Beyond Smartphones:

Designing a flexible haptic wearable and auxiliary language for virtual reality applications

Final Report

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Acknowledgements

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Chapters 1 and 3 of this report are group-written and remain the same among each capstone team member's paper. Chapter 3 includes individually written portions that are distinct among the team's papers. Please refer to Chapter 2 of Arielle Maxner's paper for more information about the workings of haptic actuators and Chapter 2 of Diego Rivas' paper for more information about the prototyping and hardware build of Tacto.

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Abstract

Beyond Smartphones is a project in collaboration with Samsung and Stanford for the exploration of flexible/stretchable electronics to solve user needs in two domains – Fetal Monitoring and virtual reality. This paper discusses our approach to enhancing virtual reality: a haptic glove, dubbed Tacto, to provide sensory augmentation through tactile feedback that, as of now, is lacking in virtual reality experiences. Our vision for Tacto is to enable people using virtual reality to gain tactile feedback for the objects they see in the virtual world in order to enhance engagement and immersion. Taking on the form factor of a glove, Tacto uses an array of eccentric rotating mass (ERM) haptic motors located on each finger to create vibrational tactile sensations when the user touches an object in virtual reality with their hand. Motion sensing through a Leap Motion controller is used to track the user's actual hand movements and positions to translate them into VR. Various vibrational patterns and durations can be set on the haptic motors to convey different textures and forces, allowing a wide breadth of sensations to be felt by the user. The concept for Tacto was inspired by user and market research in Fall 2016, and over the course of Spring 2017 has become a medium fidelity prototype. As a supplement to the glove, we discuss the potential for creating a "haptic language" that we have begun to test with Tacto.

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Chapter 1

1.1 - Design thinking process for enhancement of virtual reality

The Human-Centered Design Process

In the first stage of our project we used a process known as design thinking, which is entirely human-centered. Design thinking refers to a process of developing a technology to solve specific user needs. The process starts with a stage of inspiration, where insights are gathered from observations and interviews of end users to shape the needs to be addressed by the solution. The solution to these needs follows the value proposition that the product will provide, as well as the mission that the project has. Furthermore, transforming these needs into solution concepts occurs via design principles. Design principles are essentially understood as guidelines the product should have to solve the user needs. The next stage of the process is called ideation, which is when iterative concept generation and prototyping comes into play, providing something users can interface with and provide feedback. Once that feedback is gathered, it is incorporated into the implementation stage: develop a higher fidelity prototype and go-to-market strategy to finalize the product development cycle [Brown, 2008].

Mission and Value Proposition

The start of the project was focused on doing human-centered design to come up with needs that we could address within the virtual or augmented reality space by using wearable flexible electronics. In this process, the first step was to lay out our mission statement and value proposition for the project. Our team's mission statement came from the direction our sponsor Samsung provided. The value proposition arose through research and identification of customer and user needs that shaped our concept generation and narrowed our scope.

Mission Statement: Beyond Smartphones aims to push the form factor boundaries of current electronics into flexible and stretchable wearables to enhance the Virtual and Augmented Reality experience. We will develop use cases that hinge on the Internet of Things to connect multiple functionalities onto each device. In our case, our device will communicate with the VR headset and environment.

Value Proposition: Beyond Smartphones will develop a flexible and stretchable wearable that incorporates seamlessly into the Virtual or Augmented Reality experience, as well as increases the level of immersion and control users have in the environment.

Customer and User Needs

From our 20 interviews and observations, we gathered insights of the things that virtual reality users could benefit from by using a flexible and stretchable wearable. The interviews ranged anywhere from virtual reality hardware designers to enthusiasts, coupled with observations we did at industry panels and events. Some examples of our user research are shown in images below during UC Berkeley's virtual reality Event - VXPC.

Figure 1 - User losing perception of physical boundaries using a VR Headset

Figure 2 - User exhibiting robotic motion limited by VR controllers

While we followed a similar rubric for interviewing, our goal was to read between the lines to understand the unspoken needs that were present in the experience.

Our main needs discovered are listed below:

- Easily bringing objects from the real space into the virtual space
- Use of augmented reality to improve safety mechanisms in daily life
- Lack of motion control in Augmented Reality
- Augmentation of safety through haptics
- Aid of handicapped people with AR/VR
- Leveraging augmented reality for instructional purposes in real activities
- Preventing motion sickness when using VR headsets

Concept Generation

From these needs, we did brainstorming sessions individually and as a group to come up with conceptual solutions to address these needs. Separately, we ended up coming with a total of 53 concepts that then transformed into 75 concepts when we brainstormed as a group by using methods of idea recombination and reframing. To better visualize, categorize, and select the concepts we did a method known as 'clustering'. In this process we took all concepts that addressed similar needs and grouped them together. The concepts that did not align with our core needs we started counting out, leaving us with 27 concepts for the final selection stage. Several results of the clustering process are listed below, along with each concept description and need addressed (please refer to the Appendix section for the full list of 27).

Concept	AR/VR	Description	Cluster Experience
Kanvas	VR	A sheet with embedded electronics that quickly brings a base shape into VR, then can be drawn upon	Bringing objects/feedback from real space into VR space
Safety Glasses	AR	HUD safety glasses for construction workers that can show where dangerous areas are, monitor health (especially hydration), and send emergency signals in case of trouble	Visual Safety Augmentation
VR Meets AR: Haptic Feels Glove	AR/VR	Current VR interactions have no tangible feel with objects in the world. If we incorporated gloves that measured your hand position in space and gave you haptic feedback when you came in contact with an object	AR / VR Motion control
Sleeping Aid	AR	Custom made ear inserts (organically shaped to each user, must be flexible shape) that has noise cancelling technology. Optional fabric band connecting buds serves as face-mask to block out light. Marketed to be used to help sleep	Auditive augmentation/aid
Seatbelt	AR	Smart seatbelt that vibrates to alert driver if falling asleep, alerts, etc.	Haptic Safety Augmentation

Music Teacher	AR	Augmented reality for whatever instrument you pick up: look at a piece of music or choose from library, and see on the instrument where to place your fingers. Combine with body motion capture to determine what to improve, which notes you're not hitting.	Instructional Augmentation
Finger Ruler	AR	Device on index finger and thumb that can measure the thickness of something you're holding between the two fingers	Daily activity aid
Alphabetic Braille	AR	A finger attachment that senses letters (both from texture and color change), and outputs audio for blind people to understand what is written. This removes the need to learn braille, and allows to use one universal alphabet	Handicap aid
Inner Ear Control	AR/VR	Reduce motion sickness effects by wearing headphone or earplug devices that modulate the air pressure and flow inside the ear	Preventing VR Motion Sickness

Concept Final Selection

The next step was to narrow down our 27 concepts into a smaller number which we could move forward with. We brainstormed our judgement criteria by considering the needs of our top stakeholders: users, Samsung, Stanford Researchers, our advisors, and our capstone team. For these groups, we decided on the criteria listed on the right of the chart below.

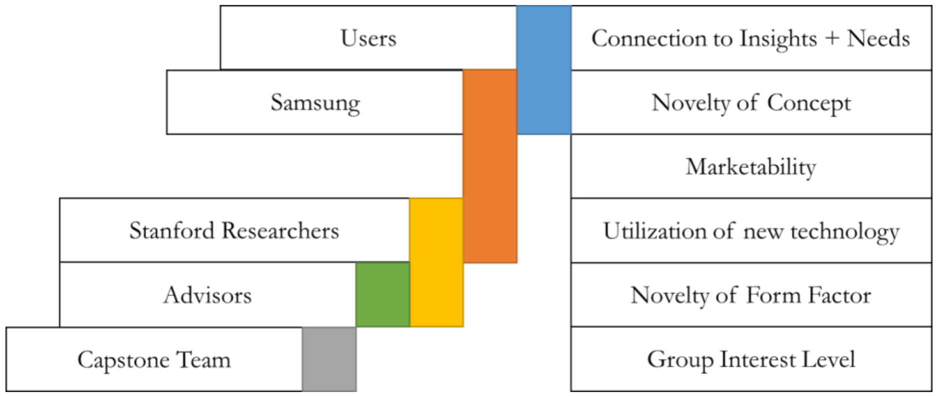


Figure 3 - Summary of the correlation between our stakeholders and the judgement criteria for our concept selection

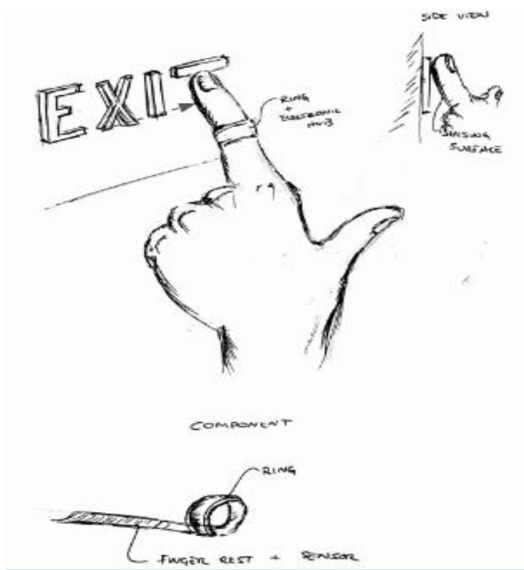
Each concept was rated against these criteria, and the top 3 concepts were chosen as a first selection stage to get feedback from our sponsor Samsung and from virtual reality experts. The main concepts selected were:

1. Instructional AR devices

A device that leverages augmented reality to provide instructions or feedback for everyday daily activities. Example scenarios include visual instructional pop-ups that help burgeoning chefs in the kitchen, symbols on the patient's body during operations for surgeons, and visual aids on the fretboard of a guitar or other musical instruments to help beginner artists practice. The team recognized that educational opportunities are a major usage scenario for augmented reality.

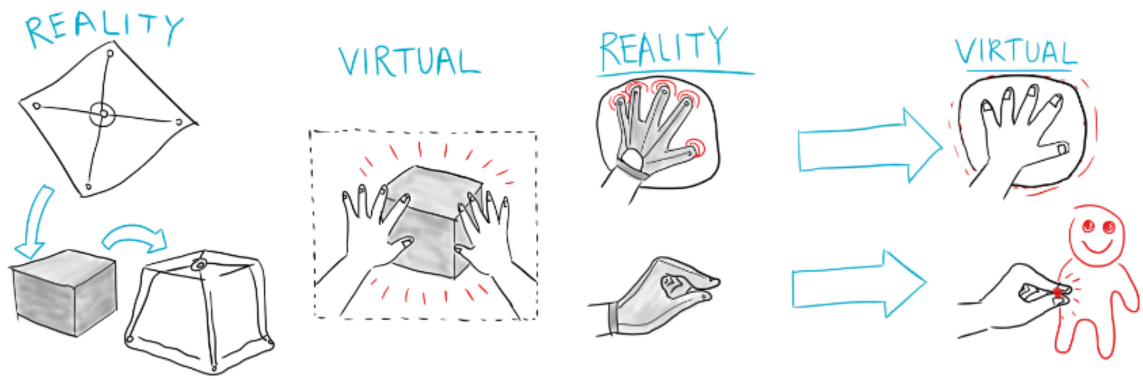
2. Augmented Reality haptic hand devices for blind aid

A hand or finger wearable that allows visually impaired people to scan their hand over any 2D surface. It will provide haptic feedback that allows them to understand any visual or text. Assistive touch for people with disabilities utilizing tactile feedback is another major area of potential. The team believes that sensory input through touch can be especially powerful and effective for those that cannot depend on other senses.



3. Flexible sensing cloth to bring in real objects into the virtual space

A flexible cloth that can be wrapped around any object and instantly captures any geometry to bring it into the virtual world. A big draw for virtual reality is the ability to manipulate and modify things in ways that can't be done in real life due to limitations in physics. There is a major opportunity in assisting users to effortlessly create virtual copies of familiar objects in real life that users could handle in unprecedented ways.



After receiving feedback from our sponsor and industry experts, we concluded that the most powerful ideas with our technology would be a hand wearable to provide haptic feedback in virtual reality, and a flexible sensing cloth to bring in real objects into the virtual world. However, as we mention in Chapter 3, the latter option has the disadvantage that the market is already saturated of much more advanced methods for capturing real geometry efficiently and bringing it into virtual reality. After compiling these insights, we finally decided to pursue a glove form factor that could bring tangible feelings into the virtual reality environment through haptic feedback, which we call Tacto.

Design Process Summary

Overall, our initial design process with each stage and takeaway is summarized in Figure 1 below:

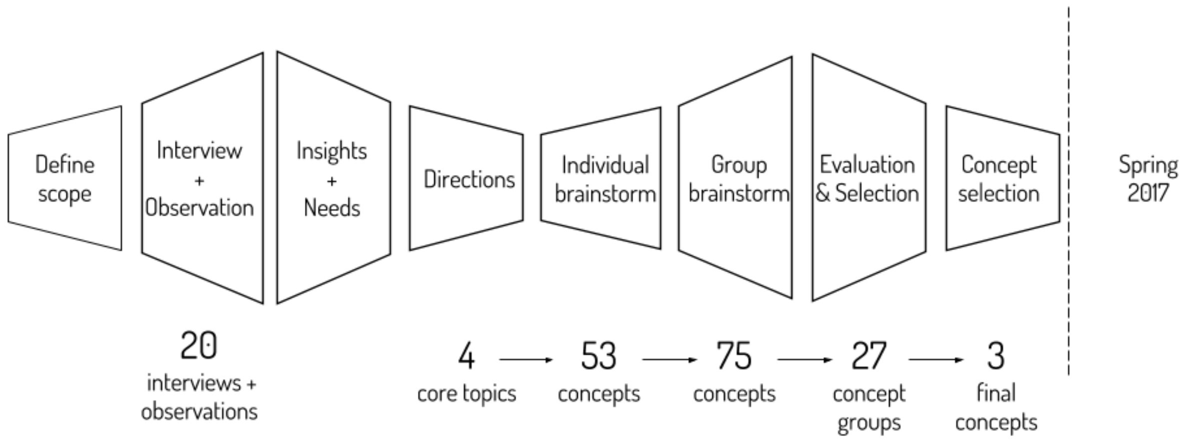


Figure 4 - Design research process

In Spring 2017 we kicked off with our final haptic glove idea and a plan for prototyping and user testing. Until now, our design prototyping strategy has relied on using off-the-shelf electronic components to develop the required functionality to generate haptic feedback in a virtual environment. For this preliminary stage of design there were no manufacturing considerations, but moving forward the device will be designed also from a manufacturable and reliability perspective. This will entail things like material selection for ME, electrical component selection for EE, and communication protocols for the software interactions.

Finally, as much as our design strategy is human-centered, it must also be technology-centered. So another component in our work will be collaborating with Stanford to leverage their flexible electronics technology. The goal will be to have a functional flexible electrode by February 2017 to incorporate into Tacto's design. In the next chapter, we discuss potential technology routes to make the prototype approach a more flexible electronics structure as it was initially intended with our value proposition.

Chapter 2

2.1 – Biological Processes

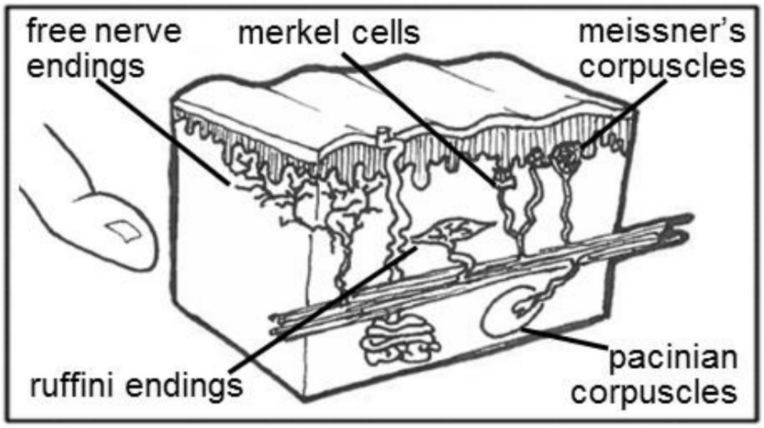
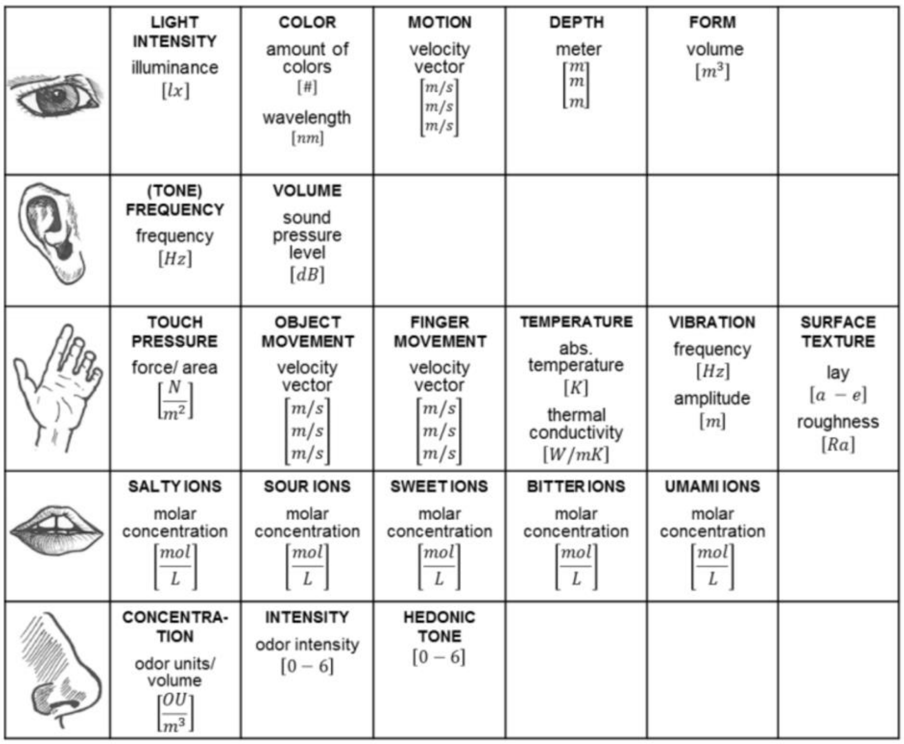


Figure 5 - The somatic sensory system (Balters et al., 2015)

In order to create a convincing haptic wearable, it is crucial to first understand how the human perception of touch works as well as the factors that affect what is perceived. Known as the somatic sensory system, the method with which humans detect and process tactile information originates in the dermis layer of the skin (Balters et al., 2015). Specialized cells called mechanoreceptors are able to generate a receptor potential by changing the permeability of cation channels when mechanically deformed due to touch, vibration, or pressure (Balters et al., 2015). Several varieties of mechanoreceptors exist, each able to react to and detect different stimuli. Merkel cells in the fingertip, for example, exist in the high skin layer and react to touch and light pressure, whereas Pacinian corpuscle receptors in the deep skin layer are stimulated by vibration (Balters et al., 2015). The mechanoreceptors pass the signal to the somatosensory cortex in the brain via the spinal cord, where the signal is processed and the area of the body that was touched is determined. Other sensations such as pain and temperature come under the jurisdiction of free nerve endings known as nociceptors and thermoreceptors (Balters et al., 2015).

In their paper, Balters et al. are thus able to categorize all the possible stimuli a person can feel based off of these biological features into 6 areas: touch pressure, object movement, finger movement, temperature, vibration, and surface texture (Balters et al., 2015). Along with stimuli for other sensory systems of the human body such as sight and smell, these six haptic stimuli are used to create the QOSI matrix as seen in the figure below.



	LIGHT INTENSITY illuminance $[lx]$	**COLOR** amount of colors $[\#]$ wavelength $[nm]$	**MOTION** velocity vector $\begin{bmatrix} m/s \\ m/s \\ m/s \end{bmatrix}$	**DEPTH** meter $\begin{bmatrix} m \\ m \\ m \end{bmatrix}$	**FORM** volume $[m^3]$	
	(TONE) FREQUENCY frequency $[Hz]$	**VOLUME** sound pressure level $[dB]$				
	TOUCH PRESSURE force/ area $\left[\frac{N}{m^2}\right]$	**OBJECT MOVEMENT** velocity vector $\begin{bmatrix} m/s \\ m/s \\ m/s \end{bmatrix}$	**FINGER MOVEMENT** velocity vector $\begin{bmatrix} m/s \\ m/s \\ m/s \end{bmatrix}$	**TEMPERATURE** abs. temperature $[K]$ thermal conductivity $[W/mK]$	**VIBRATION** frequency $[Hz]$ amplitude $[m]$	**SURFACE TEXTURE** lay $[a - e]$ roughness $[Ra]$
	SALTY IONS molar concentration $\left[\frac{mol}{L}\right]$	**SOUR IONS** molar concentration $\left[\frac{mol}{L}\right]$	**SWEET IONS** molar concentration $\left[\frac{mol}{L}\right]$	**BITTER IONS** molar concentration $\left[\frac{mol}{L}\right]$	**UMAMI IONS** molar concentration $\left[\frac{mol}{L}\right]$	
	CONCENTRA-TION odor units/ volume $\left[\frac{OU}{m^3}\right]$	**INTENSITY** odor intensity $[0 - 6]$	**HEDONIC TONE** $[0 - 6]$			

Figure 6 - Quantified Object Sensation Input Matrix (Balters et al., 2015)

The QOSI matrix encompasses all the stimuli that a person can react to, and in the design of Tacto, represents the haptic parameters that the wearable can try to simulate.

2.2 – Design and prototype build

For our first-pass functional prototype, we wanted to create something that would simply validate the feeling of haptic motors actuating on the fingertips of a wearer. At this point, we wanted to test how the motors would feel when firing under a basic vibration pattern. Actuation for the first prototype was intended to be binary – the motors would be off until triggered by some condition, at which point a static effect would be activated until the condition was no longer met.

Before a physical model was built, a 3D concept was created with CAD using Autodesk Fusion 360. This CAD model featured a slim, shape-hugging design with wires and a controller module situated on the backhand. Individual cylinders were also modeled on each fingertip to represent the haptic motors. Various angles of the model are shown below.

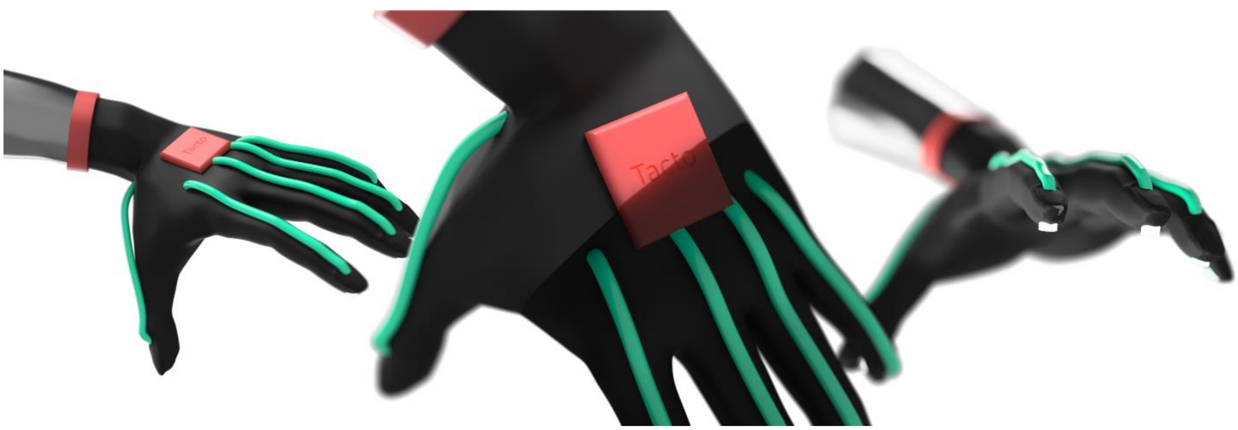


Figure 7 - Concept rendering for Tacto depicting our vision for a sleek form factor and inconspicuous hardware

Happy with the direction of design we were going in, we proceeded to assembling a physical prototype. Using a Nike running glove as the base layer, we glued eccentric rotating mass (ERM) motors to each fingertip. Wires ran down the fingers to DRV2605 motor drivers mounted around the knuckles. The motor drivers themselves were then connected in parallel to an Arduino Flora microcontroller, which acted as the central "brain" of the hardware. For our first-pass prototype, we attached a HC-SR04 ultrasonic rangefinder to the palm of the glove to use for sensitivity and cognitive perception testing (outlined in detail in the next section). The ultrasonic rangefinder would ultimately be unnecessary for use in virtual reality because the glove would not need any real-world reference points to function properly. In addition, we included an accelerometer in preparation for any potential testing during which motion tracking would be relevant.

Figure 8 - Tacto palm side features

Figure 9 - Tacto backhand features

2.3 - Cognitive perception testing provided by vibrational feedback

After building the Minimum Viable Product prototype functioning with the ultrasonic sensor for measurement and ERM actuators for feedback, we moved onto the cognitive user testing. The overall set up of this test was to have users wear the Tacto glove and wave their hand as instructed over an object or surface in front of them. In doing so, we wanted to observe the users' recognition of object boundaries and shapes without being able to rely on the sense of sight. This motion occurred at different distances from the object, and allowed us to document how accurate the perception of a shape or boundary was related to the haptic feedback provided at a distance from an object.

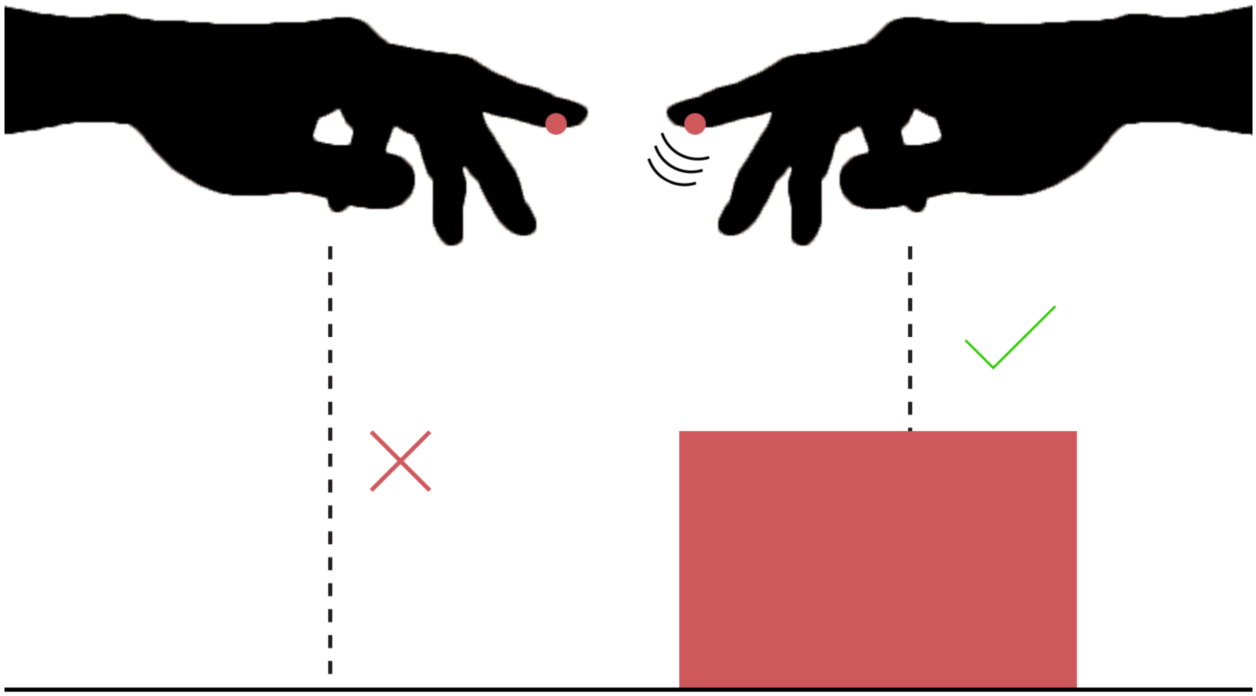


Figure 10 - Test setup - the haptic motors trigger when an object or surface is within the distance threshold

This first set of tests used a constant actuation effect that was activated when the ultrasonic sensor detected an object within a certain distance threshold. With this information, this haptic cue could be used to indicate forbidden positioning within a virtual environment in our haptic language, for instance if the hand actually penetrates into a virtual object surface. The next set of tests will use a different effect to see if a softer and less powerful vibration at a surface does not provide such discomfort.

We performed eyes-closed tests with three main types of shapes: flat objects, objects with gaps, and curved objects. Flat perception was fairly reliable, and gap perception was very good. Distinguishing edges was challenging, notably due to the location of the ultrasonic sensor. Situating the ultrasonic sensor in the middle of the palm yet actuating the fingertips uniformly produced an amorphous perception of object edges. For this reason, it was also difficult for users to understand curved surfaces, such as a cylinder. One user noted that using varying degrees of vibration intensity as the hand approaches the object could be more effective - increasing intensity the closer to the object would give a spatial perception of the approach, or communicate a warning instead of shape perception. Another thought that constant actuation was better suited for perception of textures and friction, as if your hand was brushing across the surface, but didn't make sense for stationary perception. In this regard, we plan to test various effects for their frictional and stationary perception to determine which makes sense as a stationary haptic icon to communicate the binary presence of an object and which act as texture indicators.

The open-eye test allowed us to understand the correlation of visual stimuli with haptic feedback effects, which is effectively what we will have when we bring it into a virtual environment. The main takeaway was that they complement each other by providing a pre-adjustment of the hand position however you want to interact with an object or surface. This pre-adjustment coupled with a haptic feedback is then highly convincing in generating a tactile effect.

Closing the hand into a quasi-fist with the glove on gave users semi-realistic force feedback. The feeling was described as a "magnetic" force opposing the finger pads that was as if you were holding something.

In summary, the test was divided in three stages - shape detection, gap depth perception, and open-eye exploration. From the latter, we aimed to get quantitative feedback on the use of Tacto connected to visual stimuli. Representative images of each test are shown below respectively.

Figure 11 - Box shape detection test with Tacto

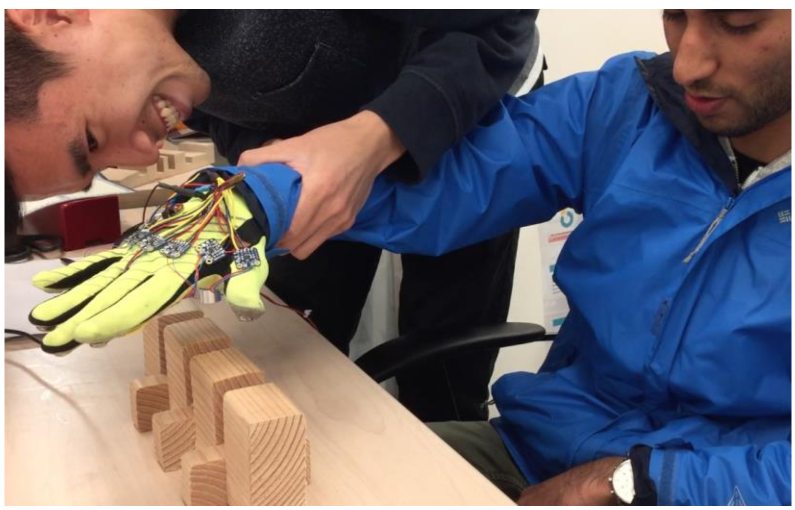


Figure 12 - Gap depth detection test with Tacto

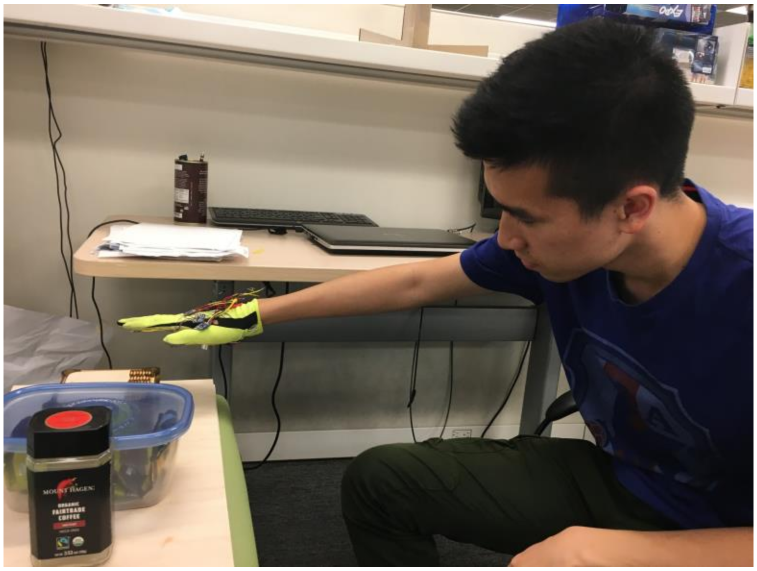


Figure 13 - Open-eye haptic feedback exploration

Figure 14 - Alternative test to open-eye: environment walkthrough by only haptics

- Optimum distance to object = 1 cm
- Haptic effect used = 'Soft bump 30%' Adafruit DRV2605L Effect 9 (This effect was noted to be somewhat uncomfortable when constantly running, as if the hand was placed somewhere it was not meant to be.)

Subject #	Test	Notes
1	Shape detection - box	Different motions of hand give perception of different dimensions, but it is hard to track shape outline
1	Gap Test	Perception of difference in depth was accurate
1	Open eyes test	Sensing should occur at fingertips for more real effect, this specific effect gives the impression that there is a field around the object pushing away, the effect of holding something invisible is much more real by closing your hand
2	Shape detection - boxes	Qty detected, but shape outline requires a gradually increasing effect to detect accurately
2	Gap Test	Gap perception was good and accurate
2	Open Eyes Test	An alternative test was made of walking through an environment and sensing walls with the sensor, the frequency of response needs to be quicker than the hand motion for users to be guided by haptics
3	Shape detection - box	Shape was detected accurately
3	Gap Test	Accurate gap perception
3	Open eyes test	Preshaping your hand from visual stimuli helps a lot to complement the haptic effect, because your hand is already in a certain shape that cognitively gives perception of something there of a particular geometry. Think about the context of these tests in a virtual environment
4	Shape test- cylinder	A constantly changing outline, such as circular, is hard to perceive since all sensors are actuated at the same time
4	Gap test	Much more "real feeling"
4	Open eyes test	This effect felt more like friction than touch. The effect of closing the hand is much more convincing because the finger motion is coupled with the haptic effect.

In conclusion, our main takeaways that we took for our next step were: the hand tracking reference needs to occur near the actuation points, a visual stimulus is critical in providing a hand adjustment before the haptic effect occurs, the effect must vary in intensity as you come closer with an object simulating the reaction force from the surface. Then, our next task was to take these results and use them as parameters for our next prototype -- merging the Tacto glove with a stationary virtual environment. For this environment, we used Leap Motion to track the position of the hand and correlate it with the proximity from the object.

2.4 - Development of a virtual reality environment for Tacto

The virtual environment and communication between Leap Motion and the Tacto glove were implemented via the Unity game engine. The environment itself was simplistic - a single glass table with several primitive objects on it, including a cube, a sphere, and a cylinder.

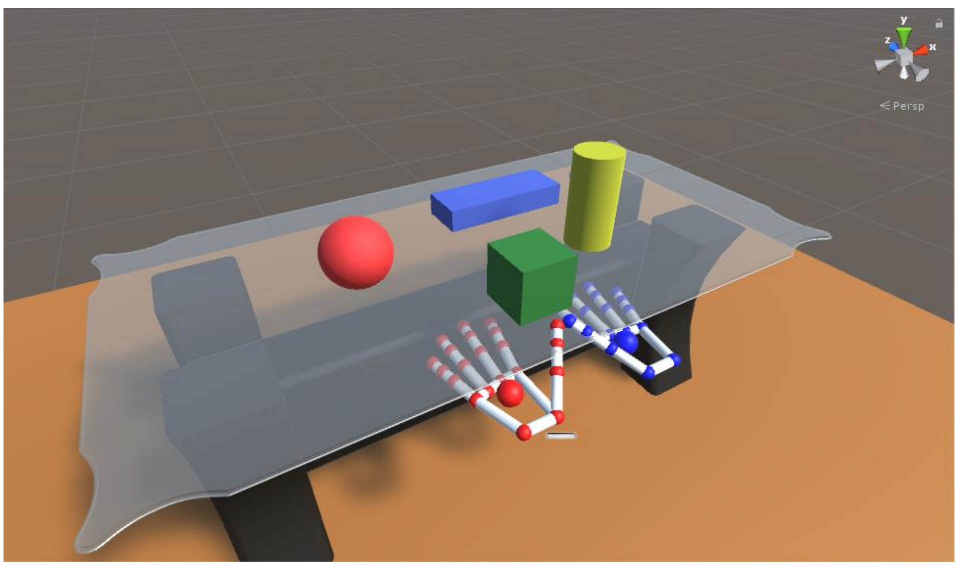


Figure 15 - In-game screenshot of the virtual environment

We used Leap Motion's provide Unity asset package to bring tracked hands into the virtual environment. Upon someone's hand going within a certain distance of one of the objects, a script would trigger a function that would send a string via serial port to the Arduino on the Tacto glove. Similarly, the Arduino could also send strings back to Unity. This allowed for end-to-end feedback between a person's physical hands and the electronics on the Tacto glove.

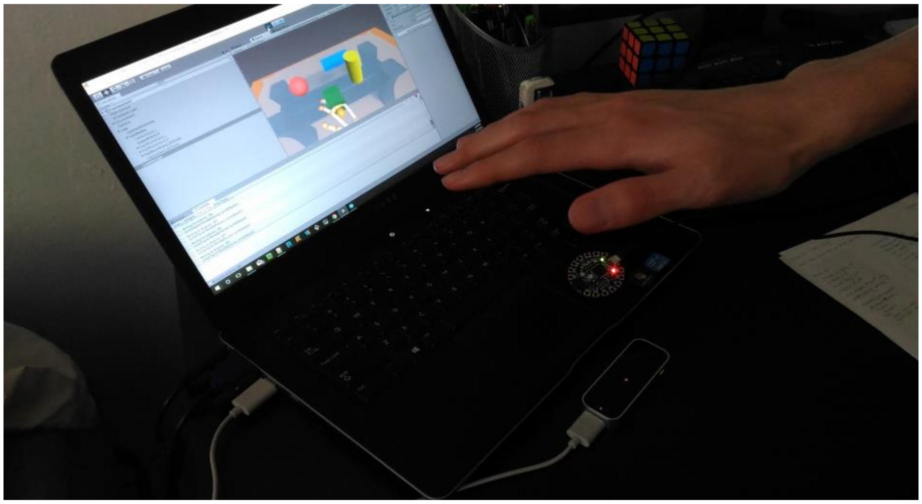


Figure 16 - Desktop setup with Leap Motion, Unity, and Arduino connected

Chapter 3

3.1 - Industry and market context of haptic product architectures for virtual reality enhancement

In this Chapter, we will focus on laying out specific areas of context where our technology is placed, which will serve to explain its purpose, competitive advantage over others, and its need within the current technology and design roadmap of the virtual reality industry. Our contextual focus has shifted as our project moves forward, given the iterative nature of our user research process and gathering insights on the most relevant need that can be solved with our technology. At first, we started with the context of looking at all VR/AR applications and technologies, we then shifted to soft electronics to capture geometry from real space to virtual space as it was mentioned in chapter 1.a , and lastly we set our contextual focus on the use of soft electronics to generate tactile feedback in virtual spaces. Our goal with this paper is to relate the immediate need and technology available to implement our product that generates tactile feedback, but also note that in the future our product could use the same soft electronics both to capture real geometry into the virtual space and generate tactile feedback.

Technology context

For this section, we will give an overview of the overall potential of technology related to soft electronics to both sense geometries and to generate tactile feedback. For geometry and shape sensing, various methods of measuring deformation across a surface exist in the field of soft electronics. A few technologies used for sensing strain are liquid metal sensors, conductive wires, flexible capacitors, fiber optic strain sensors, and piezoelectric materials. First, liquid metal sensors are substrates with embedded microfluidic channels filled with conductive liquid metal, and they function the same way solid conductive wires work. When stretched, the geometry of the channel changes, in turn changing the overall resistance of the liquid metal [Majidi et al., 2011]. Similarly, flexible capacitors also operate based upon geometric dependence, where stretching the capacitor changes its capacitance. Another method for shape sensing is fiber optic strain sensors, which embed gratings into the optical cable that when strained change the wavelength of light reflected [National Instruments, 2016]]. Lastly, piezoelectric films and materials operate based upon the principle that in certain solid materials, charges build up in response to applied stresses. These charge buildups, or potential differences, can be read out as a voltage across the material. After evaluating all these methods, we established that the roadmap for these sensing technologies is already saturated with high accuracy sensors of a different nature, so we iterated on our design process to establish what other need we could solve by using soft electronics in our product.

This led to us exploring the possibility to implement flexible electronics to bring tactile feedback into virtual reality, which we design by using haptics. Haptics is fundamentally defined as generating artificial tangible sensations by using a hardware system and carefully coordinating outputs with the human cognitive perception [Srinivasan]. Although haptics in virtual reality is not novel, most devices require a cumbersome amount of electromechanical hardware, whereas ours aims to behave as close to soft electronics as possible. [Burdea, 1996] In Chapter 2 an early prototype is shown using hard electronic components that generate haptic feedback, but in this section we layout different methods of generating haptics and their potential to move from hard to soft electronics.

One of the biggest challenges of using soft electronics for haptics is that the actuators would need to be strong enough to displace whatever mass interface it is attached to. The haptic feedback provided is directly related to the interface that it is attached to, whether it is an electronic device or directly in contact with the skin of the user, it is one of the largest considerations that can modify the end effect. In our case, our design involves haptic actuators embedded on a glove form factor, which approximates a direct skin contact and removes any concern of additional stiffness that may damp the haptic effect. To achieve this effect, there are multiple hardware alternatives that can be pursued. The first alternative is called an Eccentric Rotating Mass actuator, which is driven by an off-center mass rotating that inertially generates an effect in all directions. While these are cheap and operate well under 300 Hz, their response time is 40 - 80 milliseconds on average, which could definitely delay the cognitive perception of the haptic effect.

Another more effective actuator is called a Linear Rotating Mass actuator, which uses electromagnetic forces to displace a mass and generate a directional effect. While these provide a better timed response, they are still limited in their frequency for around 175 Hz. The last more efficient actuator is called a piezoelectric actuator, which is the same mentioned in the sensing technologies, but would in this scenario generate vibration by inducing AC voltage. These have a much larger displacement spectrum and a response time under 1 millisecond, greatly impacting the performance and ability to customize for our product [Rockland].

For the purpose of our prototype, driven by simplicity and cost, we are implementing ERM actuators, but strongly recommend to our sponsor to use piezoelectric actuators for the final refined product. Another benefit of piezoelectric actuators is that it can behave as soft electronics, by using a refined small mesh that is almost imperceptible to the user wearing the glove until the effect is actuated. Piezoelectric materials can be largely customized in the manufacturing process, since they are crystalline structures that can be tailored to any dimension. Lastly, although they can't provide large displacements, they are optimum for large frequency outputs that can be used to simulate friction from surfaces of virtual objects in our application. [Mazzone et al., 2003]
In using these actuators as approximate soft electronic components, and leveraging their properties discussed in the sensing section, we also have the benefit of incorporating into our hardware a sensing algorithm of hand position and potentially real object geometry capture. However, for the length of this project we have been using readily available computer vision techniques to capture object geometry into virtual space. Existing 3D scanning technologies generally output a point cloud which represents the surface of an object. These point clouds can be converted into 3D meshes using a variety of standardized techniques, such as Delauney triangulation. [Cavalcanti et al., 1999] This is ideal, since we need 3D meshes as our final object output as opposed to a point cloud, because we wish to integrate our outputs with Unity - a game engine widely used for VR development.

Unity uses 3D meshes, either triangular or quadrangular polygonal, to manipulate virtual objects [Unity, 2016]. The product that we will be using to generate these meshes is called Leap Motion, which functions with an array of two cameras and multiple infrared sensors to calculate the shape of a remote object by processing light and positional data through a lengthy algorithm. This algorithm generates a virtual three-dimensional shape by combining 2D cross sections with light reflections and shadows captured by the camera array [Holz, 2014]. We plan to take the integration of Leap Motion one step further by optimizing its 3D spatial approximation with the integration of the Bidirectional Texture Function as well as the Bidirectional Surface Scattering Reflectance Distribution Functions (BTF & BSSRDF respectively). The combination of these two definition functions will allow us to use the same mechanics of light reflection and refraction to approximate surface texture, and a ratio of surface reflectance and transmittance to provide a detailed 3D mesh.

In summary, our overall hardware technology system includes a sensing system: in our prototype it will be Leap Motion, but in the final product it will be using the same piezoelectric mesh for sensing. An actuation system embedded in a glove: in our prototype it is an ERM coarse mesh, but in the final product it will be a very fine and refined piezoelectric mesh approximating soft electronics. A driving circuit which should be made strictly out of flexible printed circuit boards. And lastly, a virtual space developed for users to interact with objects within proximity of them. We strongly believe that this combination will differentiate from its competitors due to its simplicity and comfort in usability, yet efficiency in enhancing the immersion to the virtual environment. To put into perspective where this product fits in the design and technological roadmap of the virtual reality world, we show the gap in the figures shown below.

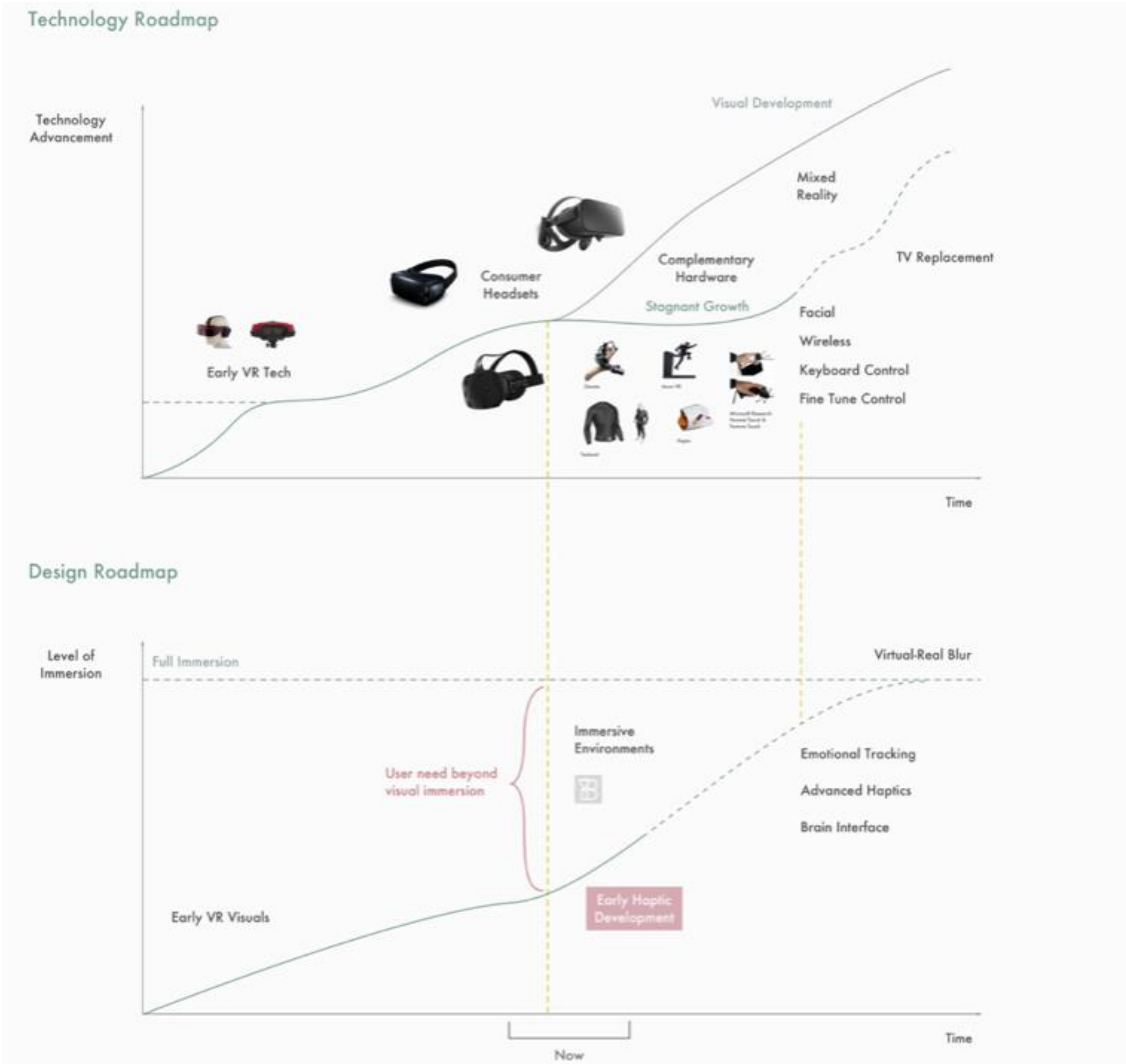


Figure 17 - Design and technological roadmaps

Industry

In very broad terms, our team explored very different applications in the industry where the incorporation of a wearable device could perhaps address current technology limitations in the use of AR and VR. Some of these applications were: virtually visualizing spaces to aid in the architect and engineer work of building new projects, and facilitating medical education and practice by providing a scaled up view inside the body. At the time, this context allowed us to receive some guidance as to where to focus our research, but now we have transitioned into narrower industry research after concluding the first stages of our design thinking process the previous semester. This section will focus more concisely on current industry players developing shape sensing technology for bringing real geometry into some virtual form. Following that analysis, we will focus specifically on technology for soft robotics technology developed for this purpose, which is what our hardware would fall into. Lastly, we will discuss the use of haptics thus far and its potential in VR.

From an industry standpoint, we have found that our most commercially developed competitor within the shape tracking mechanism is a company called Leap Motion [Colgan, 2014]. Leap Motion functions with an array of two cameras and multiple infrared sensors to calculate the shape of a remote object by processing light and positional data through a lengthy algorithm. Like one of the end goals of our technology, this algorithm generates a virtual three-dimensional shape by combining 2D cross sections with light reflections and shadows captured by the camera array [Holz, 2014]. While Leap Motion remains one of the predominant industry competitors in shape measuring technology, a vast amount of research has been done in optimizing shape tracking with computer vision. These technologies, like chordiograms, are aiming to efficiently capture object outlines by using light and comparing it with some other light contrast in the image given [Toshev et al., 2009]. This approach to computer vision has multiple downsides to our proposed technology: it is heavily reliant on lighting, quality of the images, as well as some calibration mechanism to ensure that the object is being tracked correctly. Our proposed hardware simplifies the gap between complex data processing and quality of shape recognition by providing an array of sensors in a soft robotics form that already accomplishes the three dimensional tracking these computer vision algorithms strive so hard to conquer.

The technology of soft robotics is fairly recent, and most of the industry presence is limited by small companies under R&D status, or potentially licensable technologies from university laboratories. The present main development focus for soft robotics is for biorobotics applications to generate elastic motion, which could have the potential to aid in handicap limited motion [Trivedi, 2014]. However, the shape sensing technologies using soft robotics are still early in their development, but show a lot of promise. One approach to these technologies is using conductive material that changes its resistance with elongation, as discussed earlier [Wurdemann et al., 2015]. In a similar manner, the Harvard Microrobotics lab has taken this further by incorporating multiple axes through strategically placed metallic traces that can change resistance if bent in different directions. [Vogt et al., 2012].

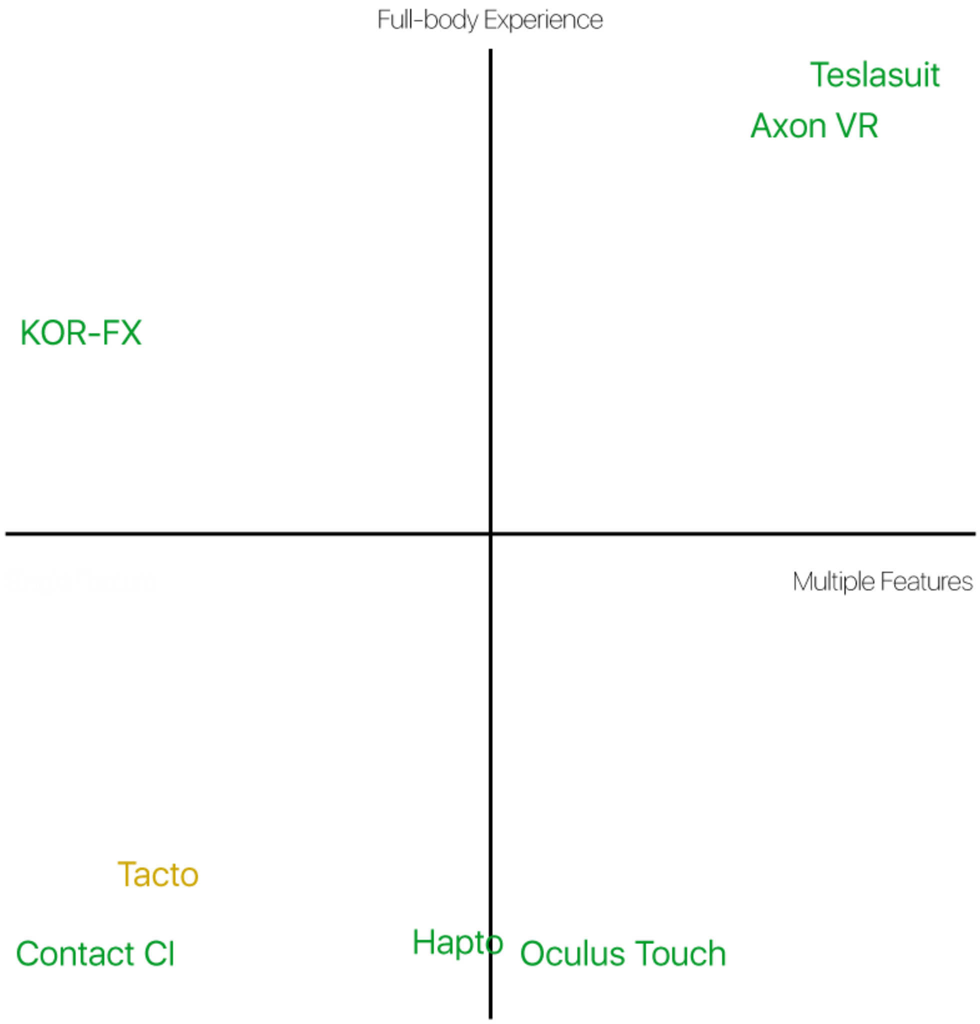
Overall, as mentioned previously, these technologies remain on the academic side. One early commercialization step is made by StretchSense, where this strain gauge concept is incorporated in your hands to track motion and output it onto an app [StretchSense]. However, none of these concepts are being applied to track geometrical shapes outside of hand motion. In summary, we can leverage some of these technologies to incorporate in our product for this entirely novel application, but we are not facing any commercial technologies that implement soft robotics in any way to capture shapes of geometrical objects.

In terms of haptics, many haptic devices are in development or being researched, but have yet to hit the market. Those that are on the market rely on the user to hold a controller, such as with the Oculus Touch. This lack of haptics in virtual reality is a huge white space for both users and developers to increase the amount of information given to the user by integrating haptic feedback with existing visual and auditory platforms.

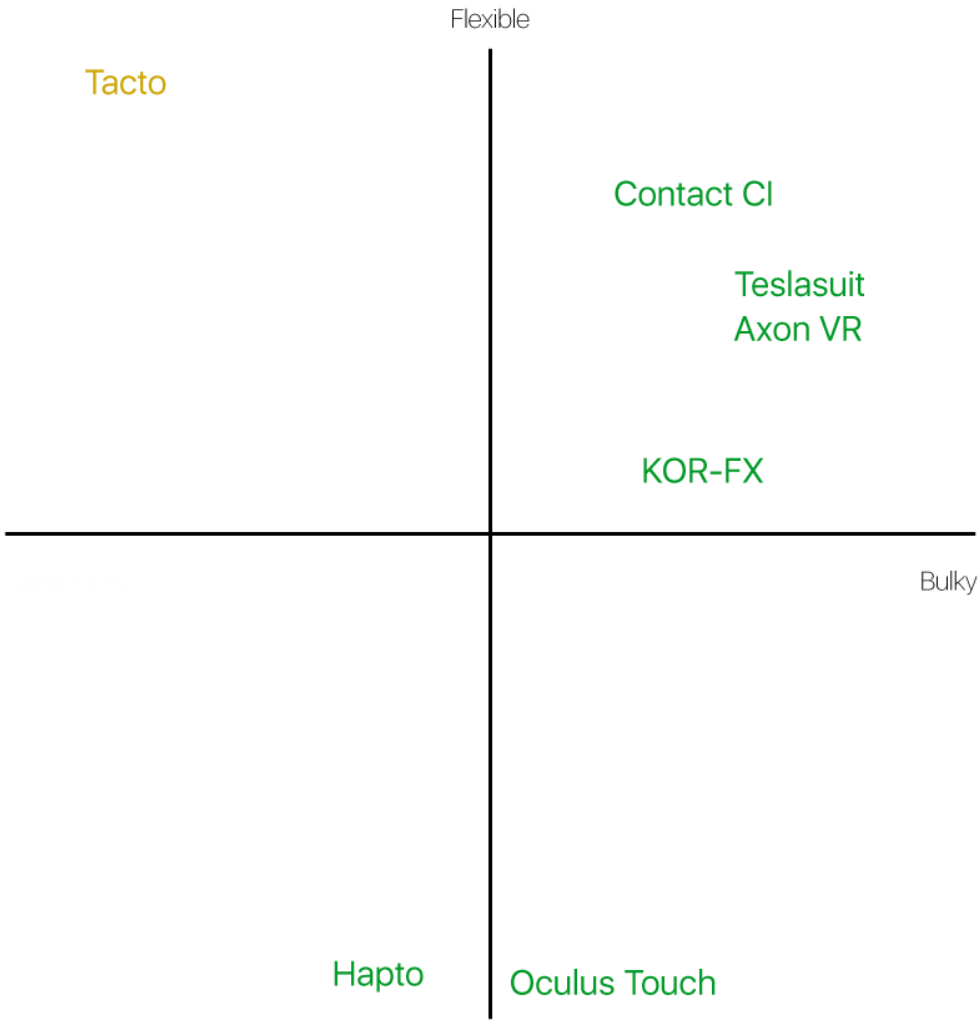
Previous work in haptics has shown the sensitivity humans have regarding different haptic waveforms parameters such as amplitude, frequency, signal duration, rhythm, and spatial dependence. However, like soft robotics, much of this haptic research remains scientific in nature and has not been communicated to a general market device. The most widespread haptics applications are in cell phones, or the "rumble" effects in video game controllers.

The VR haptic devices that are almost ready for market or are on the market fail to address certain features, illustrated by our 2x2 matrices (see following pages). For instance, many of these products are expensive, bulky, and rigid, geared toward the enthusiast and early adopter market. This leaves an opportunity to provide for the casual VR users who have so far been neglected.

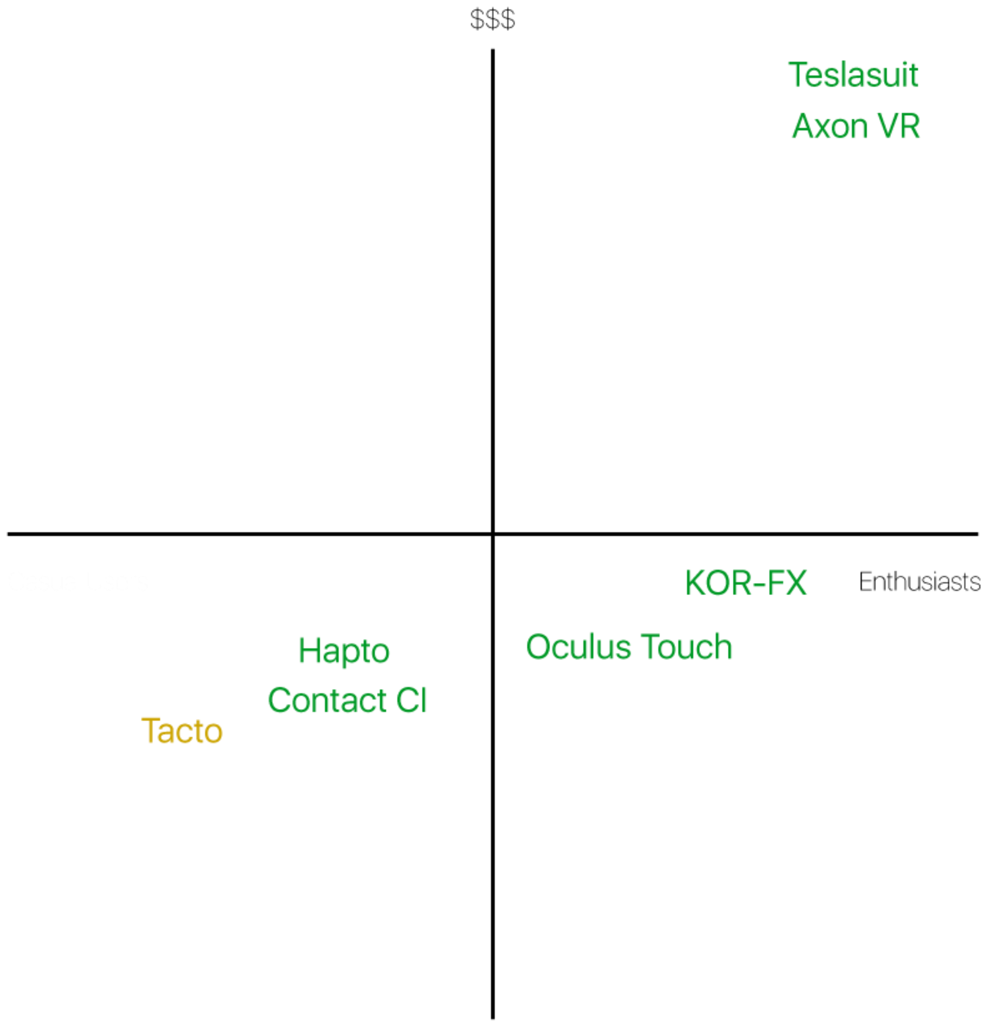
The technology used by many of these potential haptic device competitors varies. Oculus Touch and HTC Vive Controllers, the only commercially available products, use only industry-standard rumble. Quite a few devices attempt to use vibration actuation similar to Tacto, such as Contact CI, Kor-FX, and GloveOne. A class of force-feedback devices also exist which physically apply force counter to movements, pursued by companies such as Axon VR, Dexmo, and Exos. Hapto attempts to combine both force feedback and vibration. Finally, some companies pursue more novel approaches, such as Teslasuit, which uses electrical stimulation, and Tactical Haptics, which uses sliding plates to imitate shear and frictional forces. We chose to include on our 2x2s representative companies that are creating wearables that provide haptic feedback as well as more prominent industry players.



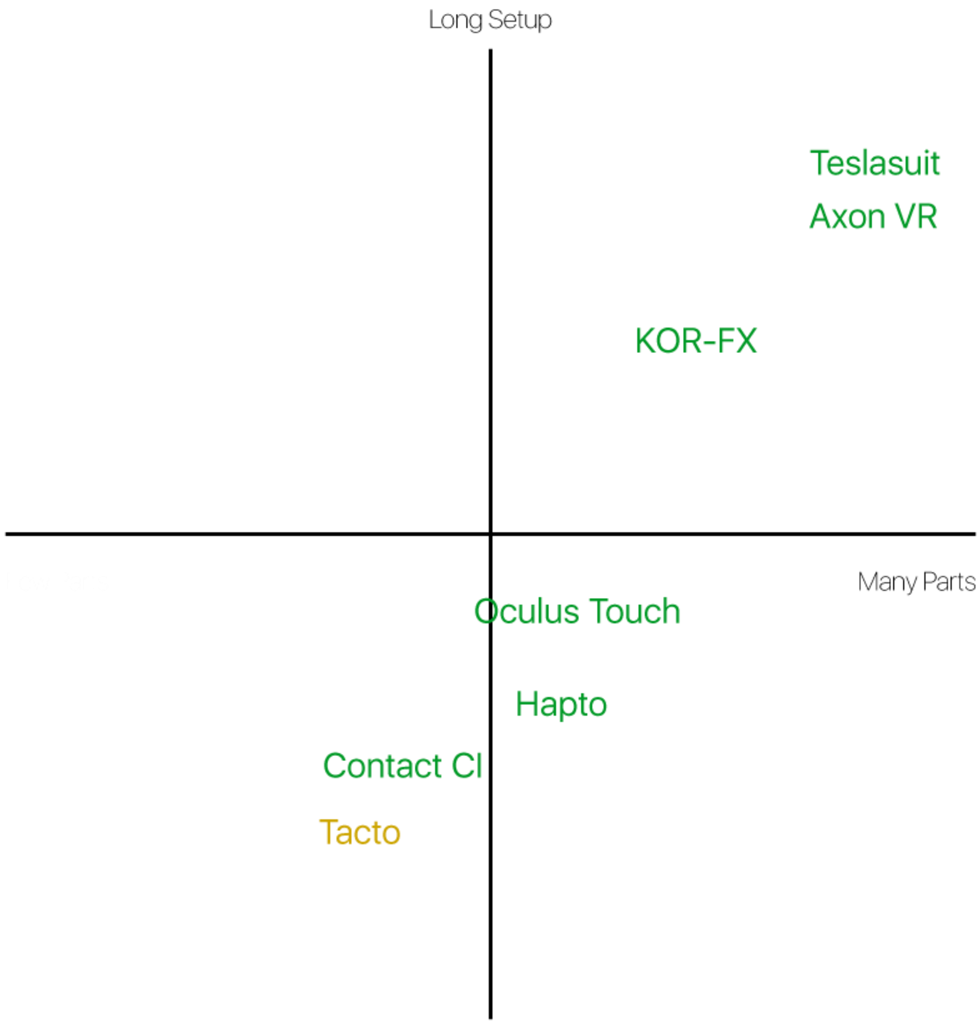
Full Body Experience vs. Multiple Features
Many of our other competitors have products that include either multiple features (eg. rumble feedback, buttons, temperature feedback, etc.), are a holistic contraption for the entire body, or both. What makes Tacto stand out from these other products is its focus on providing haptic feedback on the hands, a strategy that makes the device simpler and more effective. Focusing on a single feature will protect users from sensory overload, while targeting the user's hands will create a concentrated and more profound sensation in a localized area rather than diluting the effects across the entirety of the user's body.



Flexibility vs. Bulkiness
Tacto will stand out among the competition with a flexible and sleek form factor. Competitor products, partially as a result of the features and areas of the body they address, are large and bulky. A couple of products, namely Hapto and Oculus Touch, also have rigid form factors that do not complement the natural flexibility of the human body. Through the use of flexible electronics and stretchable fabrics, Tacto aims to be a wearable that is dictated by the way we move our bodies, rather than the other way around.



Cost of Product vs. Target User Level of Engagement
Our competitors are largely targeting virtual reality enthusiasts in areas like video gaming and professional settings. With that comes a higher price point for several of these products. While prominent devices currently on the market, such as Oculus Touch and KOR-FX, are at a sub-$200 price range and in the more "affordable" category, their applications largely target video game enthusiasts who have already invested in other more expensive equipment, such as gaming rigs and full-room staging areas. Tacto aims to deliver in the sub-$100 category (further explained in the *Marketing Strategy* section of this paper) in a space that is much more accessible to a wider audience that includes casual users. In addition, Tacto is not bound to any VR headset in particular, opening its compatibility to headsets that are also more casual by nature, such as Google Cardboard.



Setup Time vs. Number of Parts
We intend for Tacto to be a straightforward device without a high learning curve in order to cater to the casual users previously mentioned. Potential competitors with products like full-body suits could suffer with long setup times and initializations before the user acquires full functionality. In addition, Tacto is a small and simple system compared to our competitors from a mechanical standpoint. It will require fewer parts and materials, which will reduce cost, ease manufacturability, make the device less prone to breaking and improve serviceability.

Marketing Strategy

Ultimately, our vision for our project aligns with that of our sponsor, Samsung. It has been reiterated by Samsung to our team that they are most interested in pursuing virtual/augmented reality products that cater towards a general audience rather than niche market segments. This matches their approach with a majority of their consumer electronics, such as the Galaxy line of smartphones, Gear wearables, and other computing devices. Thus, our marketing strategy largely echoes the consumer-centric philosophy that Samsung has already established. However, considering the unprecedented nature of our project, aspects of our marketing strategy, such as initial distribution channels and buyers, may necessitate something different.

It is prudent to view and perhaps easiest to communicate our marketing strategy through the classic 4 P's of marketing: Product, Price, Promotion and Place. Each of the 4 P's categorizes different aspects of our marketing strategy that impact its success.

Product

The product that will come forth from our capstone project and that we will market is a haptic wearable - dubbed Tacto - for virtual reality that gives tactile feedback when the user interacts with surfaces and textures in virtual reality. Considering the rapid nature of our capstone project and our desire to have something built in the end, a good thing to think about is the minimum viable product, or MVP, which will convey the function of our product without necessarily looking as polished or optimized as a final, retail-ready design might. By creating an MVP, we will be able to show potential buyers and stakeholders what we intend Tacto to accomplish and to garner feedback about how to improve it and attract more people.

Price

According to the *Goldman Sachs Profiles in Innovation* report on virtual and augmented reality, the Samsung Gear VR, priced at $99, sold out on both Amazon.com and BestBuy.com within 48 hours [Bellini et al., 2016]. The report considers this accolade "an indication of strong demand at lower price points." Considering Samsung's strategy of approaching the VR and consumer electronics markets with products at a more affordable price point, our product should enter the market at a similarly affordable price. Since Tacto works as an accessory with virtual reality headsets and does not function as a standalone device, it would be ideally set at a lower price than the Gear VR somewhere in the sub-$100 range. This would incentivize buyers who are looking to buy a supplementary product for their VR experience to consider our product more seriously without feeling like they are making an investment as large as the primary device - the headset - itself.

Promotion

Samsung's Galaxy VR has been advertised through television and online commercials that, rather than showing off the technological features and sleek design of the headset, focus instead on the memorable experiences users have using the headset. One such commercial was shown throughout the 2016-2017 holiday season, in which multiple families and friends of different ethnicities and ages gather around to entertain themselves with the Galaxy VR headset [Samsung Mobile USA, 2016]. This is a good strategy to follow with Tacto according to the S.U.C.C.E.S. framework set forth by Chip and Dan Heath in their book *Made to Stick* [Heath, C., & Heath, D., 2007]. The acronym stands for Simplicity, Unexpectedness, Concreteness, Credibility, Emotional, and Stories. A good idea or product, that sticks, as the Heath brothers argue, will embody some or all of those elements. By following an advertisement strategy that emphasizes the emotions and stories that can come from using Tacto to digitize objects that have personal value to people, we can make our product more memorable and unique to potential buyers.

Place

Samsung products are sold through a plethora of channels, from their own website to brick-and-mortar retailers like Best Buy. While the infrastructure is certainly in place to push Tacto to buyers through all these channels, consideration needs to be taken for how initial purchases will be completed. Tacto, which has no other similar products out in the market, will be born into the earliest stage of Everett Rogers' diffusion of innovations curve [Rogers, 1983]. That is, the people to buy Tacto initially will likely be those who are particularly enthusiastic, passionate, and educated in virtual reality. According to the Goldman Sachs *Profiles in Innovation* report, the largest predicted market for virtual reality in 2025 is video games, with $11.6 billion in software revenue, a third of the market size [Bellini et al., 2016]. Many of the early adopters of Tacto will likely be from this massive group of video gamers, and the best channel to market to these buyers will be online. The Entertainment Software Association's 2015 report on the computer and video game industry states that digital sales of video games surpassed physical sales in 2014 and is projected to dominate further in the future [Entertainment Software Association, 2015]. As such, selling Tacto through Samsung's own website and other online retailers is a good starting point before the product gains more widespread use.

Product ● Haptic glove ● Tactic feedback in VR ● MVP by May 2017	**Price** ● <$100 range ● Competitive pricing ● Less than Gear VR headset itself
Promotion ● S.U.C.C.E.S. framework ● Empathize with emotions and stories of consumers	**Place** ● Sell online to early adopters ● Samsung website, other large online retailers

Figure 18 - 4 P's matrix

Competitive Advantage

Looking back at the 2x2s in the "Industry" section, Tacto stands in a white space of technological innovation, giving users a flexible, streamlined, ready-to-use form factor that is not matched by any current competitor. This form factor will be accessible to even the most casual VR user. Facilitating the outreach to these casual users are Tacto's ease of use and low price point. This way, Tacto is poised to become an entry-level haptic feedback device, paralleling the path of Samsung Gear VR for haptics.

Marketing Stance

Tacto allows you to reach out and touch anything in the virtual environment - from interacting with objects to simply feeling their texture. There is no need to learn how to manipulate objects, because Tacto uses the most intuitive controller: your own hand. It's as simple as sliding on the Tacto Glove and powering up your VR headset. This added dimension of touch enhances the immersion of any VR experience.

The product features that we would highlight are:

- Lightweight, easy to use
- Simple, intuitive interface and control

- Incredible vibrotactile feedback allows you to feel a wide variety of textures and surfaces
- Tacto will be priced competitively to allow broader market penetration

In summary, Tacto will cater to a wide audience and will be accessible to casual virtual reality in the future. Flexible electronics will provide a non-intrusive feeling for users that reinforces immersion in virtual reality. Tacto will become a complement to a wide breath of virtual reality headsets and can be distributed through a wide variety of channels, from online to in-store. Initial consumers may be virtual reality enthusiasts, but the average buyer will spread to a much more general populace, allowing more people to experience compelling feeling in virtual environments.

3.2 - Conclusion

This project began with a broad and ambiguous goal of creating a flexible, stretchable electronic device to enhance Augmented and/or virtual reality experiences. Through the human-centered design process and market research, we identified a high potential market sector with unmet needs that is projected to grow rapidly and could provide a new customer base for Samsung. More broadly, we have identified a wide open field where new modes of interaction are yet to be standardized, creating flexibility to experiment in the space and opportunity for Samsung to become an industry leader. With our medium-fidelity prototype, we have used tactile feedback to create a proof-of-concept haptic device that illustrates our goal of enhancing immersion in virtual reality. Preliminary results are promising, and with the improvements outlined in the previous section, Tacto has the potential to provide a more seamless, intuitive control scheme for interaction with VR objects.

3.3 - Future Work

We believe we have created a viable first prototype for Tacto that effectively demonstrates proof of our concept. However, there are notable improvements to be made before Tacto can become a marketable product within our vision.

The first and most important improvements must be made within the actuation scheme. As noted from our user tests, a simple binary on/off vibration is not enough to create convincing immersion or perception. A broad category for improvement is movement actuation. This includes varying the intensity of the actuation as a user approaches an object, which may elicit a better response in our users, as well as the actuation used when the user moves her/his hand across a virtual surface. After movement actuation, configuring the glove such that each individual motor may activate independently of the others would be the next step. In this way, you could eliminate the disparity between visually touching an object with only one finger yet having all fingers actuate. Furthermore, we have only used stock waveforms provided in the library that came with our actuators. Creating our own custom waveforms expands the potential for creating specific effects or haptic icons.

For a marketable product, we imagine that Tacto will have its own integrated motion tracking scheme. While we are currently using a Leap Motion module, which works well, using external products drives up Tacto's price as well as complicating setup. Ideally, Tacto would be a "plug and play" device, which simply is not possible when using Leap Motion.

At the current stage, Tacto is a medium fidelity prototype which needs further refinement. This includes not only the aesthetics and ergonomics of the product, which would be vastly improved by using Stanford's flexible electronics technology, but also improving power consumption and wiring scheme. In the future, all wires, PCBs, and the battery could be custom made in a flexible, stretchable form and directly shaped into a glove, as opposed to our current approach of gluing rigid parts to a glove. Additionally, our prototype only runs when wired - incorporating wireless functionality into Tacto is essential so the VR user is not tethered or tangling in the cord.

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Appendix

27 final concepts during the concept generation phase of the human-centered design process:

Concept	AR/VR	Description	Cluster Experience
VR Stickers	VR	Flexible electronic stickers with bluetooth, accelerometer -- bring objects into VR world	Bringing objects / feedback from real space into VR space
VR Touch	VR	wearable technologies that can provide feedback on touch senses when playing VR games	

Sculptor	VR	Hand wearables that can bring real objects into the virtual world through touch, or create virtual objects	
Kanvas	VR	A sheet with embedded electronics that quickly brings a base shape into VR, then can be drawn upon	
Search & Rescue	AR	SOP for finding people lost at sea is to get in a plane and fly around the ocean for several hours. This wearable will help navigators discriminate and amplify non-blue colors for detection; includes useful features like zooming when the user squints.	
Safety Glasses	AR	HUD safety glasses for construction workers that can show where dangerous areas are, monitor health (especially hydration), and send emergency signals in case of trouble	
Motorcycle AR	AR	Motorcycle helmet that has built-in sensors for cars, and visual display on visor (can show speed, navigation, time, traffic, etc.)	Visual Safety Augmentation
VR Meets AR: Haptic Feels Glove	AR/VR	Current VR interactions have no tangible feel with objects in the world. If we incorporated gloves that measured your hand position in space and gave you haptic feedback when you came in contact with an object	
Surface Material	AR/VR	Wearables that transmit information about the surface of VR objects to the wearer – smooth, soft, jagged, gummy, sticky, wet, etc.	AR / VR Motion control
Sleeping Aid	AR	Custom made ear inserts (organically shaped to each user, must be flexible shape) that has noise cancelling technology. Optional fabric band connecting buds serves as face-mask to block out light. Marketed to be used to help sleep	Auditive augmentation/aid

Sound Buds	AR	Earbuds that can filter sounds based upon source or intensity – for instance, hear your conversation perfectly but tune out background noise	
Seatbelt	AR	Smart seatbelt that vibrates to alert driver if falling asleep, alerts, etc.	
Crime Alert	AR	Wearable that will vibrate/glow brighter around a location where a recent crime was reported	Haptic Safety Augmentation
Karate Companion	AR	Exercise/training platform. Provides visual cues of when, where to kick or punch a target	
Muscle2Build	AR	An exercise clothing set that gives haptic feedback right after an exercise to indicate you what muscles were strained and are being trained	
Music Teacher	AR	Augmented reality for whatever instrument you pick up: look at a piece of music or choose from library, and see on the instrument where to place your fingers. Combine with body motion capture to determine what to improve, which notes you're not hitting.	
motion adjustment	VR	Wearable suit that can detect motion for motion adjustment in physical training	
Sous Chef	AR	An AR environment that provides recipe help as you cook – recognizes what recipe you're making and can overlay how much of each ingredient is needed, when, and when something is done (i.e. soft vs. firm peaks)	
Color Surgery	AR	Colors different organs during surgery via a surgeon face shield. Provides distinction between different body parts like seen in an anatomy textbook	Instructional augmentation
Finger Ruler	AR	Device on index finger and thumb that can measure the thickness of something you're holding between the	Daily activity aid

		two fingers	
Language Translation	AR	Glasses that provide instant real-time translations of signs/text/etc in surroundings	
Route Map	AR	Overlay walking directions in an AR headset (like google glass)	
Smart Headlight	AR	Flexible LED sticker on the bike with accelerometer, turns on as you are moving	
Alphabetic Braille	AR	A finger attachment that senses letters (both from texture and color change), and outputs audio for blind people to understand what is written. This removes the need to learn braille, and allows to use one universal alphabet	Handicap aid
Inner Ear Control	AR/VR	Reduce motion sickness effects by wearing headphone or earplug devices that modulate the air pressure and flow inside the ear	
Motion sickness preventer	AR	Something to prevent AR/VR users from becoming motion sick	
Pressure Point	AR/VR	Wearables that monitor body conditions (heart rate, tension, etc.) to predict motion sickness and apply acupressure at select points to reduce nausea and dizziness	Preventing VR Motion Sickness