VR Headset for Endoscopy and Microsurgery

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ABSTRACT

The application of endoscopic techniques to endonasal skull base surgery has become increasingly prevalent as the technology has improved. While endoscopic techniques offer many benefits over traditional methods, the surgeon does not have the same degree of immersiveness and visualization compared to traditional methods. Attempts have been made to address this by using virtual reality headsets, however, there currently is no method for the surgeon to visualize the operating room without completely removing the headset. Our design allows the surgeon to view the operating room through external cameras on the headset that are activated when the surgeon rotates their head superiorly.

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I. INTRODUCTION

1.1: Motive, Current Methods, and Problem Statement

The virtual reality market has grown exponentially over the last couple of years, and not just in the gaming industry. As the technology has improved, the areas of application have increased as well. One area in particular that virtual reality (VR) has taken root is the healthcare industry. In fact, the VR healthcare market could reach $641 million by the end of 2018 and $3.8 billion by 2020 [1]. The majority of the VR healthcare market share is from systems that use VR to train surgeons [2].

[Figure 1] A physician performing a procedure aided by endoscopy [3].

As shown above in Figure 1, large monitors have traditionally been used to display video feed from surgical tools during endoscopic procedures. While they offer a simplistic solution, these displays are bulky and lack an immersive effect for surgeons. Additionally, surgeons frequently have to bend forward and position their necks at awkward angles to see the display, which overloads their musculoskeletal system and can lead to chronic back pain [4]. These issues have been partially addressed by using VR headsets; however, existing VR headsets limit the surgeon's ability to see anything outside of the operative view. In order to see the surroundings and pick up a tool, the surgeon must physically remove the headset. This wastes time, threatens sterility, and interferes with tool positioning *in vivo*. The goal of this project was to design a VR headset that would allow the surgeon to transition from the operative view (what the endoscope displays) to the environmental view (normal visual field) without the use of the surgeon's hands.

There are no VR headsets currently on the market that are designed for surgical use in the operating room that also offer hands-free transitioning between views. Because the time frame for this project was only one semester, a premade headset was reprogrammed rather than built from scratch. For our purpose, it made sense to use a proven product that had been designed and developed commercially. The specific products that were considered for modification are discussed later in the preliminary designs section. The final device gives the surgeon a more immersive view while decreasing occupational hazards by allowing them to keep their necks at natural positions rather than bent forward looking at a monitor. Eventually, all monitor-based surgeries could use this system to minimize the strain on surgeons [5].

II. BACKGROUND

2.1: Relevant Physiology and Biology

Current endonasal techniques display the feed from the endoscope to a large television monitor placed in front of the surgeon. Often, surgeons need to lean in very close to the screen during these long procedures to see accurate details [6]. However, when people have screens "much closer than they normally would to view printed material, that puts an extra demand on the eyes" [7]. Along with this added demand, inadequate screen resolution can cause procedures to be difficult and lead to additional eye strain [6]. Furthermore, these procedures are conducted in a dark room. This compounds the negative impact of screens as "when using a computer [monitor,] ambient lighting should be about half as bright as that typically found in most offices" [6]. Additionally, "the constant exposure to [this] technology results in symptoms of digital eye strain leaving our eyes dry and irritated and leads to eye fatigue, blurred vision, headaches, and neck and back pain" [6]. As expected, many surgeons also report issues involving muscle fatigue and strain. In fact, one study found that surgeons experience "site-specific pain in the back (50%), neck (48%), and arm or shoulder (43%). Additionally, fatigue was reported by 71% of surgeons, numbness by 37%, and stiffness by 45%" [4].

Replacing the monitor in the operating room with a VR headset introduces new issues. In addition to eye strain, a rather unique potential concern is VR sickness. When using a VR device, the brain demands that the image "be good enough to adequately fool our senses, but not have a level of quality that is well beyond the limits of our receptors" [8]. If these conditions are not met, the brain will process the offset as visual confusion and a painful headache may result. Many variables can have an effect on VR sickness, including pixel density and retinal image slip. Most VR headsets use magnification to provide an immersive view of the screen; however, by bringing the screen closer to the eyes, the pixel requirements of the screen are far greater and may be beyond the capabilities of current headsets [8]. Another issue that can arise with VR headsets and vision is that "retinal image slip due to VR artifacts may not match the retinal image slip encountered in the real world" [8]. In other words, VR headsets must live stream the video feed without lag so that the image that the user sees matches the real world that the user is feeling. Deficiencies in either of these categories may limit a headset's effectiveness in a lengthy surgical procedure.

2.2: Fabrication Research

We used the Unity game engine to design a platform for the headset to run off of. The reason we chose Unity was because of its versatility and large community of users. There is a large database of tutorials and existing projects that we used to aid in our design as well. Additionally, the Unity platform has a collection of intuitive and built in functions that allowed for the incorporation of the endoscopic image into a Vive-compatible format. Additionally, it allowed us to program (with the C sharp language) a trigger that will switch the view from operative to environmental using the internal positioning functions of the HTC Vive pro. Some of the additional resources we used were Makerspace employees. Our main contact was Taylor Waddell, a Virtual Reality Maintenance & Operation Manager at the Makerspace. We also reached out to Kevin Ponto, a professor at the School of Human Ecology here on campus for advice.

2.3: Client Information

Our client, Azam Ahmed, MD, is affiliated with the University of Wisconsin School of Medicine and Public Health. Dr. Ahmed is a neurosurgeon seeking a novel surgical VR headset to assist him in performing endoscopic surgeries.

2.4: Product Design Specifications

The ultimate goal of this project was to build upon the existing technological standard for VR headsets and add functionality that would allow the user to seamlessly transition between views at their own discretion. Our client specified that the headset should run virtual reality (VR) as opposed to augmented reality (AR), which superimposes images onto the user's surroundings. The final product had to be more immersive and offer a more expansive view than an operating-room monitor while delivering a reliable 1080p HD image. In order to perform this task, it was necessary that the product be compatible with the endoscope's BNC, coaxial cable output. Any mechanism programmed to switch the device between views had to be hands free and intuitive. In addition, it was important that our product not inhibit or alter the current surgical procedure.

Since the device would be used in high-risk procedures, the health of both the physician and patient were paramount. To ensure the safety of the patient, it was essential that the headset provide a live feed of the endoscopic camera with no more than 50 ms of latency lag. This value was chosen as 50 ms is the average time it takes for an image to travel from the retina to the brain [9]. One of the client's largest complaints regarding the current mode of endoscopic surgery revolved around physician discomfort. For this reason, one of the main factors we considered when choosing a headset was the distribution of weight.

Modern day headsets are manufactured from a mix of fabrics and polymers and fit a profile of roughly 225x185x140mm [10]. Plastics often form the structural chassis of the device whereas fabric is used to prevent fluids from soiling electrical components and to pad the headset's interface with the user. Another factor that was considered when choosing a headset was how well it prevented chemical penetration and how easily it could be sterilized. For a full review of design specifications, refer to the PDS located in the Appendix (Section 11.1).

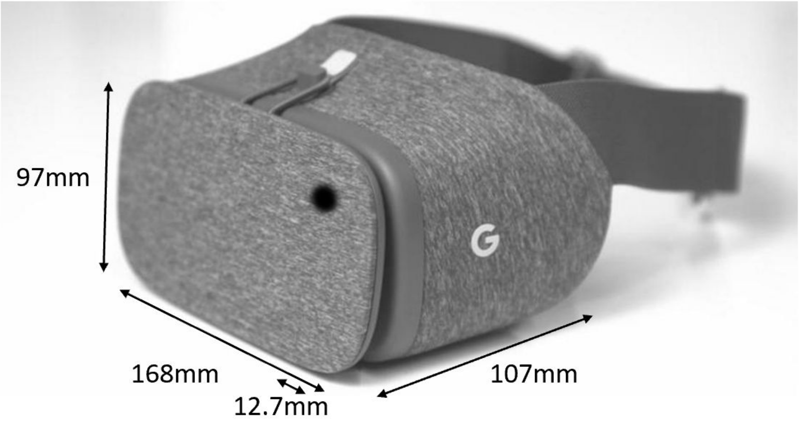
III. PRELIMINARY DESIGNS

3.1: Choosing a Starting Point

To best address our client's design needs, we reviewed various system design solutions. Our group considered making our own headset to display the endoscopic view, however, we felt this was beyond the scope of a single semester project, and it would be better to use existing headsets that have been developed for years. We started evaluating existing VR headsets on the market and the system that would be required for integration into the endoscopic procedure.

The three preliminary designs that we considered were the Google Daydream/Nexus, Dell Visor, and HTC Vive. Each design contained appropriate modifications to satisfy the requested functions of our client. Listed below are the detailed descriptions of each design.

3.2: Google Daydream and Google Nexus



[Figure 2] A schematic of the Google Daydream's dimensions. The image was retrieved from [11].

This first design is the only two-component design considered. It is composed of both a Google Daydream VR headset frame and a Google Nexus phone that is to be inserted into the frame. Despite the separate parts, it is the lightest, most cost effective, and simplest of the three design options. This headset could provide both the environmental and the endoscopic views. The camera of the Nexus phone could capture the environmental perspective. Furthermore, when the Nexus is not displaying the endoscopic video input, it would be displaying the view from its camera to give a user an external viewpoint. This transition could be triggered via a hands-free gesture.

For this headset to be of practical surgical use, there are some modifications that must be added to this system. The addition of a latitudinal head strap running across a user's head would compliment the horizontal elastic strap that comes stock with the Daydream frame to provide comfort and support. This addition would not only improve fit for a surgeon, but it would improve the safety of the design by ensuring that the headset does not slip from Dr. Ahmed's face during a procedure. As seen above in Figure 2, a hole would be cut in the the top right corner of the frame flap that holds the Nexus phone within the headset frame. This hole would correspond to the Nexus camera simply so that the camera can view the external environment.

Design Specifications [12]*:*

- Price: $290 ($235 Google Nexus + $55 Daydream frame)
- System Requirements: Nexus phone, Google Daydream headset frame, hardware connectors between headset and computer intermediate (transfers video from endoscope to Nexus)
- Weight: 19.2 oz. (10 oz. Nexus phone + 9.2 oz. Daydream frame)

- Development Environment: Android Mobile OS
- Connectivity: USB-C for video input and power

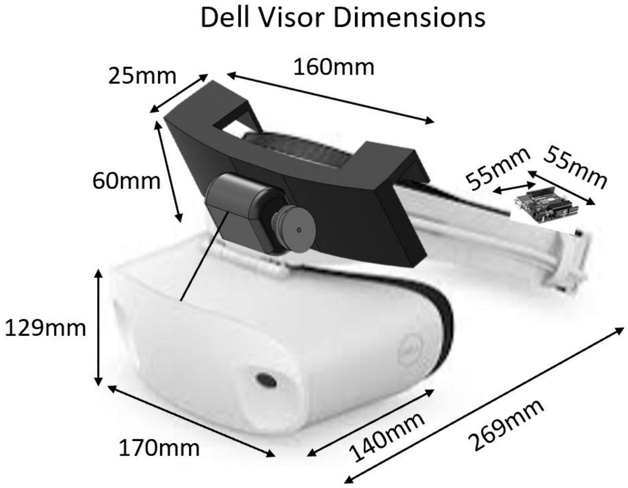
Advantages:

One of the main advantages of this design would be its limited ear obstruction because there is only a singular horizontal elastic strap wrapping around the sides of a user's head. In the event that our client needs to hear something during an operation, nothing will be in the way of hindering his hearing ability. Another benefit of this design option is that there is already an existing community of programmers familiar with operation of Android systems, so software modifications would be coherent and there is an abundance of resources available if necessary.

Disadvantages:

Because this design contains two pieces (phone and headset), there is a possibility that use of this design in the operating room could be unsafe if loose parts become disassembled during a procedure. This is not likely with properly designed fasteners, but it is a possible disadvantage of this design. There are also complications regarding the use of a phone as the display source and environmental view retriever. The Nexus would not provide as immersive of an experience as other design options with internal displays. Additionally, the environmental view would be skewed when viewed through the VR headset. As seen above in Figure 2, the offset camera of the Google Nexus located in the upper corner of the phone, would produce an offset image of Dr. Ahmed's vision field.

3.3: Dell Visor



[Figure 3] A schematic of the Dell Visor's dimensions. The image is from [13].

The Dell Visor was the second design considered for this project. The Visor includes a solid, adjustable headband that provides one of the most even weight distributions of any VR headset on the market today. The display of this headset is hinged and gives a user the option to flip the display up and out of the field of vision for temporary eye relief and environmental vision. As shown in Figure 3, this design option would include a hands-free mechanical feature that flips the display up when our client wishes to view his environment. When the surgeon wanted to raise the headset, he or she would step on a foot pedal with an attached Arduino. The Arduino would be hardwired to the winch motor. and signal which way the motor rotates, subsequently raising or lowering the display.

The design includes a few simple hardware modifications. First, the addition of a motor, wire, and hardwiring to the foot pedal and Arduino. Next, simple code would be written for the

Arduino microcontroller. No software modifications would be required for transitions between endoscopic and environmental views due to the mechanical nature of this design option.

Design Specifications [14]*:*

- Price: $540 ($450 Headset + $70 Mechanical Modifications)
- System Requirements: Dell Visor, miniature winch motor, wire, Arduino, hardwire, foot pedal
- Weight: 20.81 oz.
- Development Environment: Mechanical development and adaptation along with Arduino programming.
- Connectivity: HDMI 2.0 (video) and USB 3.0 A-Type (Data/Power)

Advantages

The advantages of the Dell Visor revolve around the even weight distribution, simplicity, and clarity of both perspective views. With the even weight distribution, Dr. Ahmed would be able to wear the headset for extensive periods of time during an operation without feeling neck strain from a front loaded display. Additionally, by flipping the display up, our client would be able to relieve his eyes of continuously staring at a display. Both of these performance factors would allow the design to be used with continuity and comfort. Because of the mechanical simplicity of this design, there would be minimal time spent programming and working with a foreign development environment which is a time consuming activity.

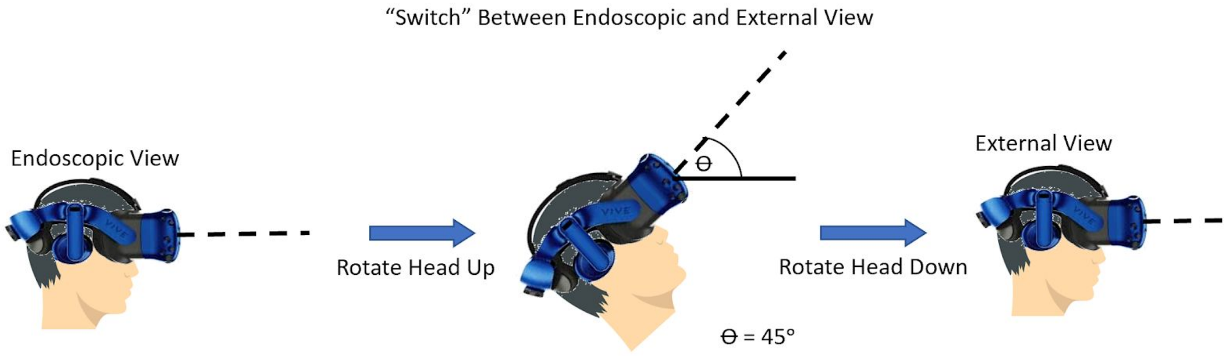
Disadvantages

Due to the mechanical nature and multiple different components of this design, there is the possibility of mechanical failure. This is a major drawback because a malfunction in the headset's ability to raise the display is unacceptable in the operating room. Additionally, if our client wishes to move about the operating table/around the patient, he would have to be cognisant of the foot pedal that is hardwired to the headset. This would be a major inconvenience and could hinder the safety of the operation.

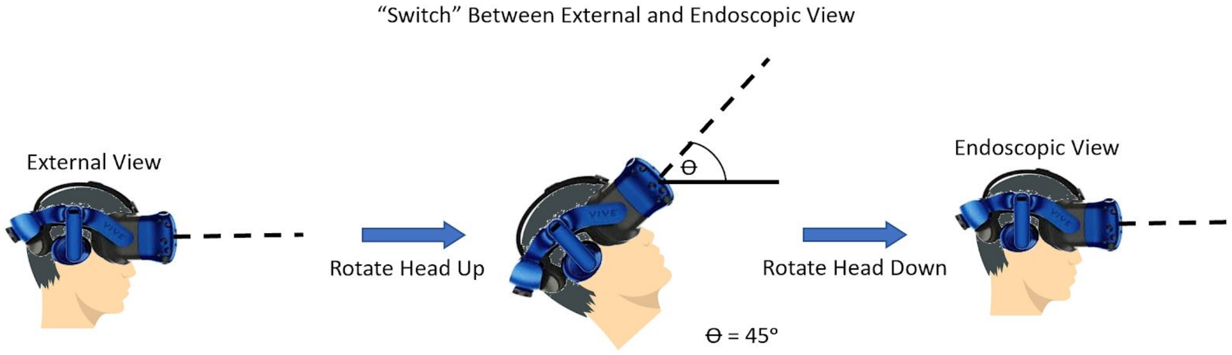
3.4: HTC Vive

[Figure 4] A schematic of the HTC Vive's dimensions. The image is retrieved from [15].

The HTC Vive is one of the most popular VR headsets on the entry level consumer market today. The headset is best known for its immersive VR experience and is widely used in the gaming community. The Vive requires an external computer to run the device, but has an option for a wireless connection to stream the display. Similar to the Google Daydream design, switching between endoscopic and environmental views will be implemented with software and the existing Vive front camera as seen in Figure 4. As shown below in Figure 5, a head rotation up 45° from parallel to the floor will switch the endoscopic stream to a live camera view of the environment. Once finished with an environmental view, the surgeon may switch back to the endoscopic view with the same head rotation up by 45° which can be seen below in Figure 6. With a live connection to a computer and numerous sensors integrated into the headset, this design has the ability to collect data on each operation for later analysis.



[Figure 5] A diagram depicting the head motion to “switch” from the endoscopic view to the external view.



[Figure 6] An diagram depicting the head motion to “switch” from the eternal view to the endoscopic view.

Design Specifications [16]*:*

- Price: $500

- System Requirements: HTC Vive headset, Vive to computer cable, computer, computer to endoscope cable
- Weight: 16.58 oz
- Development Environment: Unity game engine
- Connectivity: HDMI (video) and USB (data) and DCIN (power)

Advantages:

The strength of the HTC Vive design lies in its immersiveness and ease of software development. The HTC Vive is known as one of the best virtual reality experiences due to its display quality and isolation from the external environment. When used in endoscopy, the HTC Vive would be a notable improvement over conventional monitor displays, allowing for full attention of a surgeon to be directed towards the procedure. Additionally, the HTC Vive software can be developed using the popular Unity game engine. The Unity game engine has a strong user community and is known for being an easy to learn introductory platform. With a camera already included in the headset, no additional hardware modifications would need to be made to the HTC Vive.

Disadvantages:

The HTC Vive has an awkward weight distribution that could be uncomfortable to wear for long periods of time. Since the device may be worn for approximately ten hours, this discomfort could be a potential problem.

IV. PRELIMINARY DESIGN EVALUATION

4.1: Explanation of Design Matrix

[Refer to the Final Design Matrix and Design Criteria located in the Appendix, Section 11.2 and 11.3, respectively] The HTC Vive and Dell Visor both received the highest score for immersiveness. Both headsets were intentionally built for a high fidelity virtual reality experience. They both have high resolution displays, lense adjustments for sharpness of vision, and contoured frontal designs that isolate the user from the external device. On the contrary, the Nexus with Daydream was adapted to VR but not designed directly for it. The headset does not feature the same adjustments and contouring as the other two designs.

Equally weighted with immersiveness, comfort was the next criteria for evaluating the preliminary designs. The Dell Visor was the strongest design in this category (4/5), with the most balanced distribution of weight and most comfortable headband. The Vive and Daydream fell short of the Visor with front heavy designs and awkward headbands.

For programmability, the Dell Visor again scored the highest with a perfect score. The Visor does not require any special software implementation to switch between endoscopic and environmental view since it uses a mechanical transition (5/5). While scoring the best for programmability, the Visor scores the worst for physical modifications (1/5). The Visor requires an extensive mechanical component to be built and attached in order to raise and lower the headset. The fabrication of this would be much more difficult than the simple modifications that are needed to be made to the Daydream to expose the camera (4/5). Ultimately, the HTC Vive scores highest, with no external modifications necessary for proper view transitioning (5/5).

For the final categories, the designation was relatively straightforward. The Daydream was the cheapest option and scored (5/5). As for Safety and Sensors, the Vive won both these categories having the fewest separate components that could cause accidents and the most sensors available for data collection.

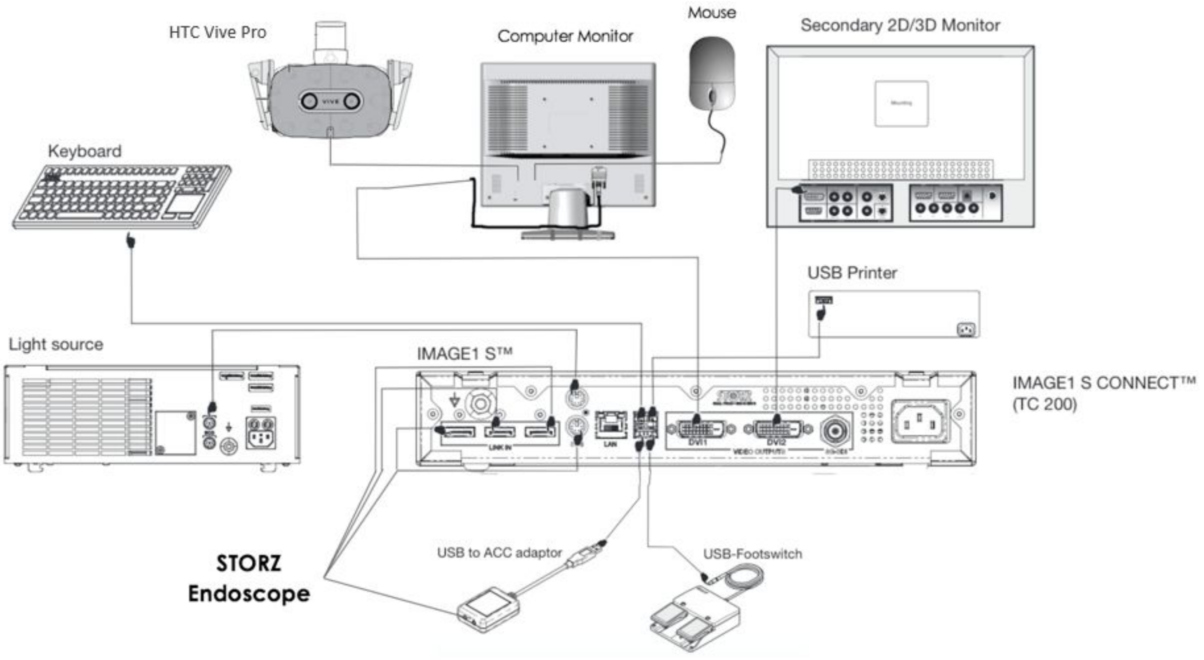
4.2: Final Design

We chose the HTC Vive because of its modifiable ergonomics, high quality resolution, and most importantly its fully immersive experience. This option allows the client to modify the headset so that comfort is guaranteed throughout long surgeries. The design features a feed switching mechanism that is triggered by a head rotation superiorly of 45°. We coded the switching mechanism with the help of two sources mentioned above. The display feed of the endoscope through the conventional monitor in the operating room will not be modified so that the nurses can be prepared. However, we will need to increase the lighting of the room so that the camera of the headset can appropriately display the environmental view.

V. FABRICATION/DEVELOPMENT PROCESS

5.1: Physical Components

The materials involved in this design project were a HTC Vive Pro VR headset bundle, computer, keyboard, mouse, an HDMI to HDMI cable, and a VGA to HDMI adapter cable. The HTC Vive Pro headset bundle for $799 includes the HTC Vive Pro headset, the headset connection cables for the computer and power, and the room sensors necessary for operation. Next, the computer needed proper specifications to support the headset. These specifications included: an Intel® Core™ i5-4590 or AMD FX™ 8350, 8 GB RAM, with at least one USB 3.0, and Windows® 10 OS [17]. Based on all of these specifications, we suggest buying the Acer Veriton for $903.30 (See Appendix 11.4). Along with the computer, any type of wireless keyboard and mouse acceptable in the Operating Room could be used with the computer. Last, an adapter cable to transition from a VGA output to HDMI input would need to be purchased to connect the computer to the endoscopy unit as well as an HDMI to HDMI cable to connect the computer to the headset.

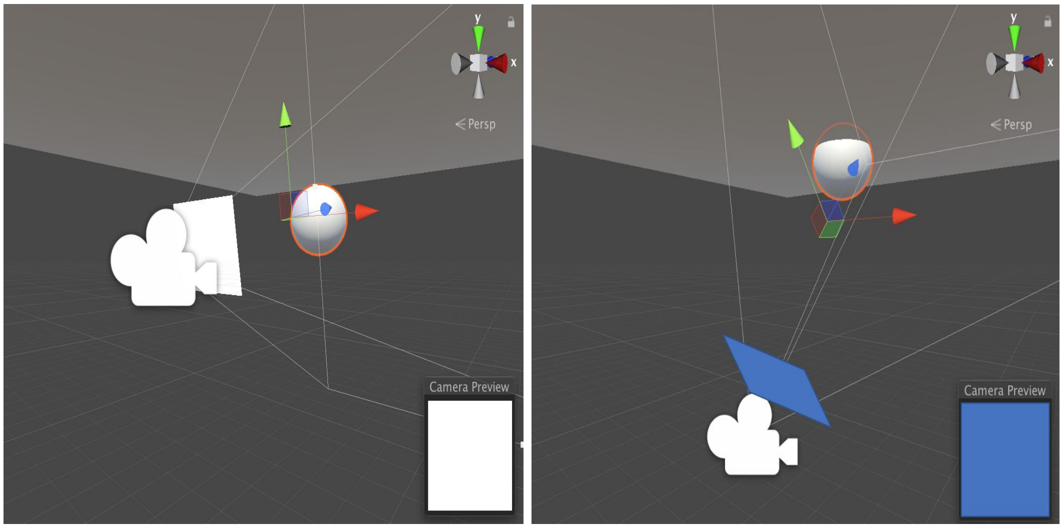


[Figure 7] A block diagram of all the components involved in the VR Headset for Endoscopy final design.

5.2: Software Implementation

The core of our fabrication was developing an application in Unity to manage the VR headset. The program consists of two main software components: displaying live video feed and transitioning between video streams. Through leveraging the library of existing classes provided by Unity, we were able to treat each video as a "Webcam" object [18]. The Webcam class initializes a live stream upon the start of the program bypassing standard compile time encodings of video files. Once both streams are initialized, the software is able to selectively display different feeds.

We accomplished the transition between environmental and endoscopic view using the graphical development aspect of Unity. A sphere object is attached to the user that is at a fixed distance in front of the user. When the user looks up, the sphere collides with a plane. Upon collision, a signal is sent to switch video feeds. This motion can be seen in Figure 8.



[Figure 8] A graphical representation of a user in the Unity environment. When the user looks up, the sphere collides with a plane and signals for the video stream to change.

VI. TESTING

Test One: External View Using Webcam Depth Perception

Depth perception is an important aspect of the VR headset because the surgeon will need to clearly navigate into the nostrils to conduct an endoscopic procedure. To address this, we tested an individual's ability to accurately pinpoint a particular location on a flat surface the size of an average adult nostril, 11mm [19]. The individuals tested had minimal to no experience using the external webcam of a VR headset which is consistent with that of a new surgeon's use of this application. However, to account for variation due to sight impairments from individual to individual, we will base this testing on the relative ability of an individual to conduct the same procedure using their normal vision.

The test procedure included four individuals that conducted the following procedure. First, the headset was set to the environmental view. Next, the tested individual was given the headset to place on their head and properly adjust so that the headset was comfortable. After two minutes of wearing the headset, the individual sat down in a chair. With this, another chair was placed in front of the individual with a piece of cardboard on the chair that was parallel to the ground and one foot below eye level as can be seen below in Figure 9. The piece of cardboard was 30 cm by 24 cm and had three dots that were 11mm in diameter randomly placed and assigned as number one, two, and three. The base of the chair was located 30 cm away from the base of the chair the tested individual was sitting in. The setup for the testing procedure was now complete.

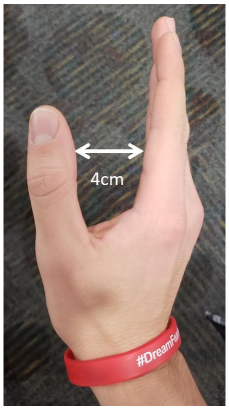
[Figure 9] A picture from the depth perception testing sequence in which a user seeks to accurately pinpoint an assigned location using a marker which represents a surgical tool.

To conduct the test, ten trials took place. A single trial was conducted by the following method. First, a test conductor announced a numbered dot for the tested individual to locate. Next, the individual placed a maker tip as closely to the assigned dot as possible, without moving the marker once it contacted the cardboard as seen above in Figure 9. Once the marker was in place, another test conductor used a ruler to measure the distance from the center of the dot to the tip of the marker. These data values were recorded in millimeters and placed in the data table shown in the Appendix (Section 11.5). This was then repeated nine more times. This entire procedure was repeated three more times for a total of four individuals.

<u>Test Two: Latency Time of the VR Headset Camera Feed</u>

The latency test of the VR headset front camera video feed measured how much of a delay is present in video displayed from the front-facing camera of the headset. This test involved two separate data sets of trials that were cross-referenced and analyzed to form conclusions. To set up the test, the necessary materials involved a yard stick, data table, and the HTC Vive Headset with assisting software and computer.

To conduct the testing, a test proctor and individual conducting the test stood face to face approximately half a meter apart from one another. To administer a trial, the individual being tested would hold their hand 30 cm in front of the headset at 15 cm below the chin so that the palm of the hand was oriented perpendicular to the ground as seen in the diagram below (see Figure 10).



[Figure 10] A visual representation of the hand orientation used to conduct the latency test for the camera feed from the HTC Vive Pro.

Next, the test administer held the 25 inch mark on the yard stick at a flush level with the plane of the thumb and pointer finger created by the individual being tested as can be seen below in Figure 11. The yard stick was oriented so that the one inch mark was closest to the ceiling. When ready, the test administer dropped the ruler at a random point in time at which the individual being tested attempted to grab the ruler as quickly as possible. The length of the ruler recorded was that visible above the thumb and palm of the hand. This process was repeated nine more times using the headset. Once this was completed, the individual repeated this testing without wearing the VR headset for a total of twenty individual trials. This test was conducted on four individuals.

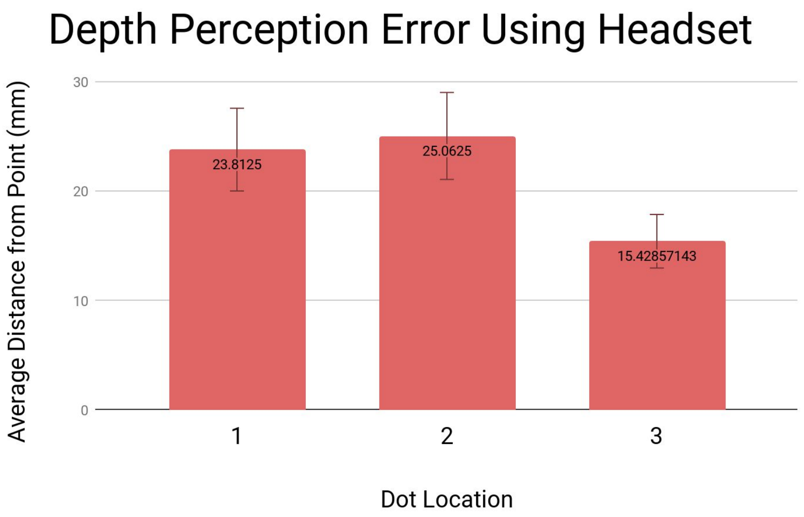
[Figure 11] A picture taken during testing showing a trial of the latency test in which a testee seeks to grab the yard stick as quickly as possible.

VII. RESULTS

Test One: External View Using Webcam Depth Perception

To conduct data analysis for test one, use of an excel spreadsheet and its calculation functions were used. For each individual tested, any extraneous data points were omitted. An extraneous data point was considered a maximum or minimum value +/- 20mm to the closest value for a given data point. Once extraneous data was eliminated, an average of the individual's distance from the assigned dot was calculated and analyzed. These values were then compared to zero based on the observation that all individuals were able to place the marker in the center of the dot every time when not wearing the headset.

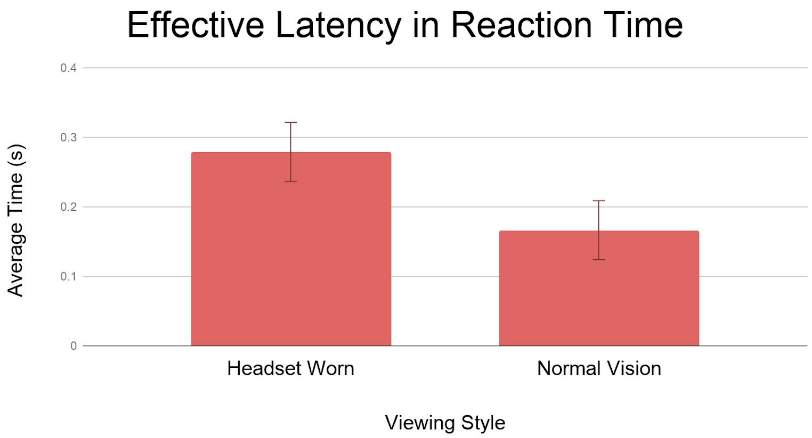
As seen below in Figure 12, a correlation between dot distance from the viewer and depth perception ability was present, though plateaued beyond a given distance. For example, the average error for dot three (the closest dot) was ~15.43mm, however, the average error for dot one and two were ~23.81mm and ~25.06mm respectively.



[Figure 12] A graph of the average radial distance test individuals' placed the tool mimic (a sharpie) to the assigned dot location on a piece of cardboard in front of the individual wearing the headset.

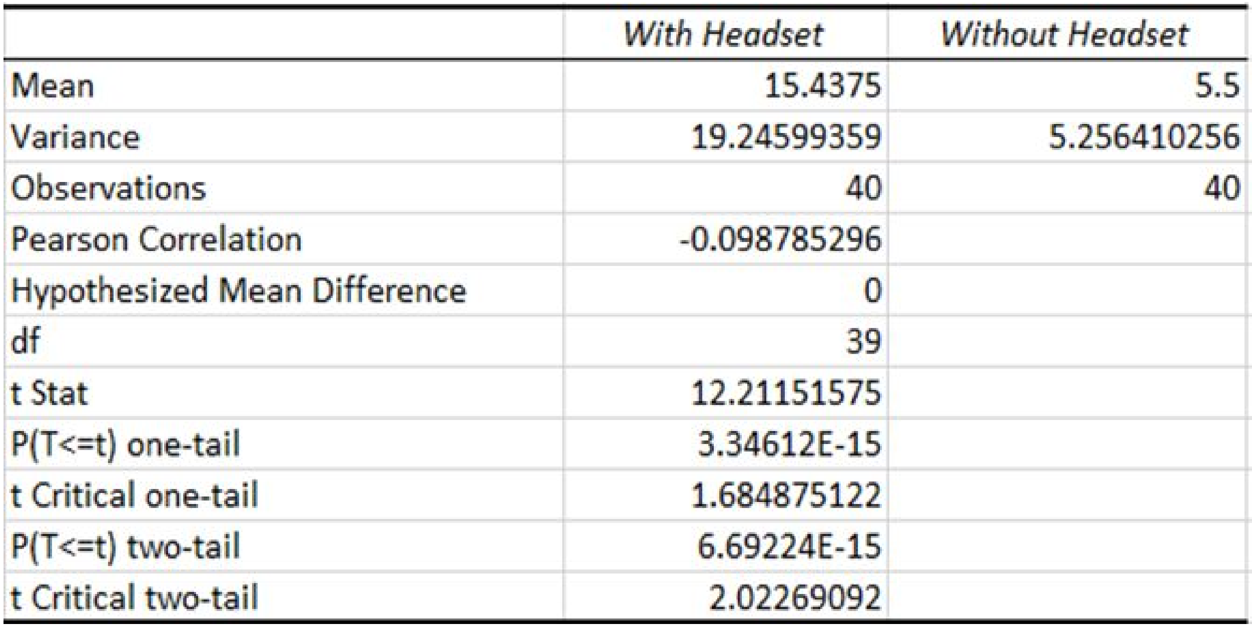
Test Two: Latency Time of the VR Headset Camera Feed

Upon completion of data collection for test two, the values recorded were then subtracted from 25 inches to give the distance the ruler fell. Once this distance was calculated, the average value of the distance the ruler fell was averaged for each individual's two data sets. The average distance fallen for each individual's two tests in inches was then converted to meters using the function: Converted Value (m) = (2.54 * Recorded Value)/100. Using the converted values, the time the ruler was falling was then calculated using the function Time of Fall = SQRT((2*(Converted Value))/9.81). Upon completion of this, the values for all individuals wearing the headset and not wearing the headset were then averaged and graphed as shown in Figure 13. On average, an individual grabbed the ruler 0.11261 seconds slower when wearing the headset. Additionally, a two sample t-test was performed between the two sets of data with a confidence level of .05 to determine if there was a significant difference between. The resulting p value was 6.922E-15 as seen in table 1, which is less than .05, meaning there was a significant difference between the populations.



[Figure 13] A graph of the average reaction time for individuals to catch a ruler dropped above their hand wearing the HTC Vive and not wearing the HTC Vive.

[Table 1] A two-sample t-test comparing the average reaction time for individuals to catch a ruler dropped above their hand wearing the HTC Vive and not wearing the HTC Vive.



	With Headset	*Without Headset*
Mean	15.4375	5.5
Variance	19.24599359	5.256410256
Observations	40	40
Pearson Correlation	-0.098785296	
Hypothesized Mean Difference	0	
df	39	
t Stat	12.21151575	
P(T<=t) one-tail	3.34612E-15	
t Critical one-tail	1.684875122	
P(T<=t) two-tail	6.69224E-15	
t Critical two-tail	2.02269092	

VIII. DISCUSSION

From the collected data and statistical analyses, we can conclude that the camera on the HTC Vive that was used to conduct the latency and depth perception tests significantly puts the user at a disadvantage compared to normal vision. There was, on average, around 100ms of lag while wearing the headset when compared to not wearing the headset as shown in Figure 13. This is about double the amount of time it takes for information to travel from the retina to the brain [20]. The extra lag time is a major concern moving forward because our client needs to accurately be able to place an endoscope in a patient's nasal cavity without any work flow interruption of the surgery. Additionally, our testing shows that the HTC Vive external camera has significant depth perception issues. Figure 12 shows that closer images are easier to navigate towards and that the quality of depth perception decreases as this distance increases. Thus, the depth perception of the camera on the HTC Vive is not adequate for the application to the operating room and further testing with a dual-camera headset will need to be completed. Testing was completed on the HTC Vive, which only has one external camera. We plan to repeat the lag and depth perception testing with the HTC Vive Pro which has two external cameras positioned in a binocular fashion. We hope that the HTC Vive Pro will provide a more appropriate stereo vision for the environmental view of the final design and testing results will improve when testing is done on the same four individuals under the same conditions. Our goal is to get results from multiple test subjects consistently located within the 11mm diameter circle, comparable to an adult nasal cavity.

While conducting the tests, we also experienced external sensor signaling issues to the VR headset system while it was in use. The external sensors placed around the VR room in the

Makerspace that allow the Vive to perceive its position in space, would lose connection to the headset when an object or person interrupted the signal. Without the completion of this signal, the headset would go blank regardless of the view it was streaming to the user because the headset could not be located. This is a concern that will require testing in the operating room to validate if it is a significant issue or not.

A final major concern is that our final design has not been tested by our client for the full duration of a surgical operation. No data has been collected regarding if there is any physical strain from wearing a headset for 10 plus hours at a time, or eye irritation from extensive time staring at the display. We must determine the practicality of wearing this final design for long periods of time before it can be implemented in the surgical setting.

Our client has also suggested some additional modifications to the final design: a hands-free feature that can cause the endoscopic camera to zoom in and out, a 3-D input option that allows endoscope feed to be seen in the third dimension rather than on a plane, and customizable gestures to initiate the switch between views. These are secondary modifications that can be made once the final design has been deemed appropriate, practical, and safe for use within a surgical setting.

Although our final VR headset design has a lot of future progress to be made, it did realize major innovative application for the operational atmosphere. The final design gives our client a truly immersive experience; he will not be exposed to subliminal vision distraction throughout the operating room while performing endoscopic surgery. Additionally, the compatibility of the VR headset with the endoscopic feed eliminates the need for our client to statically stare at a bulky monitor without being able to move himself or his vision field around the operating table. Finally, this design has demonstrated the foundational potential of VR to be used in other surgical operations. Our final design can be further applied to other surgeries that require real-time imaging from a camera and simultaneous playback on a VR display.

IX. CONCLUSION

Through this design process we strived to create a more immersive endoscopy experience for our client. Although monitor displays are the present standard for viewing procedures in the operating room, our client believed that this status quo could be outcompeted by a surgical VR headset which provides a high quality image independent of where the head is oriented. The client's main concern with headsets currently on the market was that they obstruct the normal workflow of an operation as the surgeon cannot view the surrounding environment to interact with other staff. To address this problem we developed three potential solutions. Two of the solutions used a software implementation that switched the display of the headset from an endoscopic view to an environmental view through an external camera, while the other mechanically raised and lowered the headset allowing the surgeon to see the environment. After considering the strengths and weaknesses of each design in a decision matrix, we decided to move forward with a software implementation using the HTC Vive Pro. The Vive Pro's dual front facing camera and compatibility with popular development environment made it the ideal platform for addressing our client's needs.

We sought to reach our vision by using the popular game engine, Unity. With Unity, we created a program that allowed a webcam live stream (mimicking that of an endoscope) to appear on the display of the HTC Vive Pro. Additionally, we implemented a dynamic trigger feature that would switch the view option displayed by the headset when a user tilted their head upward beyond 45°. The success of our final design was proved and tested on the single camera HTC Vive. Through statistical analysis it was determined that significant latency (experimentally determined to be 100 ms) and depth perception disparities existed when using the headset for precision movements. Some of these issues may be remedied by the use of the dual camera Vive Pro. From there, possible optical modifications could also be made to improve usability in a surgical setting for our client. In the future, our client will also need to test our final design for extended periods of time comparable to the duration of a surgery to see if wearing the headset for long periods of time causes any physical strain or eye irritation. Once the basic functionality of our headset to display and switch views has been tested and refined, additions can be made to improve user friendliness. Such changes include creating a feature that allows the user to customize the head motion that triggers view transitioning. Additionally, another feature that could be implemented in the future is a function that would adjust the zoom of the endoscope with a programmed head movement.

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XI. APPENDIX

11.1: Product Design Specifications (PDS)

VR Headset for Endoscopy and Microsurgery

Product Design Specifications

December 12, 2018

Client: Dr. Azam Ahmed
Advisor: Dr. Willis Tompkins
Team Members:

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Function:

Dr. Azem Ahmed from the neurosurgery department of the University of Wisconsin - Madison School of Medicine and Public Health presented this team with the task to improve surgeon visualization during endoscopic procedures. Endoscopic surgeries have become increasingly prevalent in the operating room along with the visualization techniques used to perform them [2]. Traditionally, large monitors have been used to display the images from the surgical tools (endoscopic view), however, these are bulky and do not provide as immersive of an experience for the surgeon as other methods do. This problem has been partially addressed by using virtual reality (VR) headsets. One major limitation of these, however, is that they do not allow the surgeon to see anything outside of the endoscopic view. This is a problem as the surgeon will have to remove the headset everytime he or she has to change instruments, or perform an action requiring a clear line of sight (environmental view). This team's goal is to create a VR headset that would allow the surgeon to transition from the endoscopic view to the environmental view without the use of the surgeon's hands, all the while presenting a continuous, non-interfering, and immersive experience for the surgeon.

Client Requirements:

- Create a more immersive view for performing endoscopy.
    - Endoscopic surgery is currently performed with the use of large display monitors stationed above the head of the patient. The monitors occupy a

    - small field of view for the surgeon and result in a suboptimal and potentially distracting means of viewing the procedure.
    - The client would like a wide field of view display that allows for fewer distractions. The more immersive viewing experience will make anatomical visualization easier and facilitate more effective endoscopy.
- Maintain smooth workflow of endoscopic procedures in operating room.
    - The client must be able to conduct surgery unobstructed by the new display platform. Any kind of immersive display must allow for an easily accessible environmental view. Cords or accessories to the display must not hinder movements of the surgeon or others in the operating room.
- Create an ergonomic platform for the surgeon using a new interface.
    - The surgeon will be using the display for long periods of time. The display must therefore be comfortable to wear and intuitive to interact with.

Design Requirements:

1. Physical and Operational Characteristics

a. *Performance requirements:*

The designed VR headset must comfortably sit upon the surgeon's head for the duration of an endoscopic surgery, which averages about 10 to 12 hours according to Dr. Ahmed. Moreover, the VR headset should produce minimal additional strain on the surgeon aside from inevitable operating pains [3]. In terms of technical performance, the headset must reliably deliver 1080p, standard HD display to the user throughout the course of an endoscopic surgery. This display must be a continuous feed from the endoscopic camera communicated through hardwire or bluetooth. Any source of video lag could be detrimental to the surgery. Additionally, the VR headset should be able to effectively switch from the endoscopic view to the environmental view through hands-free command at various times during the course of the operation.

b. *Safety:*

There are two main safety requirements for the device. The first concerns the surgeon and the second concerns the patient. Since the duration of the surgeries being conducted are so long, the headset has to be comfortable and ergonomically friendly enough so that the surgeon doesn't fatigue. If the surgeon is not performing to the highest level possible, the health of the patient is at risk. Additionally, the device has to provide a continuous and clear, immersive experience for the surgeon otherwise the health of the patient is once again at risk. The most frequent major complication of endonasal skull base surgery (the kind performed by Dr. Ahmed) is a cerebrospinal fluid (CSF) leak [5].

This results from accidental tissue damage. Any lag or deficiency in visualization by the surgeon will increase the risk of CSF leaks and other complications.

c. *Accuracy and Reliability:*

The VR headset must administer a reliable communicative feed between the endoscopic camera and the display. For seamless streaming, the laging latency should not exceed 30 ms between the video input and output [4].

d. *Life in Service:*

The device must function with perfect accuracy during all operations with a projected lifespan of five years based on technological trends and development of VR technology. It must also withstand regular use without deformation or breakdown due to standard sterilization procedures.

e. *Shelf Life:*

The device must be able to be stored in a stable environment without having contamination issues involving sterilization. Along with sterilization, batteries must be self-contained with no issues involving the spilling of harmful contaminants.

f. *Operating Environment:*

The device will be initially used in neurosurgical operating rooms. These operating rooms are dark environments with focused light on the patient. The OR contains both sterile and non-sterile fields that must be maintained through proper workflows. A variable number of monitors are in the OR which may be utilized for external displays of the endoscopy view.

g. *Ergonomics:*

The VR headset will be worn for 10-12 hours during surgery and must fit comfortably on the surgeon’s head with optimal comfort. The VR headset must also be balanced very well and fit snugly to the head to avoid any tipping or movement of the device during regular use. Along with a comfortable fit, the design must not cause any strain or pain in the head, neck, or spinal regions due to sustained use. The design must focus on easing the view of detailed information pertinent to the procedure that will minimize strain on the body. Within the design, any cords or wires used must be contained and controlled to ensure no entanglement between body parts and cords occurs.

h. *Size:*

The current oculars used by surgeons cover the eyes and part of the front of the face. This is comparable to current VR headsets which vary in size and are approximately

225x185x140mm. These dimensions will serve as a general baseline for the sizing of our VR headset.

i. Weight:

The weight of the top six major VR headsets range in weight from around 453 grams to 610 grams. The average of these is 501 grams [6]. As of now the oculars used by neurologists now range from about 453 grams to 906 grams.

j. Materials:

The base of the VR headset will be the main material needed since the plan is to modify an existing product. In addition to the headset, cameras will be needed to view the operating room during surgery. The headset could end up being connected to the endoscopic tower via bluetooth but if not we will need to acquire an HDMI cable or USB cable to connect the headset. Depending on what headset is chosen, the design would require the separate purchase of a smartphone to display surgery.

k. Aesthetics, Appearance, and Finish:

The headset will be set on the face of the operator and should fit comfortably for long surgeries. It will have appropriate weight distribution and have small cords connected to the back of the headset. The outside of the headset itself will most likely be unmodified and look similar to the factory versions of the product.

2. Production Characteristics

l. Quantity:

For this project, only one prototype will be constructed. The one prototype will prove whether it will be necessary to continue production and whether it would be feasible to create more on a larger scale for mass distribution. If the prototype excels while being used in a surgical setting, creation of more could be reality and will be pursued.

m. Target Product Cost:

This product is seeking to compete with current television display screens that are approximately forty inches if not larger. The televisions like what Dr. Ahmed is using likely are priced at approximately $500 and may be even more expensive. Our more immersive solution would likely be more expensive than this, but we would like to keep it under $2000. This price would likely involve the entire assembly along with software expenses and any other incurred costs. Though this may increase throughout the development of the device.

3. Miscellaneous

n. *Standards and Specifications:*

VR headsets of display monitors for surgical procedures fall under the Class I Medical Device FDA regulation [1]. Currently, the FDA sets the requirement of going through the 510(k) acceptance process for all new medical devices that are seeking to be offered in the future medical device market. These applications must be sent at least 90 days before individuals intend to market a device and go through a very thorough investigation.

o. *Customer:*

The client, Dr. Azam Ahmed mentioned that he would prefer focusing on VR devices over other technologies such as AR. He also communicated that he would prefer if the device can be wireless so that there is not tangling of cords that can occur. Additionally, Dr. Azam iterated that this product cannot stall as a lag in video timing or quality would be detrimental to his patients health. Last, Dr. Ahmed has warned that lighter and lighter designs would be best as they will decrease the strain put on surgeons during these extensive procedures.

p. *User-related concerns:*

The client's main concern for the device is maintaining a smooth workflow. While the immersive view allows for more effective endoscopy, a potential side effect may be preventing environmental views or adding obstacles to the surgeon or team. Our solution must be cognizant of the activity in the OR as well as the motions required of the surgeon during operation. This may be accomplished by offering a product with a seamless transition between endoscopic and environmental views, and potentially through the addition of voice commands by allowing the surgeon to change views without the need to move his hands.

q. *Competition:*

Currently, the client uses a large monitor to display the output by the endoscope, similar to that created by Synaptive Medical. This technology presents a wide image that capable of ideal image quality, but lacks the immersiveness of a VR headset and required the surgeon to crane their neck to one side and away from the patient during procedures. Other competing technologies include all VR headsets currently on the market that could be adapted to be used in the OR. Many of these existing products appeal to a recreational audience, and are not adapted to the OR desipite their use of bluetooth, 360° POV angles, and sleek designs. Similarly, AR is another type of competing technology applicable to endoscopic procedures.

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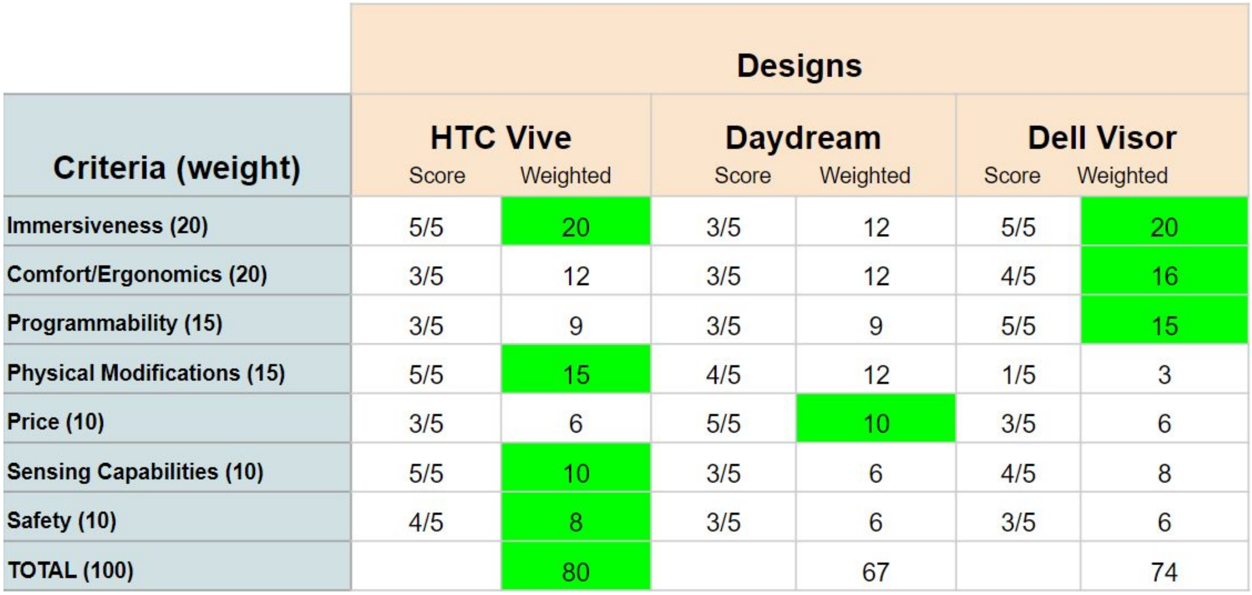
11.2: Final Design Matrix



	Designs					
Criteria (weight)	HTC Vive		Daydream		Dell Visor	
	Score	Weighted	Score	Weighted	Score	Weighted
Immersiveness (20)	5/5	20	3/5	12	5/5	20
Comfort/Ergonomics (20)	3/5	12	3/5	12	4/5	16
Programmability (15)	3/5	9	3/5	9	5/5	15
Physical Modifications (15)	5/5	15	4/5	12	1/5	3
Price (10)	3/5	6	5/5	10	3/5	6
Sensing Capabilities (10)	5/5	10	3/5	6	4/5	8
Safety (10)	4/5	8	3/5	6	3/5	6
TOTAL (100)		80		67		74

[Figure 14] The VR for Endoscopy Design Matrix. Green indicates which design scored highest in each category. The final row indicates the overall score of each design. Scores were obtained by taking each design's individual score out of 5 and then multiplying that score by the weight of each category. Final scores were obtained by adding all of the weighted scores of each design.

11.3: Design Criteria

Immersiveness (20): *The ultimate goal of the project is to create a more immersive view of endoscopy. Device experience evaluates the experience of viewing the endoscopy. This includes field of view, quality of display, and vision adjustments for reducing eye strain.*

Comfort/ergonomics (20): *The device must be used for long periods of time. Comfort evaluates the experience of wearing the headset. Factors affecting this score include weight, distribution of weight, shape of headset, etc..*

Programmability (15): *The hands-free switches between environmental view and endoscopic view must be created with software. Programmability refers to the ease and flexibility of the development environment for the headset. This includes community/documentation of the development environment as well as the relative power and capabilities of the platform.*

Physical modifications (15): *Some of the devices selected for the design matrix would require physical modifications to the project. This would increase the complexity and the work required, and could potentially ruin the device itself.*

Price (10): *While the client didn't specify the amount of money he was willing to allocate towards the project, it is safe to assume that minimizing the cost of the design is always a goal. Additionally, some devices are more expensive because they have additional capabilities that are not relevant to this project.*

Sensing Capabilities (10): *The project requires us to have a hands free trigger to switch between the environmental and endoscopic view. Sensors of some sort will be needed in order to accomplish this. The greater the sensing capabilities of the headset, the more options we will have in order to accomplish this task*

Safety (10): *This is a criteria for any project. The design we choose should minimize any risk associated with it for both the patient and the doctor. The main factor to consider with this is reliability. If the device stops working mid surgery, there could be drastic consequences.*

11.4: Materials and Costs

At this moment, there have been no purchases. Our client provided us an open-ended budget, but we decided that it would be best not to . In addition to the materials on the chart below that need to be purchased, we will use the machinery found in the operating room including a monitor, an Image1 S system to receive endoscopic input, and a surgical clip making tool. With the computer, we will need to use Unity software in order to access the program that we created.

Keyboard and Mouse	Newegg (**N82E16823126097)**	$14.44
HDMI-VGA Cable	Amazon ASIN: B06WGP2G3H Model number: 000123black	$11.59
HDMI-HDMI Cable (15ft)	Newegg **(N82E16882850010)**	$6.08
HTC Pro	Dell	$799
Desktop Computer	Newegg (**N82E16883101628)**	$903.30
TOTAL		$1734.41

11.5: Testing: Raw Recorded Data

Test One: External View Using Webcam Depth Perception

[Table 2] Raw data recorded during the depth perception testing sequence.

Depth Perception Error Using VR Headset					
*Displayed values are the radial distance from the dot in mm					
Dot Location	Sam Simon	Sam Peters	Tom Geissler	Josh Niesen	Average For All Individuals
2	20	3	0	21	11
1	8	25	13	10	14
2	24	61	19	56	40
1	35	22	36	19	28
1	25	18	32	21	24
3	20	31	17	29	24.25
2	26	16	61	12	28.75
2	18	15	26	23	20.5
1	38	55	21	3	29.25
3	4	4	3	~~55~~	16.5
Average Distance from Dot 1	26.5	30	25.5	13.25	23.8125
Average Distance from Dot 2	22	23.75	26.5	28	25.0625
Average Distance from Dot 3	15	17.5	12	16.5	15.43
Overall Average Distance from Dot	21.8	25	22.8	24.9	23.625

Test Two: Latency Time of the VR Headset Camera Feed

[Table 3] Raw data recorded during the latency time of the VR headset camera feed testing sequence.

Latency Time of the VR Headset Camera Feed			
Name	Headset Worn Drop Time (s)	No Headset Worn Drop Time (s)	Difference in Time (s)
Tom Geissler	0.2639116091	0.1592925235	0.1046190856
Sam Peters	0.296702915	0.1543392083	0.1423637067
Josh Niesen	0.3078384739	0.1509467236	0.1568917503
Sam Simon	0.2594591725	0.2048046731	0.05465449936
Averages	0.2819780426	0.1673457821	0.1146322605