Infinity Glove

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II. Overview

The market for virtual reality products seems to be hitting an inflection point in user adoption and technical development. Virtual environments have become realistic enough to offer considerable utility to end users. Headset hardware is still expensive but has become cheap enough for early majority adopters to make purchases. Growth in application development is exploding. The time is perfect for a scrappy startup to enter the VR space, and we plan to do so by filling an unmet need of the ecosystem. Current applications have taken 2D environments and extended them in amazing ways to match the realism of the physical world. But what is still glaringly missing is a way to truly experience this virtual world in ways beyond the visual. With our product, we plan to give users this ability with haptic feedback.

Most haptic systems currently in use are unrealistic and expensive. The sensations we experience are remarkably nuanced and difficult to replicate with mechanical hardware. But by structuring our approach with simplicity in mind and utilizing some unique technological innovations, we believe that we can create a system which provides improved precision and extendibility at a lower price point.

III. Executive Summary

Science fiction authors and technology enthusiasts have long dreamed of a fully-immersive virtual world where senses like sight and touch are so realistic that users cannot differentiate feeling from reality. Modern virtual reality headsets realistically trick our sense of sight to perceive virtual worlds, however gloves aiming to replicate touch lag far behind. Problems with currently available haptic gloves include weight, size, cost, and immersiveness. Most designs use large and heavy servo motors that tug at your fingers and cost upwards of $10,000 without adequately replicating touch or requiring you to fix your arms in place. A significant amount of research and development into haptics stems from the gaming industry, where use cases are dynamic and intense, but the stakes for accuracy are low compared to other industries like remote surgery. This makes the gaming industry the perfect sandbox to explore alternative designs to improve haptic gloves. We are building a haptic glove with a unique blend of vibration motors, and electrostatic breaks that is sleeker, lighter, cheaper, and more immersive for gamers.

Our design leverages two key technologies that collectively capture forms of touch feedback necessary for a robust and immersive system. First, we implement tiny vibration motors across that hand that are connected to a microcontroller and vibrate in short bursts when touch is initiated to deliver low latency feedback. Secondly, we implement an electrostatic brake using thin metal plates across the hand that clamp together when a voltage is applied. These metal plates restrict the hand from closing completely when grabbing objects in the virtual world, heightening the sense of realism.

The development of our systems required a significant amount of research and self-learning. As an interdisciplinary team, however, each member brought a unique skill set that enabled us to develop and integrate a minimum viable product of the full stack of components for our haptic glove. Saurin and Nick leveraged their MEAM background to focus on designing the electrostatic break and haptic system, Ryan leveraged his EE background to integrate the electronics and controls, and Yonah leveraged his CIS background to build a virtual environment for testing and communication with the hardware. The team has maintained ethical design practices by complying with any patent restrictions and consumer/electronic safety standards.

IV. Technical Description

a. Specifications, Requirements, and Constraints

i. Safety: Safety is the first and foremost concern when designing any consumer product but especially when designing a haptic glove that will be acting to contort the user's bodies. Even if we are able to design a low-cost, high accuracy, and very realistic glove, we would have to go back to the drawing board if that glove were unsafe to use. Hence, when designing the glove, we remained in line, not only with the guidelines of the Consumer Product Safety Commission (CPSC), but also our personal ethical and moral standards. More info on the official standards are included below.

ii. Cost: One of the major problems with current haptic gloves, as mentioned above, is the cost. It is very hard to see a world where widespread consumer adoption is possible when the systems would cost consumers thousands of dollars. Hence, when designing our system, a primary constraint that we dealt with was keeping costs low. VR headsets were also initially developed for research purposes at price points unfathomable for most consumers but were eventually brought to the consumer market. We believe the same is possible for haptic gloves.

iii. Accuracy and Precision: A major difficulty lies in the precision of our system. Making a bad haptic system is easy. Making one that mimics the many nuances of real-life touch is not. More specifically, precise touch points as well as subtle changes in the force of touch are extremely hard to mimic. To address this, we targeted particular regions of the hand where precision is important (i.e finger tips) and sacrificed precision in areas where it is less important (such as the palm). Overall, precision and accuracy was not just a specification for this project, but more of a requirement in order to have a project that is either patentable or has any commercial viability.

iv. Size: A major problem with other haptic gloves on the market is also size. Some actually require the user to attach an entire system to their arm that starts at their shoulder and runs down the length of the arm, simply to mimic touch in a few fingers. Other products on the market, primarily meant for research, don't even have a solution that attaches to the users arms or hands. They are external systems that attach permanently to tables and desks.

We can quantify the above design constraints into the following quantitative goals:

- Stopping Force: 10N (for immersion and accuracy)
- Latency: 100-150 ms (for immersion and accuracy)
- Maximum Voltage: 25V (for safety)
- Maximum Current: 1 mA (for safety)
- Brake Area: 5 cm^2 (due to the size constraints)
- Manufacturing Cost: <$50 (to keep the final cost to consumers at a reasonable level)

b. Alternative Solutions that were Considered

i. Electrorheological (ER) / Magnetorheological (MR) fluids: These fluids are ones that change material properties, specifically their viscosity and shear stress, when exposed to an electric or magnetic field, respectively. When exposed to the fields, the fluids can change from liquids to semi-hardened solids in the order of magnitude of milliseconds. Traditional uses of ER and MR fluids are in hydraulic pumps and clutches, however they could be applied to haptics as well. We hypothesized that many pockets of the fluid could be placed around a user's hand to form a glove. By hardening specific pockets, movement could be restricted and forces could act upon the user's hands mimicking touch.

ii. Pneumatics: A pneumatic approach entails an array of small bubbles across the entire glove. When part of the user's hand is touched in the virtual world, the corresponding bubbles would inflate and cause a small amount of force to act upon the user's hand. For example, if a user touched something with their fingertip, the bubble on the user's fingertip would inflate.

iii. Motors & Servos: Current haptic gloves on the market rely heavily on motors and servos. The actuators pull back on the user's fingers to restrict motion. Like we mentioned above, this approach lacks many degrees of freedom and is often bulky. Current solutions on the market either attach these bulky motors to users' wrists or mount them on the shoulder. Neither are comfortable and further break immersion.

c. Societal, Environmental, and Economic Considerations

i. Many of the societal and environmental considerations are discussed in full depth further below in the "Ethical and Professional Responsibilities" section. Furthermore, even though there are many societal and environmental considerations, they did not affect our current technical design. We recognize that environmental considerations and the sustainability of materials and supply chain are essential. However, the focus of our project was mainly on the technical innovation and the development of a prototype. We recognize that a deeper dive on these considerations are essential before taking the product to market. Lastly, the economic considerations are discussed above under "Specifications, Requirements, and Constraints". In summary of the section, our focus was to keep the product at a low cost in order to actually bring a highly immersive haptic glove to the consumer market.

d. Technical Approach

i. To pick which one of the technical approaches we wanted to pursue, we evaluated each option on each one of the specifications, requirements, and constraints listed above as well as feasibility and current options on the market. Starting with the motor and servo implementations, both have representative solutions already out in the market. Motors and servos are also bulky, costly (depending on the strength of the motors), and also only provide one degree of freedom per finger (precision is also low). Hence, an approach with motors, even though feasible, was not pursued further since it would violate 3 out of our 4 design requirements.

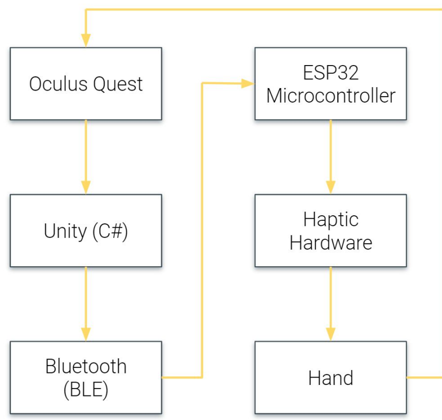
Now, we were left with our final three options: ER/MR fluids, pneumatics and thin metals. The team was initially very optimistic about the ER/MR solution. It seemed like an interesting method to recreate both small and large forces, creating a very realistic sense of touch. Basic versions of the fluids are also very low cost and could be packaged into a sleek glove. However, one major, and frankly most important, consideration remained: safety. For ER fluid, voltages of over 1kV are needed to significantly change the viscosity of the fluid. Currents would be very low (in the order of magnitude of micro amps), so under normal operating conditions the device would be safe. However, the breakdown voltage of air is at 3kV. Around this voltage, there is a high probability of sparking. Given the minimum operating voltage of ER fluid would be 1kV, the probability of sparking, and therefore harm to the user, would unfortunately be too high. For similar reasons surrounding safety, MR fluid was also deemed to be infeasible.

We were left with the pneumatic, electrostatic clutch and piezoelectric actuator approaches. From here, we changed our technical approach and took a stance of test, analyze, and iterate. In the fall semester, we pursued the pneumatic actuator approach. Wee discovered that the approach would be feasible in accomplishing a realistic sense of haptic feedback, but would be very difficult, and possibly impossible to miniaturize to the size and form factor that we wanted to accomplish. Hence, at the start of this semester we pivoted to focus on the electrostatic clutch and the piezoelectric actuators. Our approach with these solutions was also centered around testing and iterating. After many small iterations we were able to accomplish the working design described below.

e. Technical Description

Figure 01: Final Infinity Glove Design

Figure 02: System Architecture



i. Hardware:

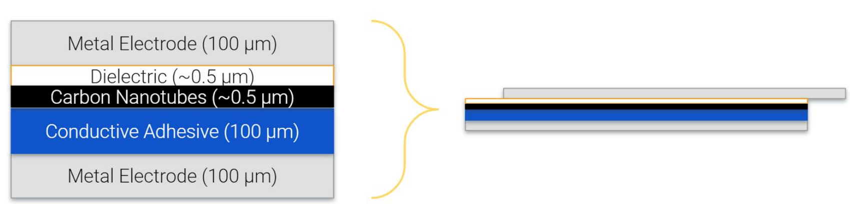
Overview

Our final haptic glove integrates two types of haptic feedback: tactile feedback and structural force feedback. We implement tactile feedback using piezoelectric actuators, or simply put, vibration motors. Tactile feedback is the light sensation of touch, similar to touching a tabletop or pushing a button. As shown on the right in Figure 01, the vibration motors are placed at the users fingertips and would be activated when the user touches a virtual object. Structural feedback is the sensation of gripping an object and feeling the force resist your hands/fingers from moving completely freely, such as gripping a pencil, water bottle, ball or any other object. We accomplish structural force feedback through the innovation of the electrostatic clutch. When activated, the clutch restricts the user from further closing their grip. Even though Figure 01 only displays the clutch on a single finger, the final product would include a clutch on each finger, restricting movement in five DOF (degrees of freedom).

Finally, both of these haptic systems are integrated in the software such that the piezoelectric actuators are activated for 300 milliseconds each time a finger collides with an object in the virtual world. The piezoelectric actuators have a very low latency. Hence, by activating them first for a short duration, before the clutch is able to fully engage, we are able to reduce latency and ensure immersion.

The Electrostatic Clutch

Figure 03: Electrostatic Clutch Design



In our glove, we have brought the innovation of the electrostatic clutch to haptics. This is a fairly new technology that was invented in a lab in Carnegie Mellon in 2017. We innovated on the design the Carnegie Mellon researchers built to adapt it to work in the form factor of a glove and operate at lower voltages (the researcher's design operated at over 1000 V, which would not be safe for a consumer product). We were able to accomplish this innovation through scrutiny in the material selection process and lots of experimentation. The clutch is thin, only involves a couple of parts, and is easy to manufacture, leading to a cost that is much lower than our competitors'.

Our innovation and complexity occur with the electrostatic clutch and material selection, but the design itself is simple. At a base level, the clutch is essentially a large capacitor: two metal electrodes with a dielectric film inbetween. The bottom half of the clutch (electrode, adhesive, nanotubes, and dielectric) is permanently attached. When the clutch is off, the top metal electrode is free to slide back and forth on top of the bottom half with minimal friction. Hence, when the device is off, the user's range of motion is not restricted at all. However, once a voltage is applied between the two metal plates, there is an electrostatic adhesion force causing friction between the top metal electrode and the dielectric film. This friction stops the top electrode from moving which stops the user from moving their finger.

Equation 01: Mathematical Model of the Stopping Force

$$F_{restriction} = \frac{\mu \epsilon_r \epsilon_0 A V^2}{2d^2}$$

$\mu : coefficient\ of\ friction$
$\epsilon_r : dielectric\ constant$
$\epsilon_0 : permitivity\ of\ space$
$A : contact\ area$
$V : voltage$
$d : thickness\ of\ dielectric$

The key reason a lot of experimentation was necessary for material selection was safety. As discussed in our requirements and constraints section, we set the goal of achieving 10 N of stopping force per finger in order to preserve immersion and accuracy of the feedback. As one can see from Equation 01, the possible variables we could adjust to achieve this 10 N are coefficient of friction, contact area, voltage, and the thickness of the dielectric. However, the coefficient of friction between metal and most dielectric films is roughly the same, our contact area is fixed due to the size of a user's hand, and we also set our maximum voltage to 25 V for safety. Hence, we could only play around with the dielectric thickness in order to adjust the restraining force of our clutch.

After our experimentation process, we were able to find a suitable combination of materials to work within our restrictions. We used thin 100 μm thick stainless steel plates, a silver conductive epoxy, a thin layer of a carbon nanotube forest, and a 0.5 μm thick mylar film. The plates were chosen such that they could easily bend around a user's finger without restricting motion when the device is off. By selecting an epoxy that is conductive, it actually acts as part of the electrode itself rather than as a part of the dielectric. Next, we needed to apply a layer of carbon nanotubes to strengthen our dielectric film. Since the film was so thin, it tears very easily. The carbon nanotubes keep the device thin, strengthen the film, and are conductive. Hence, again they act as part of the electrode rather than part of the dielectric keeping the dielectric thickness to a minimum. Through this combination, we were able to build an electrostatic clutch suitable for use in a haptic glove which operated with 10N of force.

ii. Software:

Most competitors either focus more on the software or dove into more traditional and costlier ways of manufacturing the hardware. First, on the software side, some of the competitors (like Manus VR) spent a lot of time and resources upfront to build out a full software suite capable of integrating with all of the different VR headsets and building custom software to enable hand and movement tracking. We, on the other hand, have the benefit of market timing and entry. In Q4 2019, Oculus released it's own hand tracking software package, enabling us to jump ahead and save a lot of costs in software development.

There were two elements of the software stack we needed to pursue ourselves: 1) processing signals within the Oculus environment to see when the hand needed to receive force feedback and 2) sending signals from the headset to the glove. As a result, we had two main workstreams: Unity (C#) and Arduino (C++). On the Unity side, we wanted to implement a system which reacted when two separate actions occurred in our virtual environment. This required implementing event listeners and setting the game physics to trigger them under the right stimuli. The Oculus hand tracking API streamlined the process of finding which joints were where in physical space and made the process of detecting important collisions much easier. When events were registered, the Unity environment would send signals to the glove's ESP32 microcontroller over a UART connection. (It was in our plans for March to switch this wired testing environment to a wireless one operating over a Bluetooth Low Energy (BLE) connection, but unfortunately this part of the project got cut short.) The ESP32 was then programmed to send the proper signals to both the piezoelectric actuators and electrostatic clutches.

f. Final Status and Testing

i. By the final demo, we had a product which contained several disparate pieces of technology we developed throughout the year. While these pieces were connected through a system of integration, that system was fairly inelegant compared to what we had hoped to present at the end of the semester. We had a completed technical stack but not a polished prototype. Of course, we would have liked to test many different aspects of our project against industry standards, but time did not permit this either. However, we are confident in the design of our product and think this process of testing would be straightforward.

As mentioned in previous sections, we had a set of design constraints that we had to test and verify that our prototype achieved. In Table 01 below, we list out the various metrics and testing methodologies that we focussed on and implemented.

Table 01: Testing Metrics and Methodology

Metric	**Value**	**Testing Methodology**
Stopping Force	10N	Ran multiple trials and tested with a spring force sensor
Latency	100-150 ms	Software testing in C#
Maximum Voltage	25V	Multiple trials tested with a multimeter
Maximum Current	1 mA	Multiple trials tested with a multimeter
Maximum Brake Area	5 cm^2	Simple measurement with ruler
Manufacturing Cost	<$50 / glove	Budget calculations shown sections below

g. Conclusion and Looking Forward

i. Overall, we are proud of the technical progress we made during the year. We were able to create a final integrated system that implemented both electrostatic clutches and piezoelectric actuators. This hardware system was wrapped by a custom software solution integrating with the Oculus Quest and their hand tracking system. Looking forward to the future, we aim to take our prototype and turn it into a manufacturable and finished product ready for the consumer market.

V. Self-Learning

This project required a lot of self-learning on our part. On the hardware side, no one on our team had any experience working with haptics. Moreover, there are only a few Penn professors with experience building a haptic glove, like Mark Yim, who was leaving for sabbatical and wasn't available to advise us. Without personal experience or a directly relevant advisor, and having struck out looking for and reaching out to potential industry advisors, we were forced to research and design the haptic glove ourselves. This meant researching what techniques were commonly used for haptic gloves and thinking about which techniques best fit our goals.

In addition to the design elements, we also had to self-learn some specific technologies. Our haptic glove utilizes an ESP32 to send process signals sent from the Oculus headset.. We had to self-learn how to teach an ESP 32 to communicate with the Oculus headset to receive and send messages. Additionally, we self-learned C# and Unity for creating a VR environment and communicating with the ESP32. This included both VR focused libraries as well as C# server-side libraries.

On the hardware side, we had to self-learn all of the components and physics of the electrostatic clutch. None of us were familiar with electro-static clutch technology before this project and so we read research papers covering the technology and its use in other applications to learn about it. Without any materials science background, we were forced to research diligently and consult the appropriate advisors. As described in section IV, our choice of materials is one of the keys to making our project work and it took a lot of self-learning to familiarize ourselves with the different kinds of materials available and their pros and cons.

In terms of classes, since our project required so much self-learning, our previous coursework was not particularly helpful. On the hardware side, MEAM 510 - Mechatronics - was one class that was very helpful. From building intuition for design to learning to work with microcontrollers, we have used the knowledge we learned from this class throughout the project.

VI. Ethical and Professional Responsibilities

In many ways, haptics is the next frontier of virtual reality. With technology today, we know how to create eerily real virtual environments that users can explore and experience first-hand. But, technology is sorely lacking when it comes to interactive virtual reality. Current haptic gloves on the market cost thousands of dollars to produce and are largely used for academic purposes. Our first and main goal is to bring haptics into the mainstream. By building an affordable haptic glove, we can bring an improved VR experience to mass markets.

The main ethical obligations we have relate to building a safe product that can't harm users. This means constructing a glove that operates at low enough voltages so as to be deemed safe by the current standards - we go further into depth on these standards in section XI. This is why our material selection was so important as we needed to find a material thin enough that we could operate the glove at a low voltage while at the same time ensuring the material was strong enough so that it didn't rip during usage which could cause the glove to spark.

On the mechanical side of things, the most important safety consideration was to ensure that the force applied on the hand was not too strong. In the past, there have been incidents where haptic gloves actually broke a user's finger from the sheer force the glove applied on the user's hand. We were careful to address this risk by limiting the force our glove could place on the user to 10N, low enough that there is no risk of damaging a user's hand.

Ethically, we also had a responsibility to ensure that we do not infringe on the intellectual property of other engineers and firms working in the space that have developed patentable technology. We reached out to multiple companies in the space to learn about the work they were doing, but we were very careful to respect their property rights during this process. None of the companies we talked to were willing to give us technical help and we respected that and moved forward with a design that is totally different from the existing technology on the market. Since our design was inspired by a paper produced out of Carnegie Mellon University, we were careful to mention this and cite the paper when relevant.

VII. Meetings

We tried to have as many meetings with professors and industry leaders as possible to source new ideas and develop on existing ones. During the early stages of the semester, we probably had approximately one or two of these meetings a week as we worked to select a final project. These meetings were almost always extremely helpful in helping us narrow down ideas. On one particularly memorable day, we met with three separate Penn professors with our final three project ideas and each recommended that we tackle a different one.

Once we decided upon the haptic glove idea, we began to reach out to professors whose area of expertise overlapped with our project. Among the professors we met with are Michael Posa, Mark Yim, Andre DeHeon, JD Albert, and a MEAM PhD student: Sam Azadi.

Finally, our faculty advisor, Professor Pratik Chaudhari, has been extremely helpful in guiding us on ways to think about the design of our system and fitting it into the current market for virtual reality and haptics. We did our best to meet with him once a month which we successfully did in the fall semester and the beginning of the spring semester. But, due to the current health crisis, we haven't been able to meet with him and contact has been much more difficult. Still, we reached out to him over email to update him on the final progress we made before the health crisis hit and to show him our final video.

VIII. Proposed Spring Schedule with Milestones

Our goal for the fall semester was to have the full stack of our system working for a simple version of the problem we were tackling. By splitting our project into stages that our team could easily take on, we were able to meet that goal and deliver a prototype that we were very happy with.

During the spring semester, our goal was to further iterate each stage of the stack to have a progressively more realistic and technically complex product. By spring break, we had a fairly sophisticated prototype that only required integration of separate components and some polishing of the product design. Our proposed schedule was as follows:

Proposed Timeline

January

1. Switch VR environment development from Unity to Unreal to preempt latency issues and offer a more streamlined object detection system to work with
2. Extend mechanical design of bubbles from a system of only a few points to one which covers the whole palm
3. Design system of pumps and small switches to interact with this bubble array
4. Employ hand tracking built into Oculus system to pinpoint where physical hand is in virtual space

Actual Timeline

January

1. Maintain Unity environment because it integrates most effectively with the Oculus API
2. Switch from a pneumatic system to vibration motors that enable similar feeling of touch with much simpler mechanical architecture
3. Integrate vibration system to deliver force to many points on palm and fingers
4. Employ hand tracking built into Oculus system to pinpoint where physical hand is in virtual space

February (Proposed Timeline)

February (Actual Timeline)

5. Reintegrate by switching esp32 connection from serial UART to WiFi directly between glove and Oculus
6. Extend capability of glove from simply replicating touch to force-generation by using metal plates that can bend fingers given the appropriate signals
7. Iterate on VR software to offer more precise object detection and signal processing

March

8. Iterate on complete mechanical design and look for ways to professionally fabricate final system
9. Ensure complete integration and look for ways to decrease costs of system where possible
10. Final business plan development and market research
11. M&T Summit Demonstration

April

12. Final changes to full stack of product and integration of feedback from M&T Summit
13. Final Spring Demo

5. Direct WiFi connection tabled to March
6. Extend capability of glove from simply replicating touch to force-generation by using metal plates that can bend fingers given the appropriate signals
7. Iterate on VR software to offer more precise object detection and signal processing

March

8. Technical development stops as a result of Covid-19
9. Final business plan development and market research
10. Preparation for presentations and virtual demos

April

11. M&T Summit Demonstration
12. Integration of feedback from M&T Summit
13. Final Spring Demo

IX. Discussion of Teamwork

We were able to work effectively as a team because we set weekly actionable goals for each team member and divided the work based on skills and interests. In the early stages of our project, we set a design plan as a group. This was extremely useful since each member brought a unique background to the table and was able to forecast issues we may have had and devise solutions in the many different components of our project. From there, we maintained frequent communication over Facebook Messenger and met every week to two weeks to discuss progress and next steps. As we entered January and February, we began to meet in person much more frequently to tackle building our physical product. Saurin took the lead on procurement and worked alongside Ryan to build the electrostatic clutch and glove hardware. Yonah and Nick took the software side, with Yonah leading Unity development and Nick leading Arduino integration. Because our project could be broken down into several components that needed work and had different timelines, having a heavy focus on integration ensured that the full stack system would function.

IX. Budget and justification

Our original budget was $600, including $400 for an Oculus Quest, $40 for ESP32 microcontrollers, $20 for air pumps, $30 for servos, and $110 for miscellaneous items like wires, PLA for 3D printing, bread boards, etc. At the end of the fall semester, we pivoted our design towards an electrostatic clutch and vibration motors, and forecasted a final cost range of $600 to $1000 depending on fabrication costs and progress.

Now that we have a functioning prototype, we are happy to announce that we were very well in line with our original budget, and on the lower end of our adjusted budget. Our total cost was $620 and the majority of our cost came from the Oculus Quest. We would like to thank the ESE Department, particularly Sid and Jan, for their financial support and guidance with this project. With professional fabrication, we would have been closer to our maximum budget of $1000, but we were unable to reach this step as a result of the disruption to the semester. (Note: this is the budget for the year long senior design course - not the cost for a single glove which is ~$50).

Table 02: Year Long Budget

Item	Amount
Oculus Quest	$400
Vibration Motor	$15
Air Pump	$20
Arduino x 2	$30
Shim Stock Metal	$30
Velcro	$10
Dielectric Film	$15
Nylon Gloves x 6	$10
Conductive Glue	$40
Total	**$570**

X. Standards and Compliance

Building a commercially viable and consumer-friendly haptic glove requires compliance with a variety of industry and regulatory standards. The ISO (International Organization for Standardization) sets the majority of standards for haptic interfaces and devices. ISO 9241-210 covers ergonomics for haptic human-system interactions. Haptic gloves should not put undo physical stress on the human or cause any distinct discomfort. Our haptic glove was carefully designed to fit well on a variety of hands, and implements both hardware and software controls to prevent undo physical stress or discomfort while using the glove. ISO 9241-940 covers standard methods for evaluating haptic feedback, covering both virtual environment configuration and physical response. Our piezoelectric actuators are off-the-shelf ISO 9241-940 compliant parts, and our custom built electrostatic clutch was evaluated using both quantitative and qualitative measures as suggested by the ISO standards, and meets all guidelines. Our custom built Unity test environment is also compliant with ISO 9241-940 by utilizing clear overlays and adequate object spacing to prevent user nausea.

Other important standards include the materials standards set by the ASTM (American Society for Testing and Materials). ASTM B501-10 covers standards for use of silver-coated steel in electronics. Our electrostatic clutch implements silver epoxy coated steel plates, and our silver thickness is well in line with ASTM B501-10 safety standards. Further, ASTM WK28561 covers standards for application and testing of carbon nanotube solutions. We use carbon nanotubes to coat our ultra-thin mylar dielectric in our electrostatic clutch. Our method of application is in line with ASTM Wk28561 standards, however we were unable to complete the suggested lab-based testing of our carbon nanotube thickness as a result of the current health crisis, so we will leave this to future work that will certainly get done before any consumer testing.

The IEEE (Institute of Electrical and Electronics Engineers) sets a variety of standards for wireless communication and electrostatic discharge. IEEE C63.16 covers standards for measuring and limiting electrostatic discharge in consumer electronic devices. Our electrostatic clutch is well within the safety range suggested by the IEEE, but will require further testing of charges at points throughout the glove to meet the testing standards suggested by the IEEE. IEEE 802.15 covers standards for implementation of bluetooth communication. Since we used off-the-shelf communication equipment (Arduino microcontroller and Oculus Quest), our glove is compliant with IEEE communications standards.

Lastly, the CPSC (Consumer Products Safety Commission) regulates products and sets rules for consumer safety. Our glove is safe for consumers and meets all consumer device standards set by the CPSC.

XI. Discussion and Conclusion

Our team is tremendously happy and proud of the work we did this year. We feel that we successfully scoped out a reasonable yet ambitious project and met the goals we set out to accomplish. While it saddens us that we were never able to see the project through to its conclusion and a fully finished prototype, we think that our technical progress was impressive nonetheless. Specifically, we created physical prototypes which successfully mimicked sensations of tactile and structural feedback. On the software side of things, we created a basic VR environment to experiment with and successfully integrated our software and hardware so that the two could easily communicate together.

This year has also been a great learning experience for each of us. From self-learning nearly all of the main technologies needed for the project to designing a glove on our own from scratch, we have gained a ton of valuable experiences. Among the lessons we have learned are the importance of setting clear and accurate timelines, the importance of taking those timelines seriously, the need to be flexible and take setbacks as they come, the importance of accurately scoping a project, and the difficulties that can arise when trying to integrate individual components to create a single system. As we all go forward into our careers as Penn Engineering graduates, we will take these lessons with us and be better for them.

XII. Appendix

M&T Components

I. The Problem and the Need

Science fiction authors and technology enthusiasts have long dreamed of a fully-immersive virtual world where senses like sight and touch are so realistic that users cannot differentiate feeling from reality. Modern virtual reality headsets realistically trick our sense of sight to perceive virtual worlds, however gloves aiming to replicate touch lag far behind. Problems with currently available haptic gloves include weight, size, cost, and immersiveness. Most designs use large and heavy servo motors that tug at your fingers and cost upwards of $10,000 without adequately replicating touch or requiring you to fix your arms in place. A significant amount of research and development into haptics stems from the gaming industry, where use cases are dynamic and intense, but the stakes for accuracy are low compared to other industries like remote surgery. This makes the gaming industry the perfect sandbox to explore alternative designs to improve haptic gloves. We are building a haptic glove with a unique blend of vibration motors and electrostatic brakes that is sleeker, lighter, cheaper, and more immersive for gamers.

II. Value Proposition

Our haptic design leverages two key technologies that collectively capture all forms of haptic feedback necessary for a robust and immersive haptic system. Primarily, we implement tiny vibration motors across that hand that are connected to a microcontroller and vibrate in short bursts when touch is initiated to deliver low latency feedback. Secondly, we implement an electrostatic brake using thin metal plates across the hand that clamp together when a voltage is applied. These metal plates restrict the hand from closing completely when grabbing objects in the virtual world, similar to how an object you grab in the real world applies a force back on your hand keeping your hand from closing completely. These two technologies combined allow us to deliver realistic haptic feedback at a lower price point and lighter weight than more involved systems that require servos. The idea behind this design came out of a lab at Carnegie Mellon, however our novel material selection for the dielectric and coating enables us to make the design commercially viable and consumer friendly by delivering the same lab performance with safe power limits.

III. Stakeholders

Key stakeholders for our company include gamers (our consumers) in addition to video game designers and virtual reality headset makers. Our glove currently exclusively integrates with the Oculus Quest. Oculus collaborates with game designers to make games visually appealing and immersive for VR. Once we go to market, we will have to work closely with both game designers and Oculus to ensure smooth operation of our glove and seamless integration with Oculus in all circumstances. Game designers would want to optimize games for this new form of sensory feedback.

IV. Market Research

The market for gaming is very large. It is valued at $153.2b with a 11.0% CAGR. The VR industry is also currently quite large with a valuation of $50b and CAGR of 63.3%, but much of this value is the expectation of enormous future sales, not current sales. The Haptics industry is also large at $31.5b with a 19.8% CAGR. Haptics has a lower CAGR than VR because the Haptics market includes legacy haptic systems like aviation controls that average down the growth rate. We estimate the VR Haptic Glove market is worth approximately $1.5B today with a 50% CAGR over the next 10 years.

V. Customer Segment

We view the market as millennial gamers who are not wealthy enough to splurge on an expensive haptic system, but are interested in trying new tech at an affordable price point. Essentially, we feel like our core initial market is engineering students, with a broader secondary market of gaming and tech enthusiasts aged 13 to 35 years old.

VI. Market Size and Growth

See above.

VII. Competition

Our main competition is Plexus, Manus VR, and HaptX. Plexus builds slim, lightweight, and inexpensive haptic gloves, but their tech relies exclusively on vibration motors and thus cannot apply structural feedback like our solution. Manus VR, implements servos at a much higher price point, but has not achieved a realistic feeling of touch and has instead focused on developing hand tracking software that is no longer state-of-the-art with the release of Oculus Hand Tracking. Haptx is considered the industry leader in haptic gloves and has a very sophisticated system with realistic touch. Haptx gloves are not viable for consumers, however, as they are extremely bulky and expensive.

VIII. IP

Our implementation of the electrostatic clutch incorporated a novel application of carbon nanotubes to strengthen an ultra-thin dielectric. This process for fabrication and design of a haptic glove is potentially patentable, as we devised it from scratch.

IX. Costs

We built our prototype for about $80, not including the Oculus Quest and parts used during previous iterations. We plan to sell the glove at a $300 price point that is equal to other low cost haptic gloves. Our glove's superior performance should make it an easy choice for consumers.

X. Revenue Model

Revenue Model

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
VR Haptic Glove Sales	20000	32000	51200	81920	131072	209715	335544	536871	858993	1374390
Market Share	1%	2%	4%	8%	16%	32%	40%	40%	40%	40%
Infinity Glove Sales	200	640	2048	6554	20972	67109	134218	214748	343597	549756
Glove Price	$ 300.00	$ 304.50	$ 309.07	$ 313.70	$ 318.41	$ 323.19	$ 328.03	$ 332.95	$ 337.95	$ 343.02
Revenue	$ 60,000.00	$ 194,880.00	$ 632,970.24	$ 2,055,887.34	$ 6,677,522.08	$ 21,688,591.71	$ 44,027,841.17	$ 71,501,214.07	$ 116,117,971.65	$ 188,575,585.95

Cost Model

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Steel Plates	$ 6.00	$ 5.88	$ 5.76	$ 5.65	$ 5.53	$ 5.42	$ 5.32	$ 5.21	$ 5.10	$ 5.00
Carbon Nanotubes	$ 10.00	$ 9.00	$ 8.10	$ 7.29	$ 6.56	$ 5.90	$ 5.31	$ 4.78	$ 4.78	$ 4.78
Mylar Dielectric	$ 0.50	$ 0.40	$ 0.32	$ 0.26	$ 0.20	$ 0.16	$ 0.13	$ 0.10	$ 0.08	$ 0.07
Piezoelectric Actuators	$ 5.00	$ 4.75	$ 4.51	$ 4.29	$ 4.07	$ 3.87	$ 3.87	$ 3.87	$ 3.87	$ 3.87
Conductive Epoxy	$ 5.00	$ 4.50	$ 4.05	$ 3.65	$ 3.28	$ 2.95	$ 2.95	$ 2.95	$ 2.95	$ 2.95
PCB	$ 20.00	$ 16.00	$ 12.80	$ 10.24	$ 8.19	$ 6.55	$ 5.24	$ 5.24	$ 5.24	$ 5.24
Glove Mount	$ 4.00	$ 3.20	$ 2.56	$ 2.05	$ 1.64	$ 1.64	$ 1.64	$ 1.64	$ 1.64	$ 1.64
Glove Fabric	$ 3.00	$ 2.94	$ 2.88	$ 2.82	$ 2.77	$ 2.71	$ 2.66	$ 2.60	$ 2.55	$ 2.50
Cost per Unit	$ 53.50	$ 46.67	$ 40.99	$ 36.24	$ 32.25	$ 29.22	$ 27.12	$ 26.40	$ 26.23	$ 26.06
Total Costs	$ 10,700.00	$ 29,868.80	$ 83,939.53	$ 237,480.20	$ 676,342.94	$ 1,960,745.31	$ 3,640,078.48	$ 5,670,128.01	$ 9,011,307.64	$ 14,324,680.70

Profit	$ 49,300.00	$ 165,011.20	$ 549,030.71	$ 1,818,407.14	$ 6,001,179.14	$ 19,727,846.41	$ 40,387,762.69	$ 65,831,086.06	$ 107,106,664.01	$ 174,250,905.25