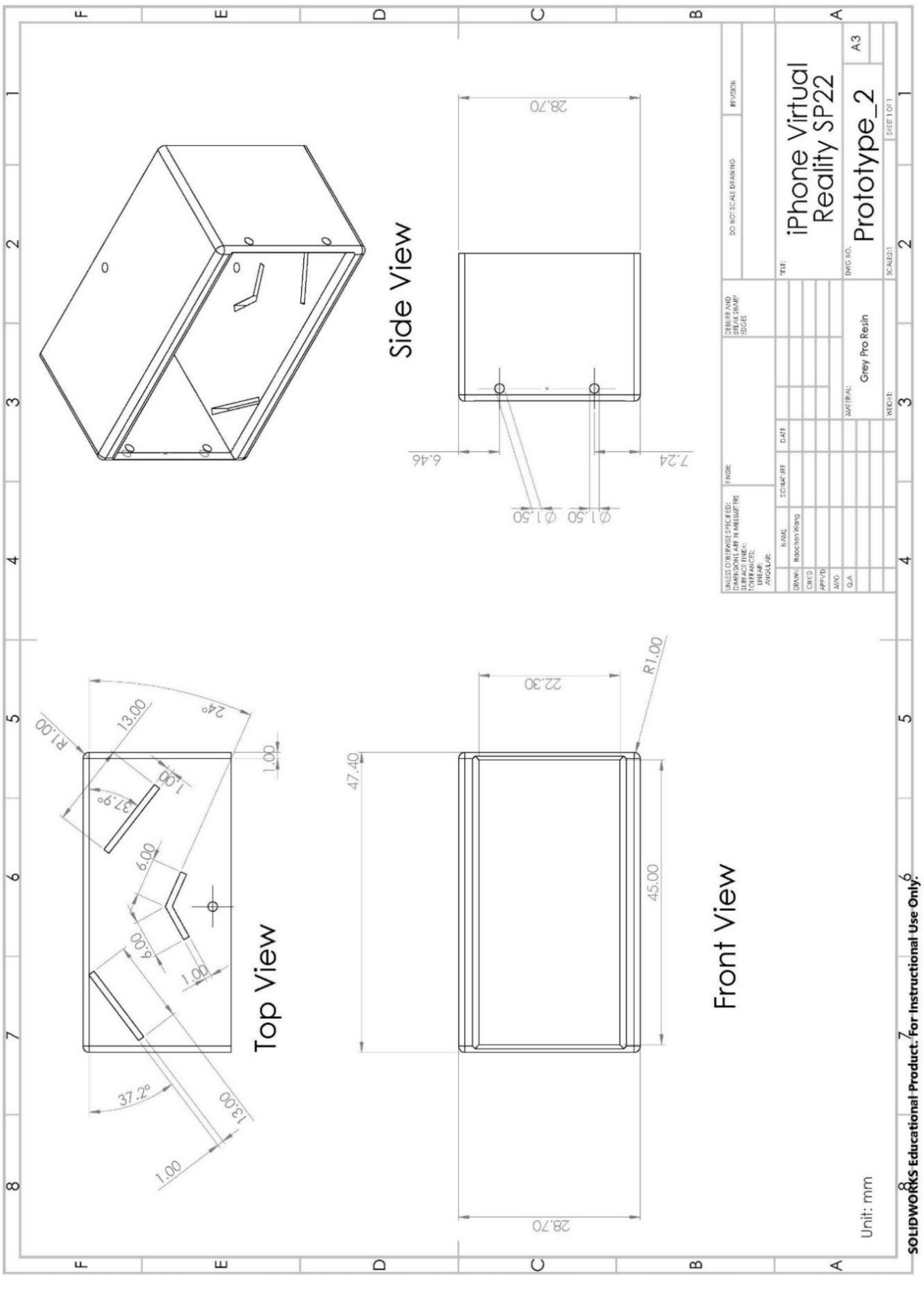
8

C.2 Prototype 2: Measured Design

This prototype is the replica of design in B.1. However, since the resin shrunk after curing, insufficient space at one edge led to broken down of the whole prototype. The team decided to proceed with the third, free rotating design, since the concept was proved to improve image quality compared to B.1.

Top View
Front View
Side View
R1.00
13.00
24°
1.00
1.00
37.9°
6.00
6.00
1.00
37.2°
13.00
1.00
47.40
22.30
R1.00
45.00
28.70
28.70
6.46
7.24
Ø1.50
Ø1.50
Unit: mm
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
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LINEAR:
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DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
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DRAWN
Haochen Wang
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
Grey Pro Resin
WEIGHT:
TITLE:
iPhone Virtual Reality SP22
DWG NO.
Prototype_2
A3
SCALE2:1
SHEET 1 OF 1
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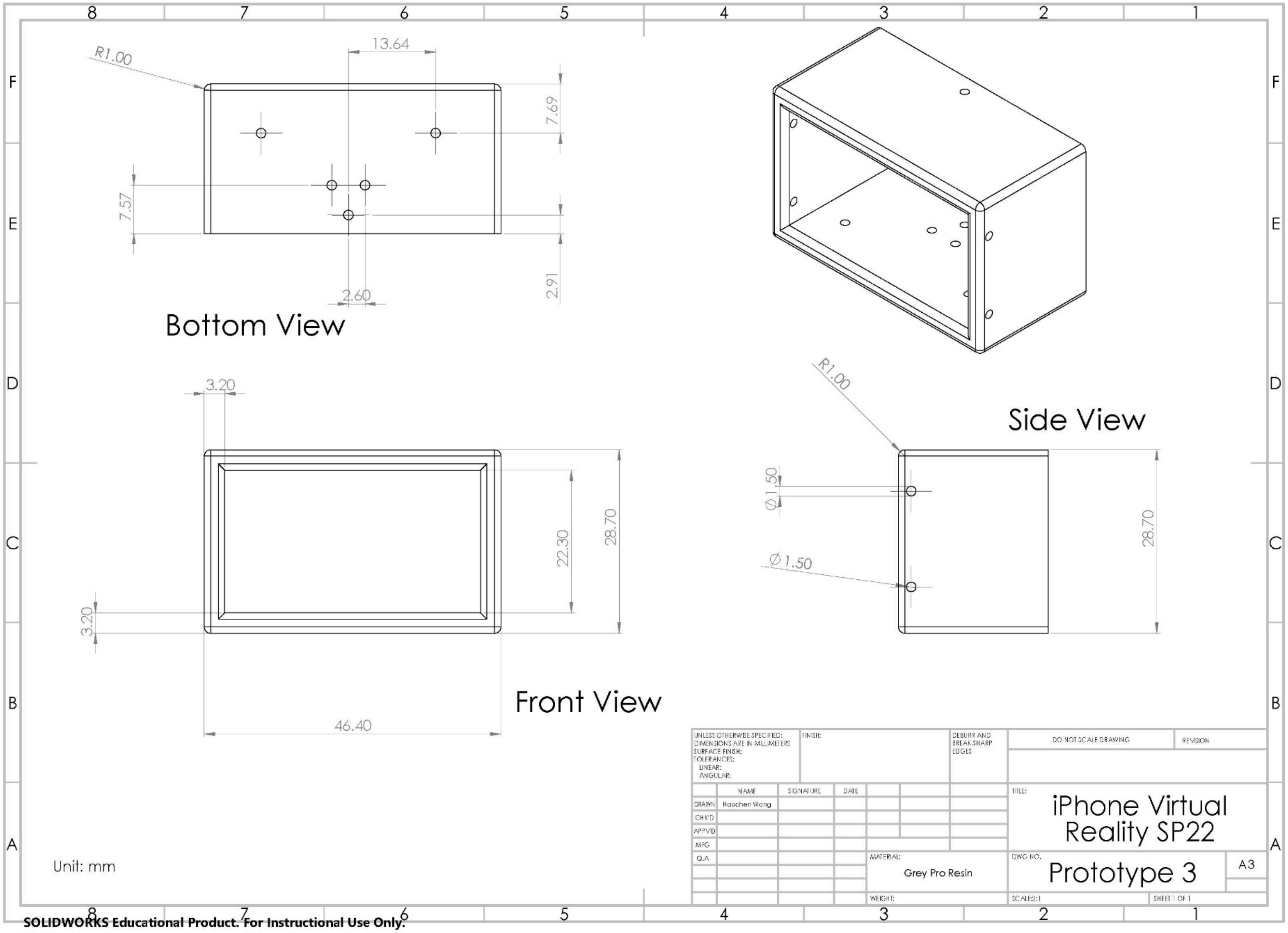
C.3 Prototype 3: Free Rotation Design

This design involves four holes at the center of the mirrors. When inserting the T-shaped pins into these holes, mirrors attached to the pin can be freely rotated to adjust the image formed on the smartphone.



8 7 6 5 4 3 2 1
F E D C B A
R1.00
13.64
7.69
7.57
2.60
2.91
Bottom View
3.20
22.30
28.70
3.20
46.40
Front View
R1.00
Side View
∅1.50
∅1.50
28.70
Unit: mm
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
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FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
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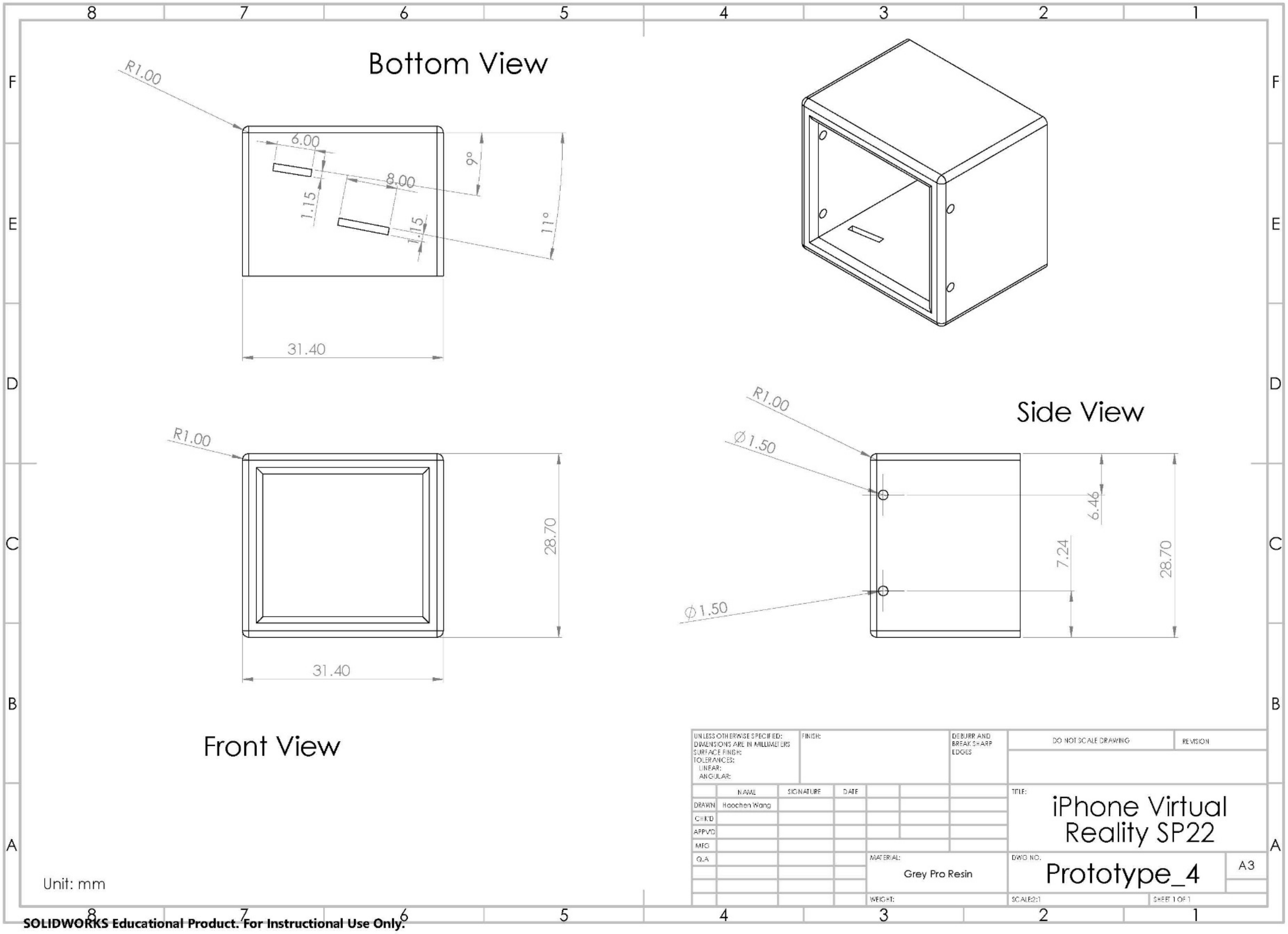
DATE
DRAWN Haochen Wang
CHK'D
APPV'D
MFG
Q.A
TITLE:
iPhone Virtual Reality SP22
MATERIAL:
Grey Pro Resin
DWG NO.
Prototype 3
A3
WEIGHT:
SCALE2:1
SHEET 1 OF 1

C.4 Prototype 4: Final Design (Unprinted)

This is the prototype based on angles determined by Prototype 3, at which the images formed on the smartphone are roughly the same.


Bottom View
R1.00
6.00
8.00
1.15
1.15
9°
11°
31.40
Front View
R1.00
28.70
31.40
Side View
R1.00
∅1.50
∅1.50
6.46
7.24
28.70
Unit: mm
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
Haochen Wang
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
Grey Pro Resin
WEIGHT:
TITLE:
iPhone Virtual Reality SP22
DWG NO.
Prototype_4
A3
SCALE:2:1
SHEET 1 OF 1
8
7
6
5
4
3
2
1
F
E
D
C
B
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D. Testing Protocol and Observations for Depth Perception Testing

I. Purpose To assess the image quality and depth perception from the final design II. Material and equipment A. Provided by the client • Surgical cloth • Sutures (5 pieces) • Tweezers (2 pairs) • Google Cardboard • Phone stand • Memory foams B. Prototype C. Tapes/adhesives D. Retractable knife E. Smartphone F. Sharpie G. Software • Zoom III. Procedure A. Mount the smartphone onto the phone stand • The lens should point down toward the station • The phone should be place at approximately 200 mm away from the desk B. Align the attachment with the smartphone camera lens • Then secure the attachment onto the smartphone with adhesives C. Adjust the magnification such that the inner mirrors fill up the screen • Take sample image of an object to ensure that two identical views are formed on the inner mirrors D. Draw two squares on the surgical cloth E. Put 5 sutures in one of the squares F. Use Zoom to project the view from the recording smartphone	**Day 1: 04/08/2022** **Observations:** The images were blurred to one Cannot distinguish the left half view from the right. The views appear to combine into one, and the image quality is poor. The result may be due to poor mirror quality; light reflected by the inner mirrors may be undistinguishable on the camera sensor; there may be error in ray tracing diagram. **Day 2: 04/29/2022** **Observations:** First tested the prototype with two pieces of paper. Dr. Zeng felt some depth perception, but not being able to promptly catch the paper in the air with a pair of tweezers. Second test of stitching with 6-0 suture on a piece of sponge. Both tests showed clearer image than last semester. Dr. Zeng could see the suture, but depth perception is still not optimal. Tried to rotate the smartphone by a small angle, and adjusted the mirrors accordingly to slightly shift the reflected view to the right. Dr. Zeng felt better spatial awareness, but still having hard time making a stich. The time delay becomes more significant (possibly due to warming battery in the smartphone, this should be taken into consideration in the future), and the video quality is obviously compromised due to video compression on Zoom.

onto another receiving smartphone G. Insert the receiving smartphone into Google Cardboard H. Have each team member and the client wear Google Cardboard, using tweezers to move sutures from one square to another. • Record the time used to complete the test • Repeat the test with smartphone only • Compare the results with data obtained from the first client meeting	