VIRTUAL TACTILITY IN AUGMENTED SURGERY

Phase III Report

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Contents

1 Executive Summary/Introduction

The following report develops an approach to finding a solution to the problem developed in the Phase I/II report: ***The lack of immersiveness and efficiency of virtual reality inhibits the ability to integrate medical training processes in a virtual or augmented environment.*** *This process began by determining the scope of work and deliverables necessary for this project:* ***Developing both a proof of concept and physical prototype utilizing virtual/augmented reality technologies combined with the use of different manufacturing techniques such as 3D printing, CNC routing, etc. to create a 3D portable environment for practice or training purposes.*** *Next, various product requirements created for when testing the potential prototypes generated for solving the initial problem statement. Some of these included the weight of the product, hand motion restriction, the ability to track the motion of the hand, and prevent physical harm to the user. Once the product requirements were covered, a Gantt chart was made for a succinct and effective management approach to reach the final scope of work and deliverable. Ideas and concepts were then discussed for any potential solutions to the problem. Finally, using various design criteria a final solution was found and a three step prototyping methodology was followed to visualize the solution. The three steps include sketching, 3D modeling, and physical prototyping.*

2 Mission Statement

Developing the scope of work and deliverables for this project required answering three questions to the problem statement: why, how, and what. The problem requiring these answers was defined in the Phase I and II report: **The lack of immersiveness and efficiency of virtual reality inhibits the ability to integrate medical training processes in a virtual or augmented environment.**

The first question that was answered to determine the scope of work was why is a solution needed. The problem stated above steered the direction of the project towards a product that can be utilized in medical settings by students and professionals for an improved training mechanism for complex procedures and surgeries. Background research has demonstrated the need for an efficient, reliable, and consistent mechanism for providing those in the medical field a readily available training environment to minimize potential risks for patients. Most risks that patients face include how the clinician responsible for their health is trained and applies this training. Therefore, a training method was needed to be developed that can give both medical students and professionals access to more frequent practice sessions to improve the ability to perform various procedures. A solution would also give current medical and residency students a chance to have a more realistic and technical approach to clinical work.

Next was understanding how to develop a solution. A current method used to help improve training given to medical students includes simulations of various surgeries and procedures. While this may give them a visual aid, it does not provide a physical approach to performing a surgery. However, the tool used for these simulations, virtual reality, was a step in figuring out the how part of the solution. Virtual and augmented reality have a large scope in different industries, the largest being health-care. The basics of these technologies is simple: integrating a virtual environment into the real world. Various mechanisms to perform this task include virtual reality headsets, infrared detecting technology for simulating real life objects, 3D scanning tools for creating virtual environments, wearable gear for simulating a physical feel of virtual objects, etc. After having figured out how to reach a solution, an attempt was made to create a method of integrating different virtual/augmented technologies.

The final question answered was what can be done to develop a working solution. Keeping in mind the constraints and requirements of the project, various ideas were generated and then combined with current technologies to create a final concept. These methodologies and the final concept are described more in depth in the rest of the report.

Once all three questions regarding the defined problem statement had been answered, a final mission statement was generated: **Developing both a proof of concept and physical prototype utilizing virtual/augmented reality technologies combined with different manufacturing techniques such as 3D printing, CNC routing, etc. to create a 3D portable environment with physical feedback for practice or training purposes.**

3 Product Requirements

Our goal is to create a solution that fits certain requirements that can be tested before and after implementation to indicate the solution's effectiveness. Before determining exactly what certain requirements that our product/solution should encompass, we wanted to verify specifically what we needed the proposed apparatus to be able to do, and what customer needs it must be able to meet. Based upon those parameters, we came up with several product needs and customer needs the apparatus must embody.

One main need we decided on was that the product must enhance or add to current AR/VR technologies so that they can be applied in a surgical setting. Secondly, the product must be able to actively relay data collected through various sensors from reality to the virtual environment, and also active relay data form the virtual world to the sensors and micro-controllers in the physical world. The perspective of our main target market, medical training, was also taken into account to determine various customer needs. Various needs such as the ability to utilize actual surgical instruments, comfort, complexity, and maneuverability were taken into account in order to generate the product requirements.

Based on the collection of our thoughts and various research into customer needs, we were able to create a list of product requirements that our apparatus should be able to meet, as can be seen in Figure 1: Product Requirements Chart. Considerable amount of the requirements went to the functionality of the product, however, other requirements were also taken into consideration, such as the safety, aesthetic, and the durability of the product. For each requirement, it was categorized into its distinct design criteria, which would be used later for the concept selection portion of the report. Each of these requirements were then given a metric based on how the certain requirement could be measured from external research. Marginal values were based off of various tests, observations, and research and what would be the most ideal limit of each requirement.

#	Product Requirements	Design Criteria	Metric	Ideal	Marginal
1	Restrict the motion of hand when needed	Difficulty/Ease of Use	Newtons	<60	<40
2	Allow users to use standard medical tools in VR	Difficulty/Ease of Use	# of tools applicable	>20	>10
3	Needs to be an easily wearable and interactive 3D environment	Difficulty/Ease of Use	Rating from 1-10	>8	>5
4	Minimize the size of the 3D environment	Footprint	cubic meters (m^3)	<1	<1.5
5	Efficiently simulate hand motions into Virtual Reality	Delay	Frames per seconds (fps)	>200	<60
6	Weight of the product	Weight	kilograms (kg)	<10	<15
7	Durability of the 3D Environment	Tensile Testing/Durability	Pascal (kPa)	>250	>200
8	Physical Appearance of the 3D Environment	Aesthetic	Rating from 1-10	>8	>5
9	Cost of Producing one unit	Cost	Dollars ($)	<200	<400
10	Prevent physical harm to user	Safety	Rating from 1-10	>10	>9
11	Utilize materials that are environmentally Friendly	Residuals	Rating 1-10	>10	>7

Figure 1: Product Requirements Chart. A list of of requirements with their Design Criteria, metrics, and its Ideal and Marginal values

To determine what force is optimal to restrict the motion of the hand, we utilized a force sensor to determine what force in average is produced by a hand in motion and when attempting to restrict movement.The average force was approximately 44 Newtons when stopping simple hand motion. In an surgery, there are in average approximately 20 different surgical tools used throughout the surgery. [1] However, due to possible limitation of the leap motion, we set the marginal value to 10 surgical tools. When deciding the ease of usage or interaction with the 3D Environment, a rating system was created based on how comfortable we would like our environment to be and what our threshold is for comfort over functionality. When deciding on how we want to minimize the footprint of the actual environment, we decided the maximum dimensions that would allow for free motion in 3D space without wasting unnecessary materials. In order to measure how determine efficiently and quickly our product can simulate our hand in the virtual environment, we looked in the delay of the Leap Motion which is approximately 200 frames per second. We wanted to create an product that portable from one work space to another, therefore we determined the optimal weight would be around 10kg.The durability of the apparatus was mostly based on intuition as there are no similar prior arts, and at this point of the project, we did not know which materials we would be using to make the 3D environment. The cost of producing one unit most be below our $400 budget, but ideally we would like to only use half of the amount. We created a scale for 1-10 for both aesthetic and safety of the product. 10 signifies the safest product possible and the most aesthetic.

4 Project Management

During the first few days of exploring Virtual and Augmented Reality (VR/AR) we realized that as a still developing field there would be thousands of various issues we could attempt to explore. Specifically, the fundamentals behind how humans perceive our surroundings still remains a huge area for discussion. The specific sensation our team decided to research is touch and how to mimic the associated stimulation without the need for invasive, complex machinery. Our minimal viable product at the end of the semester is to have explored one method of mimicking physical touch and evaluating the pros and cons across the medical industry.

To make our project successful and ensure we produce results that we, as well as others, can learn from, our project was split into four stages. We used a Gantt chart to organize this process.

The first stage was basic research and analysis of prior art and what issues still remain in the VR/AR fields (see Figure 2: Gantt Chart of Project Deliverables). Furthermore, we explored how these technologies have been implemented in the current medical and construction industries. We specifically chose these industries as VR/AR has shown potential in improving occupational training methods and we believe our solution best directly targets these markets. After this initial research, it was necessary to dive further into the current technologies attempting to mimic touch and evaluate the pros and cons of each. This research was necessary for two main reasons:

1. *To ensure that we understand the role VR/AR can play in a medical setting*
2. *To ensure that our designed solution would be unique and a building block for future exploration.*

At the end of the initial research process we would discuss the specific problem we wanted to target and narrow down and frame the question.

Once completing the first stage, we moved onto Concept Brainstorming and Selection (see Figure 2: Gantt Chart of Project Deliverables). This consisted primarily of hashing out and refining ideas that we all had in relation to the problem statement. Initially we did individual research and idea generation in order to develop unique perspectives and bring a variety of solutions. Later, in the second and third weeks of this stage we began creating physical representations and compiling lists of required resources. The largest part of this section would consist of the final discussion of how to integrate the various components of this project, specifically, the physical machinery, the computer program, and the medical environment.

The third stage of our project would be Solution Visualization - implementing our research and brainstorming into a physical prototype that would be tested and critiqued by medical professionals it would seek to assist (see Figure 2: Gantt Chart of Project Deliverables). This stage would involve a high level of communication as each member of the group would be in charge of developing their area of the project however he/she would also need to communicate any constraints that may arise. The final aspects of this stage involved integrating the various components each member worked on and performing rudimentary testing to ensure all functions work as intended.

The final and fourth stage of our research project was Testing and Refinement (see Figure 2: Gantt Chart of Project Deliverables). This stage would be especially useful to those who desire to build off of our research as we would collect outside feedback and prepare a "Future Exploration Summary" providing specific avenues we think would be the most promising. We would also compile a list of proposed refinements in descending order beginning with those deemed most critical.

Regarding the funding received for our research, the bulk of the funds would go towards purchasing the necessary technology to develop the prototype. Fortunately, we did not need to purchase the HTC Vive as we were able to use the resources available at UVA's Makerspace labs and Robertson Media Center saving us around \$ 800 dollars. Roughly \$90 was spent on the Leap Motion Developer Kit. Additional funding was spent on resources to 3D print the exoskeleton type glove and servo motors to mimic various touch sensations.

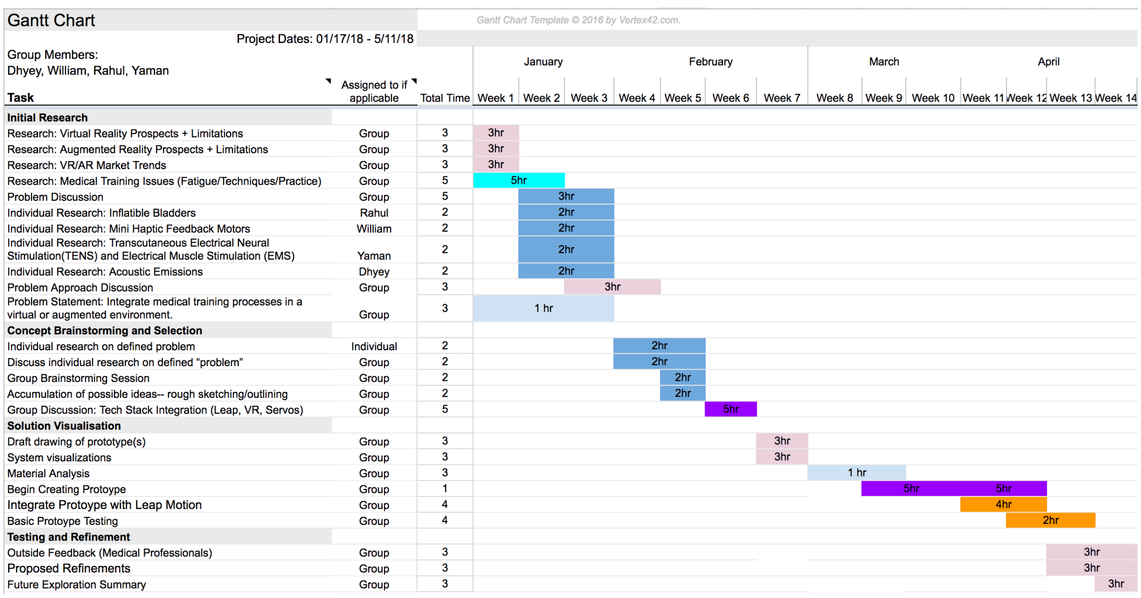


Figure 2: Gantt Chart of Project Deliverables

5 Internal Searching/Concept Generation

Our group was inclined to take an augmented/virtual reality approach as demonstrated in the Phase I and II report, so we broke down the field into four major areas that needed to be addressed with new ideas combined with current concepts: virtual tactility, 3D environment, hand restriction and finger restriction. We then researched and synthesized new ideas related to each specific topic that we could innovate or build up on as virtual reality is a type of technology with limited scope of improvement besides enhancement of the senses. Miscellaneous ideas were also generated that deviated from virtual reality approaches. The reasoning for combining the idea generation and concept generation section arises from the inability to actually generate new ideas about virtual reality due to its limited scope of enhancement beyond simulating the human senses.

5.1 Virtual Tactility

Our group researched and developed innovations to stimulate touch. We looked at current technologies in Phase I/II and brainstormed three major ideas on how to stimulate touch.

The first tactic to stimulate touch was utilizing haptic feedback to allow for a sensation of weight or force. Current research and technologies include the Tesla Suit which is a full body haptic VR suit. The Tesla Suit has 46 haptic points surrounding the user which provides haptic animations throughout the user (see Figure 3: Tesla Suit Haptic Points Diagram). This allows to feel real time simulations and weight in a virtual environment. Therefore, with its ability to stimulate the basic feelings of touch, weight and force, haptic technology could be a potential method of stimulating touch. [2]

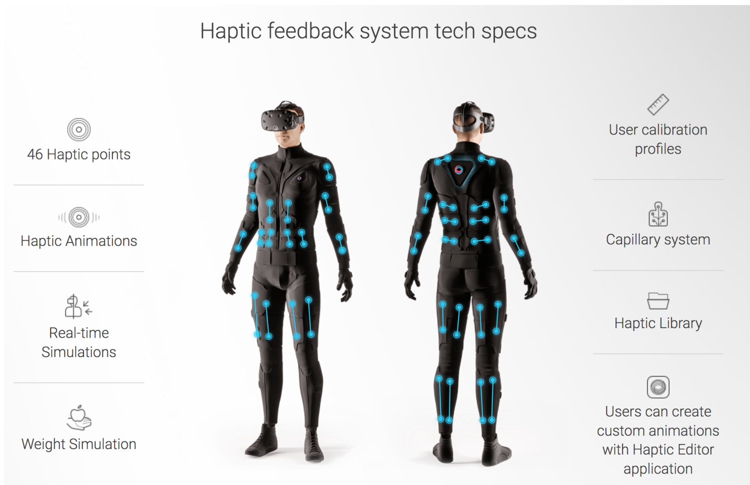


Figure 3: Tesla Suit Haptic Points Diagram [2]

Another idea was to use a system of pressure or micro pneumatic bladders to allow for sensation of touch and texture of an object. The best implementation of this was done through the HaptX gloves. Within the gloves there are various "haptic pixels" as can be seen in Figure 4, which are micro-pneumatic technology that HaptX has patented. These bendable fabrics, which are manufactured with a series of tiny air pipes along their length, are distributed throughout the users hand and finger tips. When the user touches something in an virtual environment, certain pixels inflate, creating a sensation of touch. In addition, this pixels are close enough such that it can also replicate the sensation of texture throughout the users' hand. [3]

Figure 4: HaptX's Haptic Pixels [3]

The third idea was actual objects being implemented into a virtual environment while said objects are still being used in the real world. This would provide a more in depth tactile and textural feel of a tool as it would be both in the real and virtual environments. For example, a tool such as a pencil could remain in the real world while still in the virtual environment. This would be possible when coupled with the ideas described in the 3D Environment section.

5.2 3D Environment

One of the most critical aspects of our project was establishing a 3D environment in which medical professionals would be able to train and utilize our technology and research. In order to accomplish this we needed a noninvasive method of analyzing objects within an area large enough for surgeons and medical professionals to mimic a procure.

One idea was utilizing the Leap Motion Infrared Sensor. This technology has been in the consumer market for over 4 years providing us with the benefit of highly documented resources for taking advantage of the built in sensors. One of the main perks of the Leap Motion was through its associated developer software having built in functions identifying objects and movements related to the hands and arms. Furthermore, if there were any areas that needed to be more precisely recognized by the leap motion we could attach various materials that would produce,emit, or reflect a differentiating infrared signal from the rest of the object.

Another idea was using the 3D scanner gun at the Robertson Media Center in Clemons Library. This would allow for the objects in the real environment to be scanned and programmed into the virtual world. A 3D scanner would provide the ability to put in any object into a virtual environment thus providing no limits to the different surgical tools necessary to put into a virtual world.

Another idea was utilizing 3D printed organs as done by the Peirce-Cottler Lab. This would give a more accurate representation of the physiology of a human body. When coupled with a virtual reality headset, the 3D printed organ could remain in the real world as a physical presentation of what is going on in the virtual world as well.

A fourth and final idea was a 3D portable unit which would have a constrained footprint but include different tools that could be used in a virtual environment. This is a better option for surgery training as most surgeries are not performed with excessive movement so providing a constrained space would truly imitate an actual surgery.

5.3 Finger/Hand Restriction

Next we focused on how to restrict finger and hand motion in 3D space. Most of the prior arts that have worked on finger restriction, had used some form of pneumatic system. For example HaptX Gloves create the sensation of touch through their patented micro-pneumatic technology (Figure 5), which works by inflating stoppers along the joints of your fingers to restrict their movement. [3]

Figure 5: Haptx Finger Restrictions [3]

While researching other ways we could also use pneumatic systems within our gloves to restrict finger motion, we ran into soft robotics. Unlike other pneumatic systems that normally utilize some form of hard material, these soft robots (Soft fluidic actuators) are flexible materials capable of bending and twisting with simple control inputs such as pressurized fluids as can be seen in Figure 6. Such movements are extremely critical in terms of our project, as we will need to restrict motions of the fingers in various forms, which soft robotics allows us the flexibility to do so. However, the main concern of this idea, is that, it is still a developing technology and such materials can be quite expensive. [4]

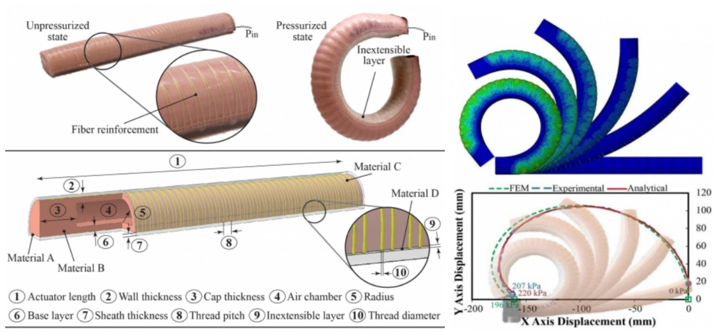


Figure 6: An example of the make up of soft robotics and its fluid and flexible range of motion [4]

Another idea that came up within our research, specifically while talking to a previous Rodman,(Adam's older brother), was the utilization of shape memory alloy (smart metal). Unlike other metals, the shape memory alloy has a special capability of remembering its original shape (see Figure 7). So even when the metal gets deformed, it can return to it's deformed shape when heated. In addition, this material, is extremely lightweight. Such a metal can be used within the glove we can create to restrict certain motion throughout the finger. [5]

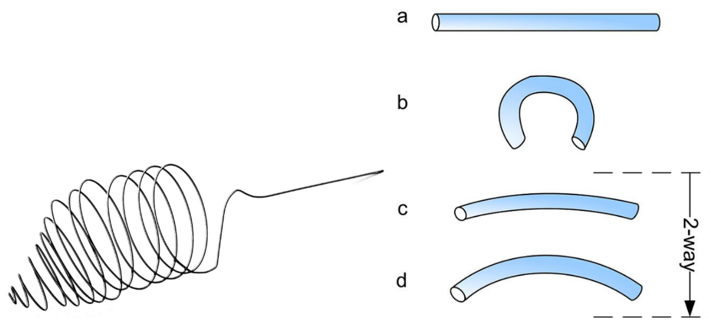


Figure 7: Image to left: example of shape memory alloy. Image to right: There are also two way shape memory: the alloy has the capability of remember two shapes: one at low temperature, and one at high-temperature. [5]

To specifically restrict hand motion, a wristband/cuff with strings could be used with any external force to control hand motion in 3D space. The wristband/cuff would require some method to allow for strings to move freely regardless of the orientation of the hand.

To control the motion of the of specific muscles groups throughout the hand, another option was to use electrical stimulation, such as Electrical Muscle Stimulation (EMS). EMS functions by simulating various nerve endings, which leads to muscle contraction. By doing so, we can contract certain muscle groups to create the sensation of touch and possibly even weight.

The use of a Hydraulic system would allow for a gradual increase in resistance when needed in 3D space. The fluid could be pumped or transferred using a series of syringes to create pressure chambers that would restrict hand or finger motion. Another idea would be a tape measure method with a ratcheting gear-Inspired by the system used in tape measure, a design using an innerspring with a reel to pull and retract a string freely would allow the user to move the hand with minimal resistance. The addition of a ratcheting gear would allow for a controlled stop for when the hand or fingers need to be restricted through the use of a servo.

5.4 Overall Summary of Ideas Generated

Below in Figure 8: List of Ideas Generated is the 17 ideas thought of through combination of concepts in virtual reality with any other enhancements to motion restriction or the simulation of touch in a virtual environment. While the number of ideas is less, it is important to emphasize how the problem has zoomed in on enhancing virtual reality and the user experience of immersiveness thus limiting the amount of ideas that are possible and that can actually be combined with VR/AR tech today.

Idea #	Subgroup/Idea
1	Virtual Tactility/Vibration Mechanism
2	Virtual Tactility/Air Pressure Bladders
3	Virtual Tactility/Physical Object Use
4	3D Environment/Leap Motion in conjuction with HTC Vive
5	3D Environment/Containment Unit
6	3D Environment/3D printed organs
7	3D Environment/3D scanned objects
8	Finger Restriction/Soft Robotics
9	Finger Restriction/Tape meausre mechanism with ratchet gear
10	Finger Restriction/Inflating Joints
11	Finger Restriction/Actuator System
12	Finger Restriction/Hydraulics System
13	Hand Restriction/Electrical Stimulation
14	Hand Restriction/Tape Measure with Ratcheting Gear for hand
15	Hand Restriction/Wrist Band/Cuff restraining motion
16	Hand Restriction/Actuator System
17	Hand Restriction/Hydraulics System

Figure 8: List of Ideas Generated

5.5 Miscellaneous

Some other ideas not related to the sections discuss above are listed below in Figure 9: Miscellaneous Ideas.

Idea #	Idea
1	Implementation of a surgical course that uses simulations for surgical procedures for medical students
2	Adding a physical portion to the exam given to residency students before entering clinical work
3	Educating medical schools and residency programs about the importance of actual training of students rather than theoretical knowledge
4	Educating hospitals about maintaining the skills of current working surgeons for surgical procedures
5	Creating an additional course that can be taken by current medical professionals for potential retraining to ensure they are up to date on different training methods
6	Implementing patient education course about current issues in medical training issues
7	Utilizing synthesized materials in hospitals to help train surgeons
8	Using different tissues developed by stem cell researchers to practice training

Figure 9: Miscellaneous Ideas

6 Concept Selection

After brainstorming different ideas and solution, our team created nine design criteria that each idea or concept had to fit: ease of use, delay, safety, durability, footprint, residuals, cost, weight, and aesthetic. We also created three design constraints which must be met or else the solution could not even be considered: a $400 budget, one semester to arrive at a perceived solution, and the team comprises of only four members.

After creating our design criteria and constraints, our group brainstormed 15 ideas related to AR/VR solutions and divided them amongst four different categories: virtual tactility, 3D environment, finger restriction, and hand restriction. They were organized by category since our group wanted to combine and target multiple areas of interest to improve current AR/VR technologies to solve our problem. After categorizing and organizing our ideas, we researched more in depth about each idea, and their implementation in current AR/VR technologies. We then ranked them according to Figure 10 below where each idea is categorized and ranked against each other within their respective categories. The ranking of each idea was discussed by the entire team and was supported by background research conducted during the concept generation phase. In addition, some ideas between hand and finger restriction were repeated due to similarities of the problem and that one solution could be consolidated to solve for both problems. The rankings were then totalled and the top two ideas were selected to be further explored or combined if possible.

	Ease of Use - (Out of 15)	Delay - (Out of 15)	Safety - (Out of 15)	Durability - (Out of 15)	Footprint - (Out of 10)	Residuals - (Out of 10)	Cost - (Out of 10)	Weight - (Out of 5)	Aesthetic - (Out of 5)	Total Rank
Virtual Tactility										
Vibration	13	13	15	13	10	10	5	2	2	83
Air Pressure	10	14	15	13	10	10	3	2	2	79
Physcial Object	15	15	15	15	5	5	5	5	5	85
3D Environment										
Leap Motion & HTC VIVE	13	13	15	15	10	10	5	2	5	88
Containment Unit	14	15	15	13	5	7	10	4	3	86
3D printed organs	15	15	15	5	5	5	5	3	5	73
3D Scanned Objects	10	13	15	15	7	7	5	5	5	82
Finger Restriction										
Soft Robotics	15	13	15	13	9	9	1	3	5	83
Tape Measure with Ratcheting Gear	15	12	15	10	8	8	8	3	3	82
Inflating Joints	10	13	10	10	8	8	3	5	5	72
Actuator	15	12	12	13	8	8	4	3	5	80
Hydraulics	15	8	10	15	9	9	3	1	2	72
Hand Restriction										
Electrical Stimulation	10	13	10	10	7	5	5	2	2	64
Tape Measure with Ratcheting Gear	15	12	15	10	8	8	8	3	3	82
Wrist Band/Cuff	15	15	15	12	8	8	10	4	3	90
Actuator	13	12	12	13	8	8	4	3	5	78
Hydraulics	13	8	10	15	9	9	3	1	2	70

Figure 10: Criteria Chart for VR/AR Related Ideas

In addition, our group brainstormed eight ideas outside of a AR/VR relation solution in order to consider possible options outside the original scope of this project. For these eight ideas, we created five new design criteria to rank against one another. The Figure 11 displays the miscellaneous rankings against one another and the top idea was chosen to be considered and expanded upon further down the project.

Miscellaneous	Patient Outcome Safety (out of 25)	Ease of Use (Out of 20)	Impact on Medical Field (Out of 20)	Cost (Out of 20)	Implementation (Out of 15)	Total Rank
Implementation of a surgical course that uses simulations for surgical procedures for medical students	20	18	15	6	4	63
Adding a physical portion to the exam given to residency students before entering clinical work	21	18	14	6	4	63
Educating medical schools and residency programs about the importance of actual training of students rather than theoretical knowledge	18	18	17	16	10	79
Educating hospitals about maintaining the skills of current working surgeons for surgical procedures	22	19	17	16	10	84
Creating an additional course that can be taken by current medical professionals for potential retraining to ensure they are up to date on different training methods	21	18	10	6	5	60
Implementing patient education course about current issues in medical training issues	20	18	10	6	6	60
Utilizing synthesized materials in hospitals to help train surgeons	19	14	13	3	2	51
Using different tissues developed by stem cell researchers to practice training	19	12	13	3	2	49

Figure 11: Criteria Chart for Misc. Ideas

7 Prototyping

The reasons for prototyping the solution generated from the concept selection section included answering the following questions:

1. How is it possible to restrict the motion of the hand in a virtual space without focusing too much on fingers and simulating touch?

2. What can be done to restrict the space used for virtual simulations without too much restriction of the hands overall?

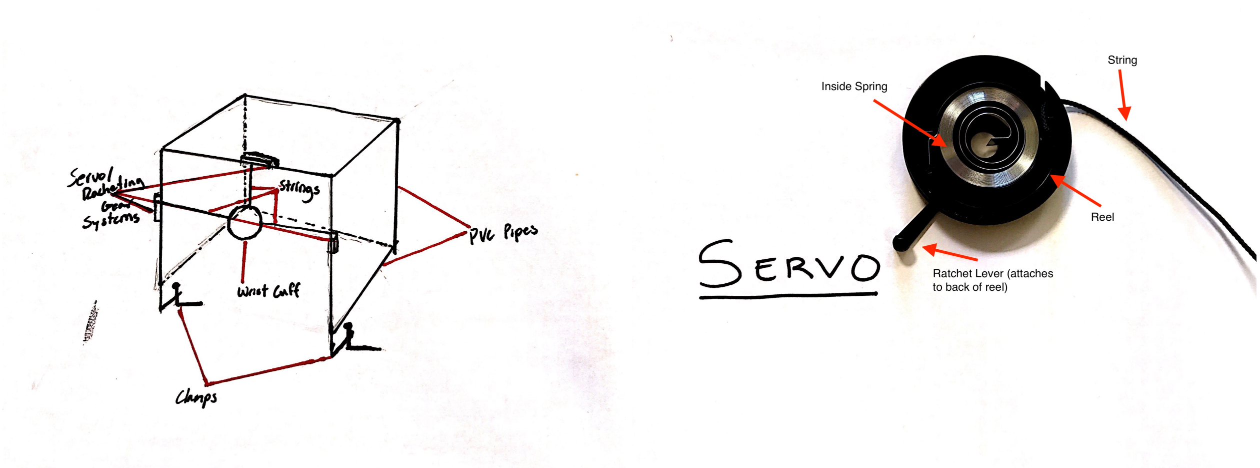
The answer to these following questions are demonstrated in the following prototyping sections. Each section attempts to show a progression of a prototype that can give a set of potential answers to the questions asked above.

7.1 Sketching

The first portion of prototyping involved generating a proof of concept of some sort of 3D environment combined with an HTC Vive virtual reality headset and a Leap Motion Controller. This contained two major parts: a wrist band meant to promote hand restriction and a 3D containment unit housing all tools to be implemented in the virtual environment.

The 3D containment unit was designed first as this would house all important processes and tools for a user to interact with a virtual environment. As seen in Figure 12a: 3D Containment Unit Sketch w/ Ratchet Gear, the environment comprises PVC piping, clamps, servo/ratcheting systems, string, and the wrist cuff. The PVC pipes are used to construct the cubical frame which encloses the 3D environment that the user can interact in. The clamps are attached to the bottom of the cubical frame so that the frame can be secured on a flat surface, such as a table. Then the servo/ratcheting systems, which are discussed later in this section, are attached to the upper PVC pipe and to the two side PVC pipes in the front. The strings connect from each servo/ratcheting system to the wrist cuff creating axis' along the x and y plane for restricting the hand motion. The details of wrist cuff system are mentioned later on in this section.

The servo/ratcheting system comprises of a ratcheting gear, a string winded around the gear, an inner spring, and a servo as seen in Figure 11b. The ratcheting gear allows for the string attached to the gear to move freely or not move at all when the ratchet lever is at a certain angle. The inner spring of the ratcheting gear allows the string to return to its initial state. The servo will be controlling the angle at which the ratchet lever is at using a micro-controller.



(a) (b)

Figure 12: 3D Containment Unit Sketch w/Ratchet Gear

The design for a wrist band promoting hand restriction began with a sketch demonstrating the look of the band and its restrictive capabilities when combined to the 3D containment unit. As seen in Figure 13: Wristband Design Sketch, the purpose of this wearable was to have the ability to connect the 3D containment unit and user all while providing restriction of hand movement when moving up, down, forward, or backward. The wristband was designed to have two portions containing a pathway in the middle. The two portions were connected by screwing them together after the bearings had been placed inside them. The pathway in the middle would have two to three small spherical bearings with a hole in then to then attach some sort of strings which would also be connected to the containment unit. This would allow for the user's hand to freely rotate along with being restricted due to the an increase in tension in the strings when the hand is moved in any direction. See Figure 11: 3D Containment Unit Sketch above to see how these strings would be attached to the wristband.

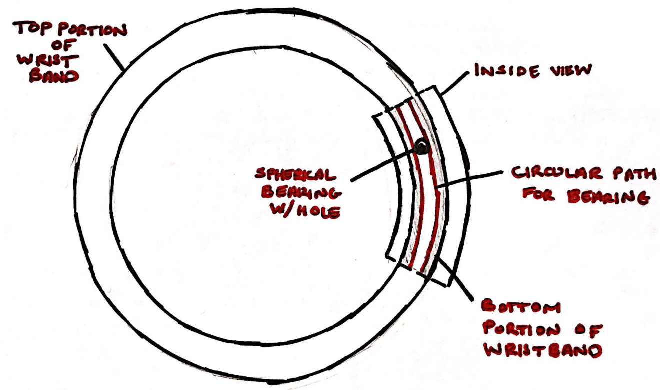


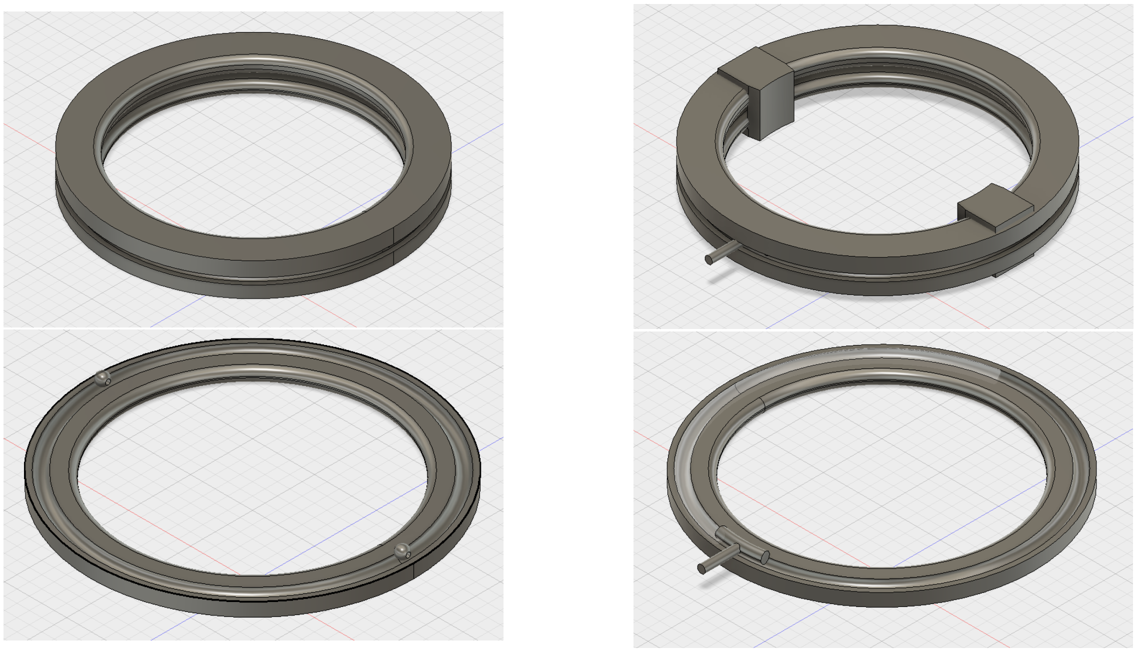
Figure 13: Wristband Design Sketch

Both of the sketches above represent the first phase of the design process of sketching or visualizing what the concept selected will look like and how it will function. In summary, this first part of prototyping contained a breakdown of a proof of concept into two components. Each component was sketched out to have an initial understanding of how to move forward in terms of 3D design and physical prototyping.

7.2 3D Modeling

After the first phase of sketching, the prototyping methodology moved onto 3D modeling. The computer-aided design software used in this project was Autodesk Fusion 360 in which the wristband was modeled through various iterations.

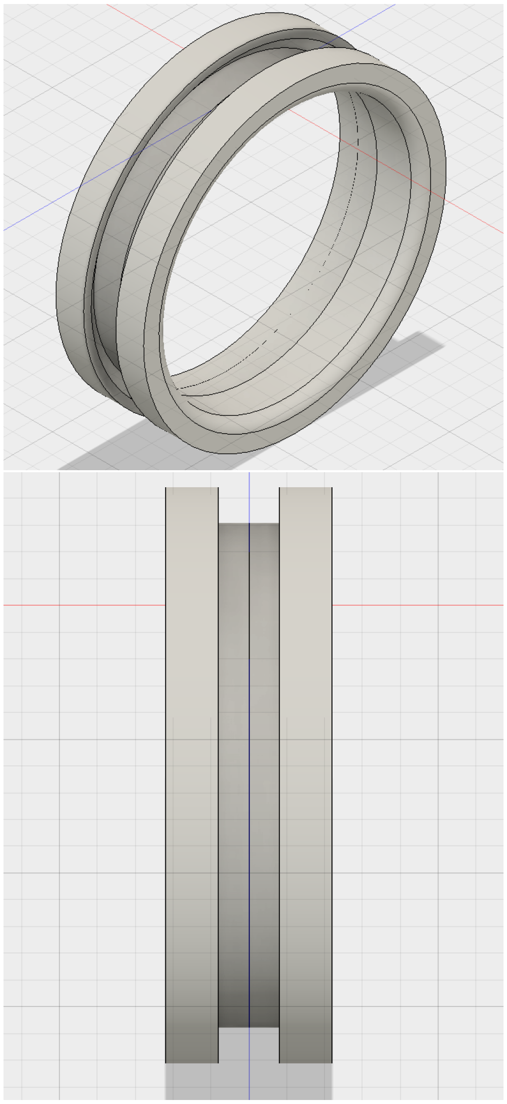
The first iteration of a 3D model of the wristband, as seen in Figure 14a: 3D CAD Wristband Designs w/ Middle Pathway, matched the initial sketch where a circular path was modeled in between two outer cylindrical portions containing two spherical bearings with holes in them to attach to the strings on the containment unit. However, it was realized that spherical bearings would be difficult to 3D print due to their small size and circular shape causing a lack of multiple points of contact to the bed on a 3D printer even with support or raft structures. Therefore, the next iteration of a wristband with the same circular pathway replaced the spherical bearings for a cylindrical sliding components and two clamps to hold the two portions of the band together. Figure 14b illustrates a new cylindrical sliding component and the two clamps. The reason behind the clamps was to replace screws as they would have caused fracturing in 3D printed parts versus using snug clamps to simply slide onto the two wristband portions. The first issue with this second iteration was the complexity of printing the sliding component due to its curved edges. Also , another issue was the two portions of the wristband not in contact with each other which would cause potential wobbling movement of the band when being used.



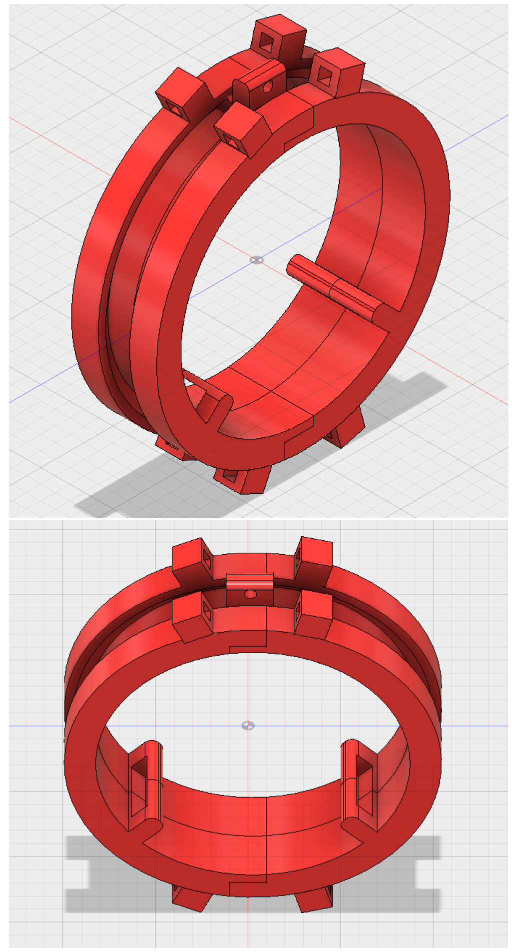
(a) (b)

Figure 14: 3D CAD Wristband Designs w/ Middle Pathway

The first two iterations had shown how the two portions of the wristband needed to be in contact to lessen the potential of wobbling or sliding movement caused by extreme use and how a sliding component needed to be more simple for 3D printing. Figure 15a: 3D CAD Wristband Designs w/o Middle Pathway illustrates a basic model of the wristband with now two portions connected in the middle with an outside pathway for some sort of sliding component. Now, with a simpler base wristband model, the final 3D model iteration contained only additions. As seen in Figure 15b, these additions included a more rectangular sliding piece with a top portion containing a hole for tying a string through. Another addition was two protrusions on the inside of band with rectangular holes to place in an additional Velcro strap for wrist size adjustment for the user. The final component of this last iteration was it being cut into quarters with zig zag cuts and four protrusions on each side with square holes through each. This was done to allow for the user to slide in their hand (which is larger than wrist) through the wrist band and then tighten together the pieces afterwards.



(a)



(b)

Figure 15: 3D CAD Wristband Designs w/o Middle Pathway

7.3 Physical Prototyping

The final part of the prototyping methodology was physical models. Again, the physical models include two major components: the wristband and the 3D containment unit.

Currently, only the physical models for the wristband are being made through the fused deposition modeling system (FDM) of 3D printers using the plastic material Acrylonitrile butadiene styrene (ABS). The final iteration of the wristband design as described in the 3D modeling section can be seen in Figure 16: 3D Printed Wristband. These components were printed twice with the first time being with a different material than ABS. First it was printed with high impact polystyrene or HIPS, because of its increases impact strength and smoother print result. Issues that occurred when printing with HIPS included its sensitivity to changes in temperature when printed on a heated bed of a 3D printer causing the print to warp and disform.

Figure 16: 3D Printed Wristband

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