DESIGN WITH HANDS

The creation of a haptic feedback device for
VR CAD applications using the Manus VR Gloves

Graduation Report
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TU Delft - MANUS·VR

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Assignment

"To design a multi-purpose physical peripheral for virtual reality to be used in conjunction with the Manus VR gloves. This should provide the user with an increased immersion by providing haptic feedback of what is happening in the virtual world. It should also be useable in a variety of VR experiences, meaning that it can represent multiple virtual objects, taking into account the ergonomic challenge of using this product while wearing a head-mounted display. In this project haptic feedback technologies should be evaluated so a balance between realism and increased immersion it provides versus the cost can be struck, leading to a product that can be mass produced."

ACKNOWLEDGEMENTS

When I started thinking about what I wanted to do for my graduation project, virtual reality soon became the field of my first choice. Even to such an extent that I purchased a VR system myself, partly for entertainment, but also with graduation in the back of my mind. When I stumbled upon Manus VR when following VR news online, and finding out that not only they are a Dutch company, but later also that they previously worked with an IPD graduate, I saw a great opportunity. After emailing Manus VR, Roel van Deventer quickly replied and was able to set up an appointment with me the same week. From the very beginning, Roel was confident in my abilities and motivation to make this a successful project, and I would like to extend my gratitude for doing so and giving me the opportunity to do such an interesting graduation project. As well as for the continued support throughout the project. The same applies to my coaches Jouke Verlinden and David Abbink, who were enthusiastic about the project from the start and throughout, and whose individual fields of expertise were a great addition to the project.

On a more personal level I would like to thank my family, especially my parents, grandfather and brother for their continued support not only during this project but throughout my entire time at IDE. And a special thanks to Iris for motivating me through tougher times in the project, which definitely helped me reach the end the way I did.

People who I also want to thank for supporting me in the project are all the people at Manus VR. All of whom were always very willing to help. A special thanks to Arsène, Tim and Ricardo, for supporting the development of my prototype and to create the visual for the poster and cover of this report. And finally I would like to thank the PMB department at IDE for providing the free to use Ultimakers, without which I would not have been able to develop my design and prototype the way I did.

SUMMARY

This report follows the development of a haptic feedback device for use in virtual reality computer aided design application, using the Manus VR data gloves. To arrive at this product, first the VR market was analysed. By looking at the history of VR and current VR technologies, the project is placed in context. Looking at tracking technologies and control methods the conclusion was drawn that the HTC Vive will be used as the platform to develop for in this project. Haptics play a key role in the project, and a study into VR and hand-specific haptics shows that there were a number of options for the project. The choice was made to focus on tactile and proprioceptive feedback to simulate the interaction between the user's hand and objects. This is followed by the formulation of search areas in which the project could continue. Using a number of selection criteria, the selection was limited to the following areas: Entertainment in VR Arcades, VR exposure therapy and VR CAD & Sculpting. VR CAD was chosen as it offers the most opportunities to create a haptic feedback device that is innovative and utilises the strengths of the Manus glove.

The project continues with a conceptualisation phase. By further analysing the field of VR CAD using hand controls, a number of key functions are established which will play a central role in further development. These are the utilisation of a 3D point grid, the scaling and moving of 3D objects, and the adjustment of 3D objects. The three functions were in turn translated to interactions using the users hands, with relevant haptic feedback. This resulted in tactile feedback on the index finger using a vibrating motor for the point grid interaction, tactile feedback using a vibrating motor on the back of the hands for scaling and moving, and tactile and proprioceptive feedback by stopping the user's finger for the adjustment of shapes.

With a rough idea of the functions the haptic device should perform, a list of requirements could be created to guide the conceptualisation process. First ideas were immediately built into simple prototypes, which gave a good insight in the feasibility of these ideas. An additional design step for these ideas showed the pro's and con's for each concept, leading to the decision to continue with the concept that was both the most effective and least complex. This concept will provide tactile feedback between the index finger and thumb by placing both fingers in holders that are connected by a rod. While pinching these fingers, a solenoid can lock the rod giving the impression of pinching a physical object. Additional prototyping lead to an evolution of the design, which through roughly five generation provided a prototype useable for user testing. A final design was also proposed which more closely matches the envisioned end product that could be put on the market. In the embodiment phase of this report, the components needed for the design are shown, as well as a more detail description of the interaction based on the three main functions.

The project is concluded with a validation of the design. Prototypes were built in both hardware and software to evaluate the design and perform a user test. This resulted in a number of recommendations for the design, of which the most important one is that the product should be as ergonomic and comfortable as possible so the user is almost unable to notice they are wearing the device. This improves the immersion when using the product and legitimises the existence of the product the most.

SAMENVATTING

Dit verslag beschrijft de ontwikkeling van een haptische feedback apparaat voor gebruik in virtual reality computer aided design, gebruik makend van de Manus VR handschoenen. Om tot een product te komen werd eerst de VR markt geanalyseerd. Door te kijken naar de geschiedenis van VR en de huidige VR technologieën wordt het project in zijn context geplaats. Haptiek speelt een belangrijke rol in dit project, dus is er onderzoek gedaan naar VR en hand-specifieke haptiek wat leidde tot een aantal opties om het project mee te vervolgen. De keuze werd gemaakt om de focus te leggen op tactiele en proprioceptische feedback om de interactie tussen de hand van de gebruiker en virtuele objecten te simuleren. Dit wordt vervolgd door het opstellen van zoekvelden waarbinnen het project vervolgd zou kunnen worden. Door gebruik te maken van selectiecriteria werd de selectie beperkt: Vermaak in VR Arcadehallen, VR blootstellingstherapie en VR CAD & beeldhouwen. VR CAD is gekozen omdat het de meeste kansen bood om een haptische feedback apparaat voor te ontwikkelen dat zowel innovatief was als goed bij de Manus handschoenen past.

Het project wordt vervolgd met een concept-ontwikkelingsfase. Door eerst het gebied van VR CAD met handbesturing te analyseren, werden een aantal hoofdfuncties vastgesteld die centraal staan bij de verdere ontwikkeling. Dit zijn het gebruik maken van een 3D puntenraster, het schalen en verplaatsen van 3D objecten, en het aanpassen va 3D objecten. Deze drie hoofdfuncties vertaald naar interacties met gebruik van de handen van de gebruiker, met daaraan toegevoegd de relevante haptische feedback. Dit resulteerde in het toevoegen van tactiele feedback voor de wijsvinger door gebruik te maken van een trilmotor voor de interactie met het puntenraster; tactiele feedback door gebruik te maken van trilmotoren op de achterkant van de hand voor het schalen en verplaatsen; en tactiele en proprioceptische feedback door middel van het tegenhouden van de vingers van de gebruiker bij het aanpassen van objecten.

Nu de functies van het ontwerp grofweg bekend waren, kon er een programma van eisen worden opgesteld om de conceptgeneratie te sturen. Eerste ideeën werden direct uitgewerkt tot simpele prototypes, wat een goed inzicht gaf in de haalbaarheid ervan. Verdere ontwerpstappen lieten de voor- en nadelen van de concepten, wat leidde tot een conceptkeuze op basis van de oplossing die het meest doeltreffend en minst complex was. Het concept geeft tactiele feedback tussen de wijsvinger en duim door deze beide in houders te stoppen die verbonden zijn met een stang. Als deze vingers een knijpbeweging maken, kan een zogeheten solenoid (magneetventiel) de beweging van de stang blokkeren, wat de indruk aan de gebruiker geeft dat deze een fysiek voorwerp beet heeft. Door iteratief prototypes te maken evolueerde het ontwerp, wat na ongeveer vijf generaties leidde tot een prototype dat geschikt was voor een gebruikerstest. Een eindontwerp werd ook voorgesteld dat een beter beeld geeft van hoe het ontwerp er uit kan komen te zien mocht het op de markt komen. In het hoofdstuk materialiseren (embodiment) worden de componenten die nodig zijn voor het ontwerp getoond, alsmede een gedetailleerdere beschrijving van de interactie gebaseerd op de drie hoofdfuncties.

Het project wordt afgesloten met het valideren van het ontwerp. Er zijn prototypes gemaakt zowel in hard- als software om het ontwerp te evalueren en om gebruikerstests te kunnen doen. Dit resulteerde in een aantal aanbevelingen voor het ontwerp. De belangrijkste hiervan is dat het product zo ergonomisch en comfortabel mogelijk moet zijn, zodat de gebruiker bijna niet door heeft het product te gebruiken. Dit bevordert de immersie van het gebruik van het product en geeft het bestaansrecht.

CONTENT

PART 1: ANALYSIS

Introduction

To obtain a better understanding of the field Manus VR is operating in, and to find opportunities for this project, the phenomenon of virtual reality will be analysed in this chapter. By looking at the past and present of VR some perspective can be added to this project. By looking at the state of the art of VR, including different control methods, tracking technologies and the Manus gloves and their competitors, it will become more clear what this project can still add to the VR market. Following the assignment of this project, haptics will play a vital role. Therefore a specific look into haptics for VR will be taken. When this knowledge is available, and possible applications are found, a choice can be made on what search area to continue the project with.

1.1 THE HISTORY OF VR

The first experiments with what we would now call virtual reality devices were done by Morton Heilig in the 1960's, which resulted in his Sensorama (medienkunstnetz, 2016), a device that let users experience a pre-recorded movie in stereoscopic 3D, along with stereo sound, motion and even wind and aromas (Figure 2). The first iterations of head-mounted displays (HMDs) were done by Ivan Sutherland (1968), with what was to be called the Sword of Damocles (Figure 1), as it required a large mechanical arm that suspended the device over the user's head. These devices however never had any large success with the general public. From around 1985 through the 1990's saw a period of renewed interest in VR. This was partly due to science-fiction novels and movies, such as Lawnmower Man (1992) and The Matrix (1999), but also technological progress that made new products possible. It were predominantly game companies that sought to bring VR to the consumer market, but also to arcade halls (cultronix, 2016). The product closest to current HMDs was the VFX1 for the PC (Figure 3), with which games could be played in stereoscopic 3D and featured head tracking on three axes (mindflux, 2016). After this period in the 1990's, there was little development in the VR market until the announcement of the Oculus Rift Kickstarter in 2010. This sparked the public interest in VR once more and six years later there are now fully features VR systems for people to buy.

Figure 2: The Sensorama


Figure 3: The VFX1

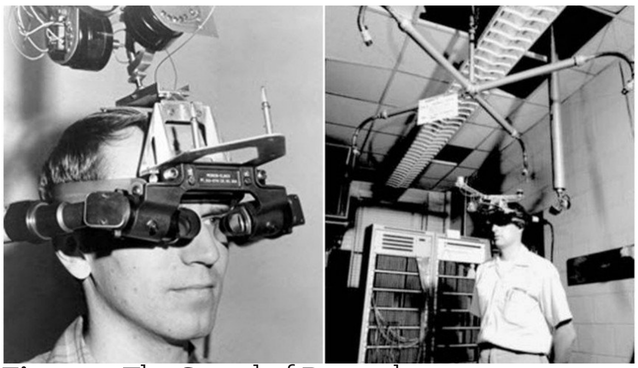


Figure 1: The Sword of Damocles

1.2 CURRENT VR

The products Manus VR and by extension this gradation project focusses on are the modern VR headsets such as the HTC Vive, Oculus Rift and Samsung GearVR. However there are multiple VR sets available or coming in the near future, and Manus VR has stated that they have no platform loyalty. For practical reasons, the current iteration of the Manus VR works on the HTC Vive since its Lighthouse system has the most accessible prototyping possibilities and there is a close relationship between Manus and HTC (R. Van Deventer, personal communication, January 17, 2017). Therefore this project will also utilise the Vive system. More on the Lighthouse tracking system will be explained in later chapters. This chapter serves to give a short overview of the currently available VR headsets. The focus of the project will be on haptics and user interaction, but a good understanding of the complete system can be beneficial as well.

Current VR systems can be divided in a number of segments, an overview of which is given in Figure 4. These are partly based on price, and partly on the level of technology implemented. First is the Google Cardboard or similar devices. These are very cheap smartphone holders that are best used to give users a glimpse into the possibilities of VR. Second are the Samsung GearVR or similar devices. These still use the user's smartphone as a screen and for its sensors, but these devices have a better build quality, control options, adjustable lenses and head-straps, which improves the experience. Finally there are the fully featured high-end VR systems such as the HTC Vive, Oculus Rift and more recently also the PlayStation VR (PSVR) from Sony. These system have their own high-quality displays and optics, and use (different) tracking technologies to spatially track the user in a 3D space. These devices all feature roughly the same components, an overview of which is given in Figure 5. While this project will not redesign the HMD, it is useful to know the inner workings of the HMD in order to better understand the VR system as a whole.

In conclusion, the higher end VR system are currently more interesting and feasible to develop for from both Manus' perspective as for this project. The Vive system will be used for the development as prototyping for the lighthouse system is currently the best option. For the purposes of this project, the HMD itself can be used as-is, while the tracking system could possibly be incorporated into the design.

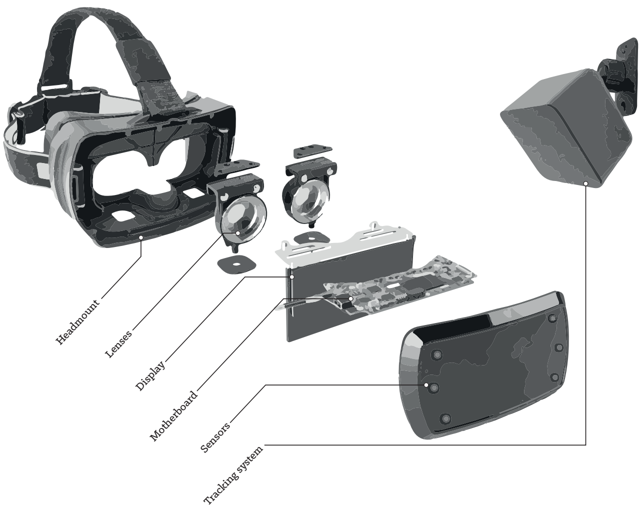


Figure 5: HMD components overview

Figure 4: Current VR systems

1.3 CURRENT VR CONTROLLERS

In the past the most straightforward way to control VR applications was through the use of traditional input devices such as existing gamepads or keyboard and mouse. Even with the possibilities tracked controllers offer today, some VR applications today are still designed to be used with gamepads. Tracked controllers, the second category, were used in the experimental phase of VR, such as the Nintendo Wii Remote or the Razer Hydra controllers.

The modern tracked controllers offer much better accuracy and were designed from the start to be used in VR. The most advanced offerings come from HTC/Valve and Oculus, in the shape of the Vive controller and the Touch controllers. Apart from a different ergonomic design and tracking solution (more on this in chapter 1.4), the controllers have similar capabilities in that they allow the user to interact with the virtual world with great accuracy. Improvements in the tracked controller category are for example the Manus VR glove itself, as it expands tracking to the hand and fingers. Valve is also working on improving the controllers for the Vive with their prototype (roadtoVR, 2016), that does not require the user to hold the controller at all times and can track finger movement as well.

The final category of controllers that are used for VR are the haptic controllers. Past solution such as racing wheels or joysticks and flight controllers lend themselves very well to VR in the corresponding applications. For example the force feedback on a steering wheel can make a VR racing game feel much more immersive. Several companies are experimenting with haptic feedback in controllers in different ways. For example Tactical Haptics (2016) and Microsoft TextureTouch (uploadVR, 2016) focus on simulating the sense of touch, called tactile feedback, while Dexmo (dextarobotics, 2016) and Wolverine (Stanford, 2016) simulated the resistance from grabbing virtual object with your hands, called kinaesthetic or proprioceptive feedback (more on this in chapter 1.6).

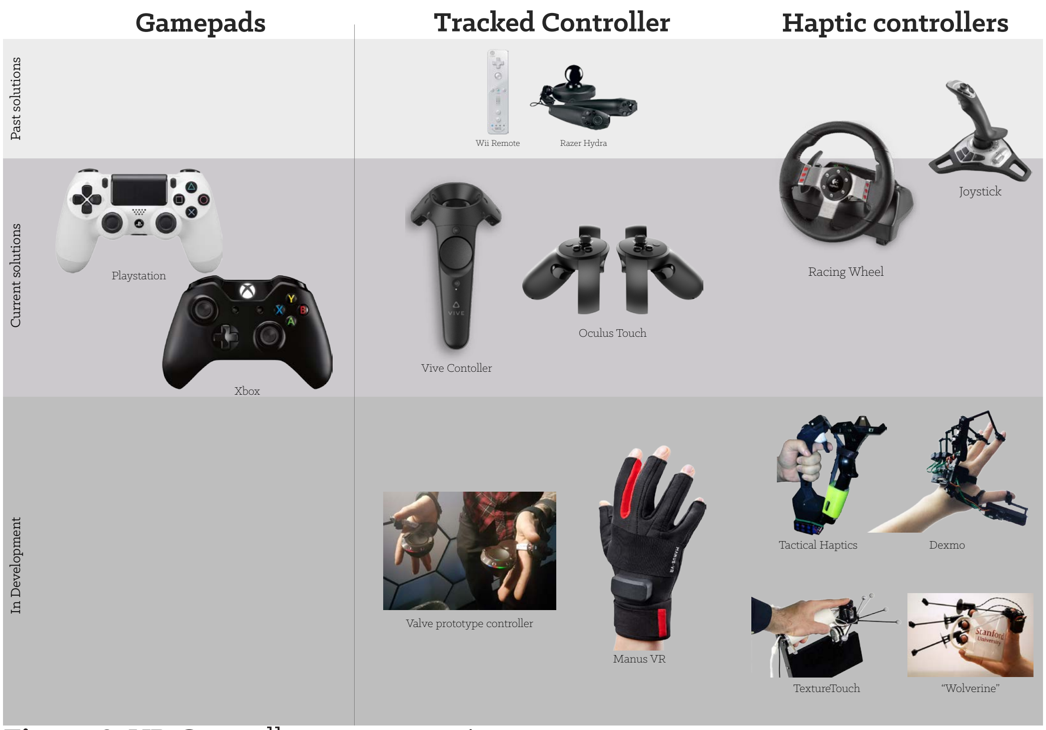


Figure 6: VR Controller types overview

1.4 TRACKING TECHNOLOGIES

This chapter will look into the tracking technologies used by the major VR systems. In particular the HTC/Valve Lighthouse technology will be examined, as this is the most feasible technology to design for in this project. Manus VR has decided that for the time being further development will be done in the Lighthouse ecosystem, meaning that it makes the most sense for this project to go along with this decision. Manus VR has made this decision for the reason that prototyping hardware for the Lighthouse system is now available in the form of sensors and microcontrollers (Lang, 2016). This combined with the open design of the system makes prototyping relatively straightforward. This is in contrast to other major VR systems such as the Oculus Constellation tracking system, where there is much less possibility for prototyping, as Oculus' own tracked controllers are not yet available at the time of writing.

The Lighthouse technology itself works through infrared laser light and a number of sensors on the HMD and controllers. Two emitters, known as Base Stations, are placed in opposite corners of the VR play space. They sweep the room with light in both x and y directions, while they also emit a flash between each sweep for timing corrections. The sweeps of light hit the photodiode sensors on the devices and different intervals. Since the exact timings are known, this way the location and orientation of the devices can be calculated through triangulation (pcper, 2016). This data is combined with data from the IMU (inertial measurement unit, featuring e.g. gyroscopes and accelerometers) in the devices, which leads to very accurate positional tracking up to 0.3 mm (doc-ok, 2016).

To implement tracking in eventual prototypes, separate sensors and controllers can be obtained from Valve's partner Triad Semiconductor (steamcommunity, 2016). For this project, the acquisition of parts and assistance in development will be done through Manus VR. They will have the necessary licenses, parts and in-house expertise to work on such a prototype and implement this tracking technology, since they also need to do this for their main product.

Since it is certain the HTC/Valve Vive system will be used in this project, the other way of tracking as used by the Oculus Rift will only be discussed briefly. The Rift's tracking is in a way opposite to what the lighthouse system does, as here the HMD and controllers emit infrared light themselves. This is captured by one or more camera, after which the position and orientation of the devices can be calculated (Nield, 2016).

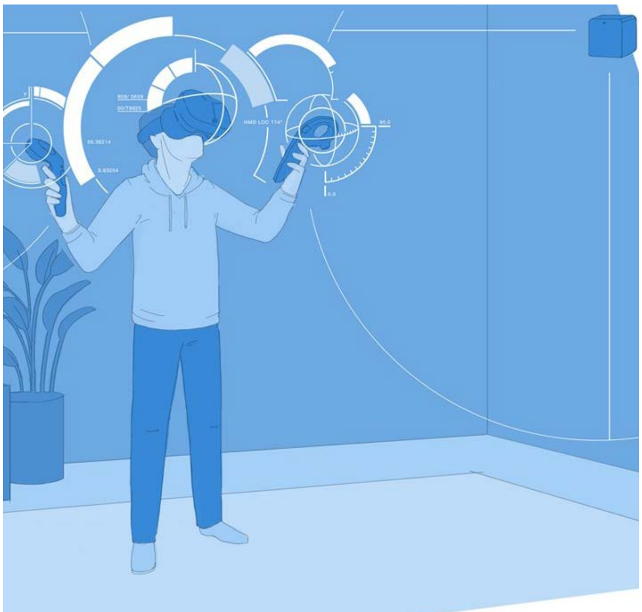


Figure 7: Lighthouse tracking

1.5 THE MANUS VR GLOVE

The Manus VR gloves have gone through a lot of development since the company started in 2014. Especially in 2016 this progress became apparent as Manus was able to showcase their prototype at game conventions complete with an in-house made demo game. With the opening up of the Lighthouse platform by Valve (see chapter 1.4), Manus VR is now able to integrate arm/hand tracking in a product of their own, instead of relying on the Vive controllers as a temporary solution.

The current design of the glove features a number of sensors to track the various movements of the users fingers, hand and arm. Each finger of the glove features flex sensors to measure the curvature of each individual finger, the back of the glove features an IMU to measure movement of the hand around the wrist, and a lighthouse enabled tracking bracelet measures movement of the whole hand and arm in 3D-space. For the purposes of this project the glove itself will be taken as-is.

This Manus VR glove already sees use in a number of (experimental) applications. For example NASA is doing tests in using the glove for astronaut training purposes using a mixed reality setup (uploadvr, 2016). Mixed reality means part of the virtual world is also build in the real world, in this example a guide rail on the ISS in VR can be physically grabbed in real life. Another application is that of the training of professional engineers, such as IDE graduate M. Sandoval developed for in his project for Manus VR (Sandoval, 2016). Finally there is also the application in the gaming market. Manus VR first focussed in this market, since it speaks to most the consumers, but since the glove is not yet widely available game developers are also not making games for the glove yet. In the meantime Manus has decided to focus more on the business-2-business market.

1.5.1 Competitors

There are a number of competitors and alternatives to the Manus VR glove (Figure 8). The Dexmo from Dexta Robotics is a VR glove that can simulated resistance on each individual finger to give the sense the user is grabbing something (James, 2016). This is a feature the Manus VR glove lacks as the users simply 'grabs air' without much feedback. The Gloveone (kickstarter, 2016) is quite similar to the Manus VR glove with the main difference being that it features haptic actuators in each individual fingertip. However from the Kickstarter page it appear development is behind on what Manus VR has achieved. The Powerclaw (Hayden, 2016) is a VR glove that focusses on giving the users the sensation of heat, coldness and electric shocks. No tracking is implemented however. In addition to these products the more experimental devices mentioned in chapter 1.3, such as the Wolverine prototype, are in the same field as Manus VR.

Figure 8: Competitors and alternatives

1.6 HAPTICS

Haptics or haptic feedback is the recreation of the sense of touch (Mihelj et al., 2016). For virtual reality applications this means that haptics can provide the user with feedback when they, for example, touch or grab a virtual object. Different types and gradations of haptics can be used, from simple tactile feedback by using a vibration motor, to elaborate exoskeletons that exert realistic forces on the body.

A common and straightforward area to focus haptic feedback on is the user's hand. But also for the human hand multiple kinds of haptic feedback can be implemented. Currently the Manus VR glove uses a vibration motor to provide tactile feedback when grabbing an object for example. A different solution can be seen at competitors such as the Dexmo, where the movements of the users fingers are limited by an exoskeleton glove and actuators. This is a different kind of haptics since instead of purely tactile feedback it acts on the proprioceptive sense as well, since the position where the fingers are stopped corresponds to what the user would expect to happen in the real world.

The goal for this project was to develop a haptic feedback device that uses components creatively to improve immersion in VR. Given this, expectations about the result of the project should be kept realistic, as some types of haptic feedback will not be possible to achieve. For example stopping a user's arm in 3D space when they collide with a virtual object would require some type of robotic exoskeleton that is fixed to the outside world. These types of solutions are not within the scope of this projects. Instead, a more realistic outlook would be some small device that fits in or around the user's hand and provides haptic feedback from there.

1.6.1 Immersion and presence in VR

Immersion, for VR, refers to the amount of sensations of the VE (virtual environment) are simulated and the realism or fidelity thereof (Mestre et al., 2016). This means immersion can be measured quantitively. For example, a new HMD with a higher resolution display and field-of-view will be more immersive than the old version, and a VR experience with accurate hand and finger tracking is more immersive than a system using a gamepad. Presence is a subjective measure of to what degree a person feels like they are in a virtual world. Therefore it cannot be measured in amount of pixels or accuracy of tracking, but instead interviews and questionnaires with participants can give an indication of the amount of presence an experience provides.

To improve immersion and presence in VR the virtual world should act on the different senses of the user in a believable way. This does not always mean that it has to be as realistic as possible, as people can also be immersed in a stylised or abstract representation of the world. It means that the world has to be portrayed, towards the senses, in such a way that the user's brain accepts it as a new reality. This can be done in number of ways, using different devices to feed the different senses. For example an HMD can feed the visual sense, while haptic feedback in the controllers give the sense of touch. The sense of proprioception can also be matched with the real world using inverse kinematics. Provided the user's body is tracked sufficiently, the software can work out the position of the user's limbs and portray this in the virtual world on the user's avatar.

1.6.2 Haptics in VR

To see how the different senses of the human body are currently being used with virtual reality devices, an overview was made in Figure 9. This figure shows a schematic overview of a person using the different devices that are used in VR applications. First of all the head-mounted display provides visual information. Sensors in the HMD make sure your position, rotations and tilt of your head match in the virtual world, meaning there is a match with the user's vestibular system. Using some form of tracked controllers in the users hand, in this case the Manus VR gloves, the sensors and inverse kinematics can be used to determine the position of the fingers, hand and arms (R. Van Deventer, personal communication, January 17, 2017). This can be translated to the virtual world, meaning the user sees (most) limbs match with their position in the real world. This means the virtual body allows for correct proprioception, increasing immersion.

In terms of feedback from the virtual world to the user, current systems allow for visual feedback through the HMD. This means the user can see the effects of their actions for example, and since vision is the most dominant sense it is important to provide the most believable feedback possible. Headphones can provide 3D-audio feedback, which helps the user in positioning sound sources. When this is done realistically it also improves immersion. The final commonly used form of feedback is tactile haptic feedback through a controller. This allows for feedback during different kinds of interactions, for example grabbing or hitting something in the virtual world. Current commercial VR systems use piezo electric linear actuators to provide tactile haptic feedback that is more granular and versatile than simple vibrating motors would provide. The Manus VR gloves use vibration motors on the back of the hand for feedback, as implementing more advanced feedback has a number of difficulties and is not the company's priority (R. Van Deventer, personal communication, January 17, 2017). The vibrating motors and linear actuators do add to the experience with the feedback they give, however they are limited in the realism and fidelity of feedback they can provide. Improvements could be made to this feedback in a similar vein to the experimental controllers shown in chapter 1.3.

Since the user's hand is key in most kinds of human-computer interaction, and the project involves a VR glove, the logical conclusion for his project is to improve VR haptic feedback at the hand. The next section features a closer look at the possible haptic feedback implementation for the hand.

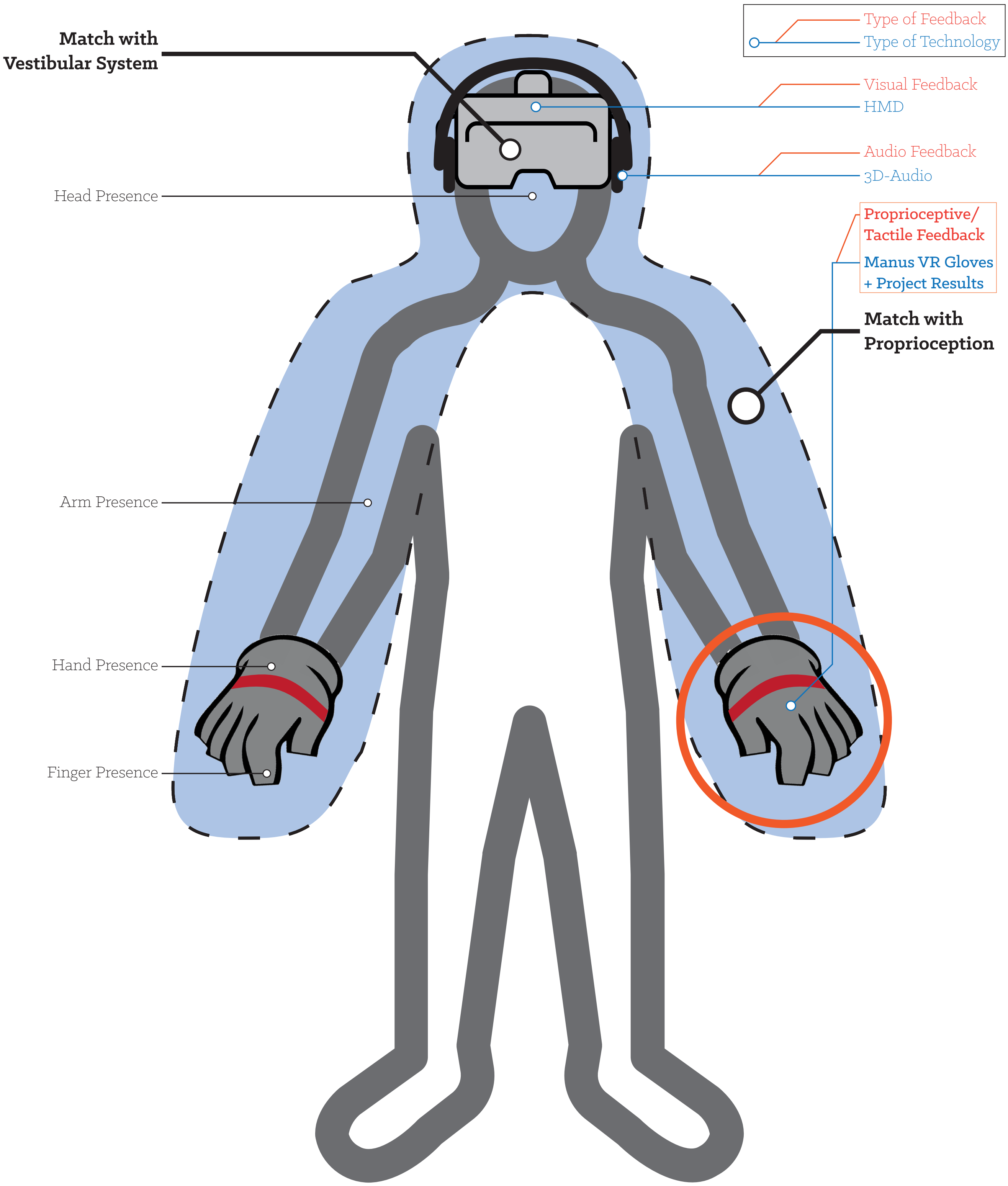


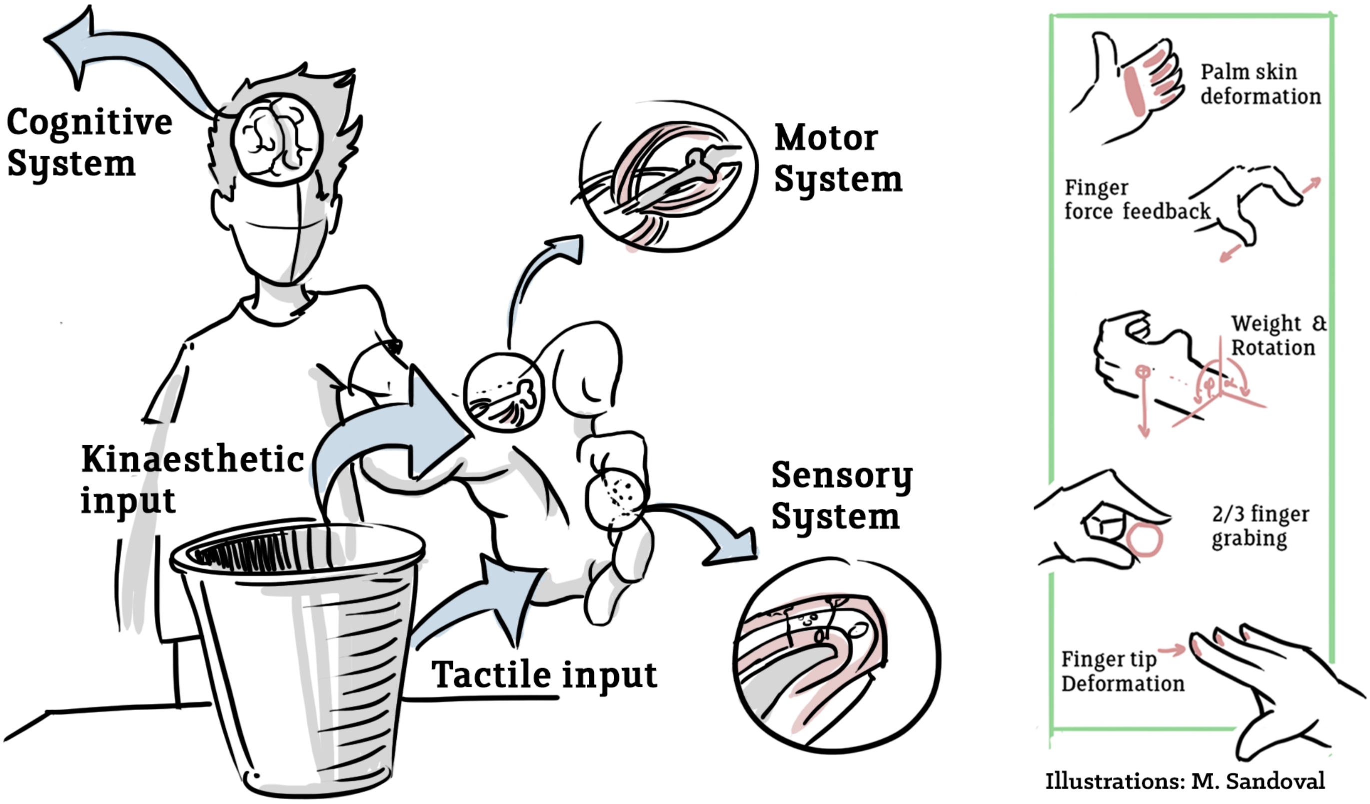
Figure 9: Haptic Feedback overview

1.6.3 Haptic Feedback for the Hand

Haptic feedback for the hand, similar to feedback for the rest of the body, can be divided in the two categories tactile and proprioceptive/kinaesthetic feedback. An overview of these systems was schematic illustrated by M. Sandoval (Figure 10). The different types of tactile feedback the human hand can sense are illustrated in Figure 11, all of which could be interesting for use in VR applications.

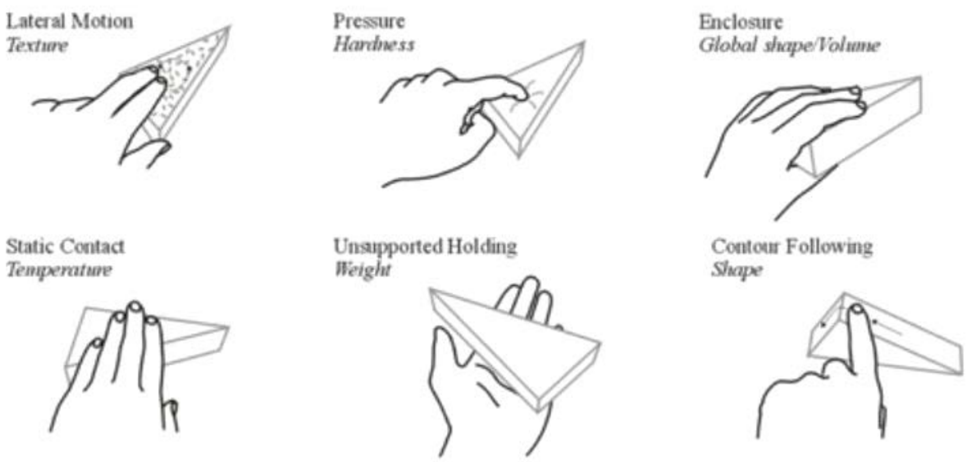
Proprioceptive feedback of the user's hand also has a number of aspects. The visual confirmation of the position of hand and fingers will be fulfilled by a combination of the tracking done by the Manus VR glove, the software that performs the IK (inverse kinematics) and renders the virtual world and the HMD that displays this. For the purposes of this project it is a given that is done accurately. Additional feedback can be given by stopping or resisting finger and/or hand movement. For example, when grabbing an object in VR, the user's fingers can be stopped at the correct position, meaning what the user sees in the virtual world matches with what happens in the real world. This could greatly improve immersion. An additional step would be to forcibly move the user's fingers or hand if the situation if the virtual world asks for it.

However, the type of feedback required for this project will depend on the type of application and the concept that is created for this specific application. Depending on the concept, it will also require different types of components to simulate their effect. No further selection of types of feedback will be done here, but instead the selection of search areas and idea generation will narrow the scope of the project. This in turn will lead to one or several of the types of haptic feedback to be used in the project.



Illustrations: M. Sandoval

Figure 10: Types of feedback overview



Adapted from R.L. Klatzky, et al., "Procedures for haptic object exploration vs. manipulation," Vision and action: The control of grasping, ed. M.Goodale, New Jersey: Ablex, 1990, pp. 110-127.

Figure 11: Tactile feedback on the human hand

1.7 SEARCH AREAS

This chapter tries to give a complete overview of the different areas VR can be used for, which will be called search areas. This is followed by a comparison of these search areas on a number of criteria to come to a selection that has the most potential for this project. The search for applications of VR has been going on for a considerable amount of time as can be seen in Virtual Reality Technology (Burdea, 1994). The number of applications found back then have remained largely unchanged, while advancements in technology have made many of them a reality.

Professional and Training

VR can be used for training in a virtual environment (Seymour et al., 2002 & army.mil, 2016) . This allow for hands-on training of otherwise risky, dangerous, expensive or impractical activities such as soldier combat training, surgical training or pilot training.

For businesses VR can have a number of use cases, both internally and towards customers (VRS, 2015). Virtual shopping allows consumers to view and experience products more hands-on than traditional online shopping. This could be used for small products, but also for touring a house that is for sale or to pick a holiday destination for example. Internally, businesses can use VR to remotely visit trade shows, conferences, take job interviews or train employees. To help understand the vast amount of data some business collect, VR could be used to view this data more intuitively.

This data visualisation could also be used for scientific purposes (Figure 12), for example to view the results of experiments, or to explore places or object from the very large scale, such as the stars and galaxies, to the very small, such as cells or atoms. In medical science this could also be applied on the human body, for example to view the results of a MRI-scan. VR could also be used for more intuitive teleoperation, of for example robotic arms in a nuclear plant or to control a Mars rover from earth.

To give judges or juries a better overview of what happened at a crime scene, VR can be used to reconstruct this scene, making it easier to understand (BBC, 2017). This can lead to fairer and more accessible court cases. This reconstruction can also allow law enforcement to preserve a crime scene in an untouched state, meaning everyday life can continue at the scene of the crime will investigators have time to do their work in VR (Poelman et al., 2012).

Figure 12: Scientific Data Visualisation

Mental Healthcare

Research has shown that VR experiences can help people with certain mental disorders, such as autism (Senson, 2016), and phobias (Hoffman, 2004), such as arachnophobia treatment. VR can also help with PTSD (Rizzo, 2015). In general, exposure therapy using VR can be much more effective than traditional exposure therapy using flat images. It can also be beneficial for people with these disorders to try a VR treatment as an alternative to medication.

VR can also be used to rehabilitate inmates and make their return to society easier and reduce the risk of repeat offenses (VirtualRehab, 2017). This can be done going through certain scenario's or training, depending on the inmates offense, and by generally educating them.

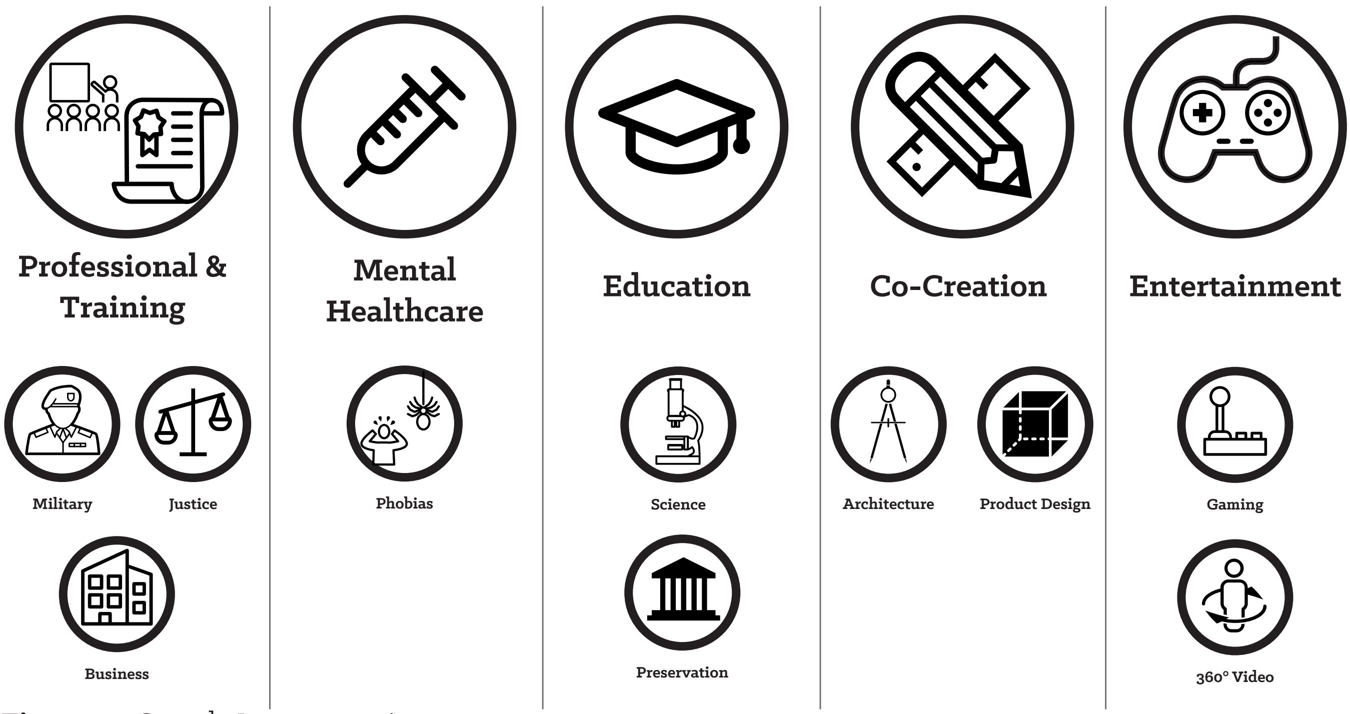


Figure 13: Search Areas overview

Education

It also enables education through experience, such as students learning more about the International Space Station by being able to virtually explore it, which otherwise would be impossible. Another possibility for education is distance learning, as students could virtually take part in classes from anywhere in the world, with more engagement than traditional distance learning through video lectures for example. Finally VR enables the preservation of objects, places and people (such as the 3D scan of Obama (DPO, 2014) , Figure 14) by being able to view them as they originally were, on a 1:1 scale.

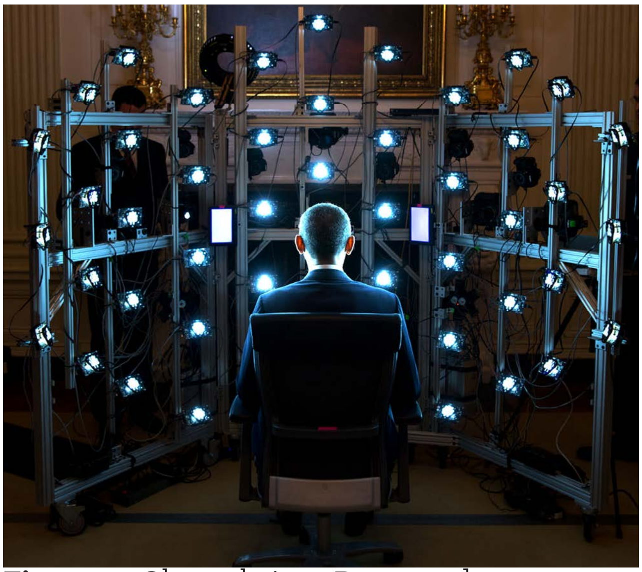


Figure 14: Obama being 3D scanned

Co-creation

VR can enable designers, engineers, architects and artists to work on their projects in a new way. Designers and engineers can prototype in VR and see their work on a 1:1 scale (uploadVR, 2016), architects can get a better sense of the spaces they work on (IrisVR, 2016) and artist can sculpt 3D-models and work on their art pieces in a new way (such as in Google Tilt Brush, Figure 15). Engineers can also simulate how a building will be constructed, which can help with the organisational aspect by spotting problems early on.

Figure 15: Google Tilt Brush

Entertainment

VR is also used for multiple forms of entertainment products. Gaming has often been a driving force behind VR development, and also the current high-end HMD are (on the consumer side) mainly marketed as gaming devices (such as for the game Audioshield, Figure 16). Arcade halls and amusement parks are also adopting VR to offer their guests unique experiences. VR also allows for the viewing of 360 degrees video, with or without a stereoscopic 3D effect. This allows for the viewing of films, sporting event, concerts and so on.

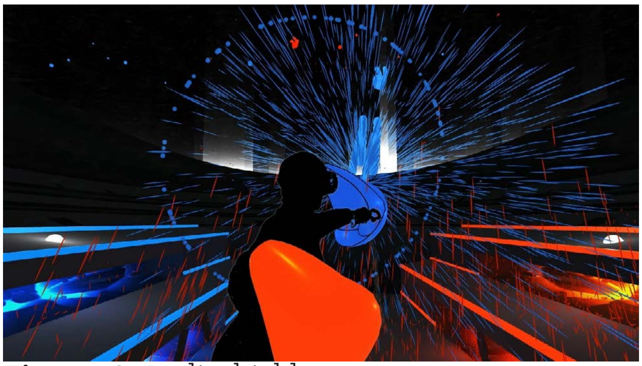


Figure 16: Audioshield

1.7.1 Selection Criteria

To narrow down the number of search areas to the ones most suitable for this project, a number of criteria are defined. These are discussed below.

A - Match with Manus VR

Since this project is done for and in collaboration with Manus VR, the company should have a say in the selection of the search areas. This is done by discussing the search areas with them directly. Personal communication with R. van Deventer (January 19, 2017) shows these are the main points of interest for Manus VR:

- The project could result in a product that is actually useful to a company (a client of Manus).
- Contact with this company can be done through Manus' existing network, or new contacts can be made.
- The project results in a prototype with a demo that can serve as a showcase for their company and their glove product.
- The project results in a product and prototype that is nearly finished and has a practical application.
- The project is of interest to the student, as intrinsic motivation will lead to the best end results.

B - Match with the Manus VR Glove

The project is done to develop a product for the Manus VR glove. Therefore the search area should have opportunities for a variety of interactions in VR with the user's hands.

C - Match with the assignment

The selected search areas should fit the assignment of the project. The search areas will be evaluated on their potential for a product to be developed in that area that fits the aspects covered in the assignment.

D - Potential of market

The market behind the different search areas will be evaluated on their size, growth and their likelihood to invest in VR applications.

E - Accessibility of the market for this project

Some market will be easier to develop a product for than other, within the scope of this project. This could have financial reasons, or it could simply be difficult to get in contact with and collaborate with businesses in certain markets.

F - Match with the student

This being a graduation assignment, the search area should be of interest to the student as well.

1.7.3 Selected Areas

After the selection criteria were applied, the following search areas proved to have the most potential for this project. Information on these areas will be expanded upon with newfound knowledge, and considerations will be shown. To what extent the search areas match with the selection criteria is explained below, with the corresponding criteria noted in brackets, for example (A). The company's feedback is taken into account, the full version of which can be found in Appendix A.

Entertainment - VR Arcades

With the appeal of VR on the one hand but the high barrier to entry for consumers on the other hand, it makes senses for arcade halls, amusement parks, internet cafes and shows or conventions to provide VR experiences to their visitors. These experiences could focus on a short, single-time experience per user, and could therefore also incorporate more elaborate setups and accessories compared to a home VR system (Figure 17). Since the investment in the system will be earned back over time, more funds will be available for investing in the system compared to consumer VR as well.

While Manus is not focussing on consumer VR entertainment at the moment, arcades differ in that Manus could sell their product business to business even though the end user is still the consumer (A). Applying this search area to the Manus VR glove, specific experiences could be built around the glove in combination with a product developed in this project (B). It matches with the assignment in terms of haptic feedback possibilities and increasing immersion (C). According to Manus, a large number of companies are currently working on these kinds of VR Arcade experiences, meaning there is a large market potential (D). These companies will most likely also be open to collaboration, as they will look for experiences to differentiate themselves from the competition in this new market segment (E). It also matches well with the student, as videogames are a hobby of the student (F).

Figure 17: VR Skydiving

Figure 18: VR Arachnophobia Treatment

Figure 19: Artist using Oculus Medium

VR Exposure Therapy for mental disorders with a physical aspect

VRET is gaining popularity in mental healthcare. However many of the treatments are mainly or purely visual: the patient wears an HMD and is exposed to, for example, their phobia. Examples would be to place a patient on a virtual town square if they have agoraphobia, or the place them in front of a virtual audience if they have a fear of public speaking. To make this search area applicable to the assignment, the disorder will need to have a 'hands-on' aspect. Treatments that can benefit greatly from hand presence and realistic feedback would be, for example, arachnophobia (Figure 18) or fear of other animals and germaphobia. By exposing patients incrementally to their fear they can be helped.

Manus has stated that mental healthcare could be more feasible to develop for than regular healthcare, as the barrier to entry and regulations are less strict (E), and they see a number of possibilities in this field (A). The glove can provide this hand presence, which could greatly add to the effectiveness of the exposure treatment (B), and could be strengthened by haptic feedback (C). If the product proves helpful, it has the potential to be used around the world, meaning the potential market is large (D). This direction is also interesting to the student, as using the latest technology to help people is a noble cause (F).

VR CAD & Sculpting

VR can provide a new and intuitive way for designers to interact with computer aided design and sculpting software, as the user can see their model in true 3D, have a better sense of scale and view the model for all angles. With tracked controllers, users can also work on their models more intuitively. A number of software products are already on the market, such as Oculus Medium (Figure 19). These products or often meant as free-form sculpting tools. More parametrically based CAD software packages, such as SolidWorks, have not yet found a way to VR. There are however a number of VR 3D-model viewers available, such as IrisVR.

The company finds this subject very interesting and promising, but is cautious about this project becoming software focussed (A). The Manus glove could be used for more natural interaction and editing of 3D-models than with traditional VR controllers (B). For example, the user could use their fingers to work on clay on a pottery wheel, or use pinching gestures to expand a shape. This project could then focus on feedback for the user, for example on material properties, delivering certain feedback when using tools or for collision feedback, so the user can feel feedback when they touch their 3D-model (C). The CAD software industry is very large and is most likely interested or already working on VR application (D). Accessibility to the main players in this market might be difficult, but smaller companies are also working in this field (E). This subject is also very interesting to the student, having used CAD software for a number of years (F).

1.7.4 Search Area Choice

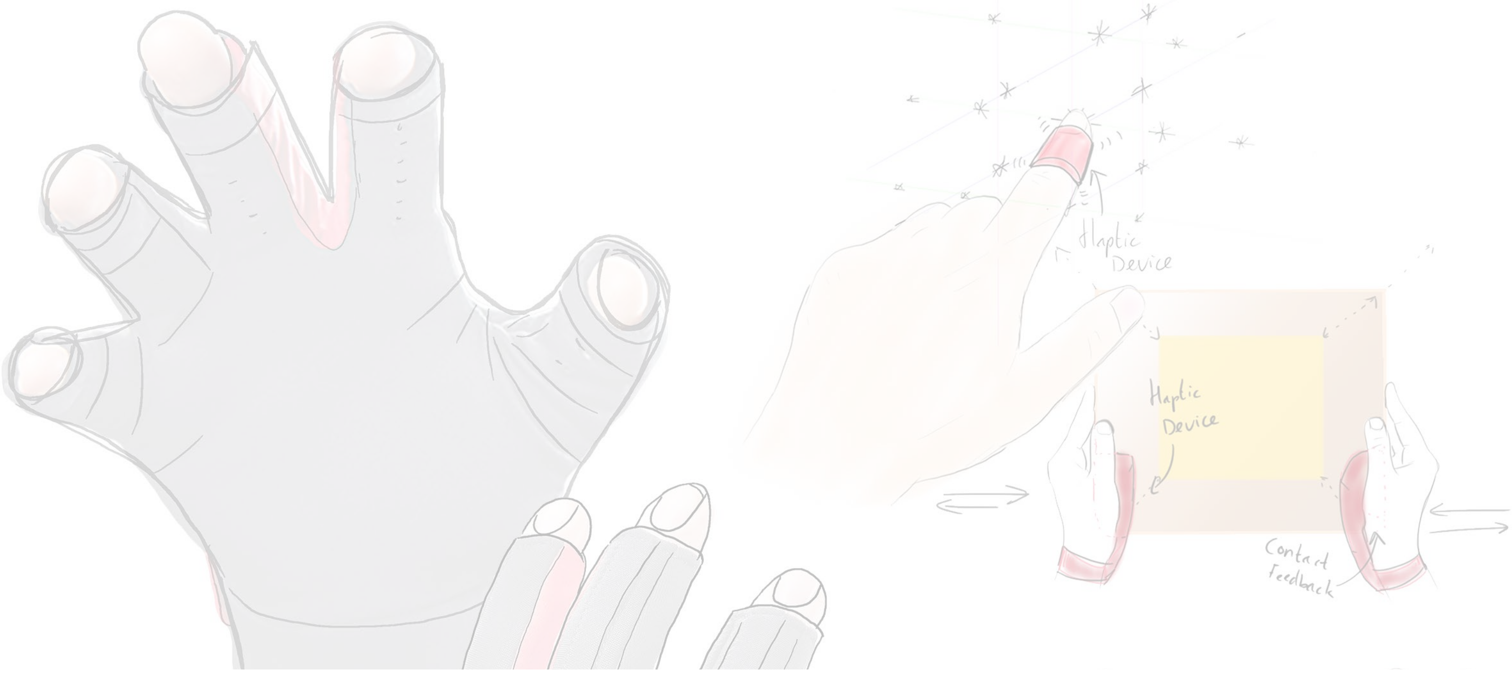
The project will continue in the area of VR CAD. First of all it offers the most opportunities for the Manus VR glove, and uses the potential of the glove in a new way. Current VR sculpting and CAD software use controller based interactions, but with the gloves designers can truly interact with their models in a new and more intuitive way, for example by using gestures. These capabilities can then be enhanced by a haptic feedback device that can be developed in this project, to make the user experience more intuitive, faster and enjoyable. VR CAD in itself is a very promising market, and while research and development has been done throughout the years, is has not yet been widely adopted. However, major players in CAD software such as Dassault and Autodesk are working on VR support for their software (engineersrule, 2016 & autodesk, 2016).

This area also matches with the company's wishes of the project having opportunities for new or improved business relations with CAD software companies. It also matches with the supervisory team, as both haptics and advanced manufacturing play key parts. And finally the subject also matches very well with the student. As a design student, working with CAD is essential and enjoyable. These aspects combined make VR CAD a suitable direction for the continuation of this project

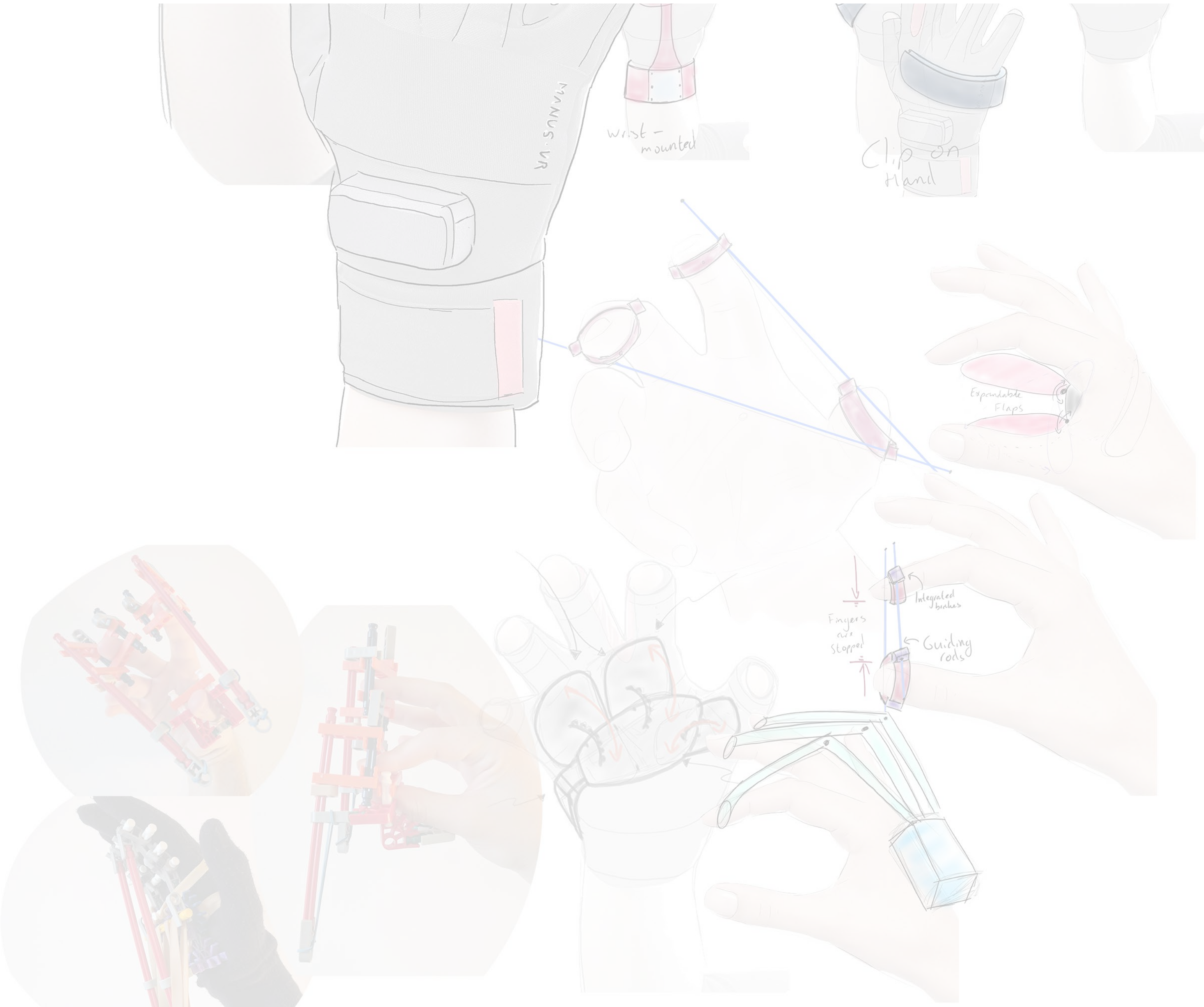
Figure 20: VR CAD by Virtalis

1.8 ANALYSIS CONCLUSION

This concludes the analysis part of this report. This part discussed the history of VR, the VR systems currently available and how they work and implement tracking. As well as the controllers they use, and other controllers that are available or are being developed and the Manus VR glove itself. This led to a brief but complete overview of the state-of-the-art of VR today, and shows the context in which to develop a product for in this project. A look into haptics shows there are many types of feedback possible to make VR more immersive. For this project, as a feedback device for the Manus glove will be developed, it was chosen to focus on feedback for the user's hand. With this knowledge and additional research, a number of search areas were formulated. Using selection criteria and the company's input, a selection was made of VR Arcades, VR exposure therapy and VR CAD & Sculpting. The final decision was made to continue with VR CAD as it offers the most opportunities to create a haptic feedback device that is innovative and utilises the strengths of the Manus glove.



PART 2: CONCEPTUALISATION



Introduction

Now that a search area has been chosen, it can be examined in more detail. In this chapter, first a closer look at the use of CAD in VR will be taken. By determining the goal for this project, and the functions the product will need to fulfil, ideas can be generated. Narrowing down these ideas will lead to a number of solutions for the main design challenges in this project. The chapter will end with a chosen concept with which the project will be continued.

2.1 VR CAD IN THIS PROJECT

First the goal of the project will be reaffirmed, namely to create a haptic feedback device for the Manus VR glove. With the chosen area of VR CAD, the ‘risk’ exists that the project will lean more towards a software project, as existing programs are most likely not suitable to be used with a prototype. However, with the formed assignment and this being an IDE project, the focus will be on the haptic feedback device itself, with software development being there mainly to serve as a platform to test prototypes.

At its core, CAD software like SolidWorks is used by adding and subtracting geometric shapes. This starts with cubes and spheres, but models can quickly become more complex using advanced editing features. Given the limitations within this project, it would be beneficial to focus on certain essential CAD features that can be translated into VR with the help of the Manus gloves. These features should be translated into intuitive hand gestures and should be supported by helpful haptic feedback.

Research has shown that free moving, two-handed input devices for CAD software are easier to learn and use than traditional mouse and keyboard (Gribnau, 1999). This is mainly true during the conceptual phase, where accuracy is less important. Improvements to tracking technology over the years, such as the Vive system, could mean more accurate design work can now also be done.

Hummels (2000) investigated how designers and non-designers can use hand gestures to visualise product designs. Where, at the time, only a groundwork for gestural design tools could be developed, with the Manus gloves this could be put into practise. For this project, the dissertation teaches us the different ways people intuitively use their hands to express certain shapes. Open hand gestures following the contours of a product are used to express the general shape, while a pointed index finger is used to carve out details, and a pinching of the fingers while moving upwards can represent a tapered volume (Figure 21). Within this project it is the goal not only to allow for hand-based designing, but also to provide helpful feedback. The remainder of this chapter will discuss the different ways in which this can be achieved.

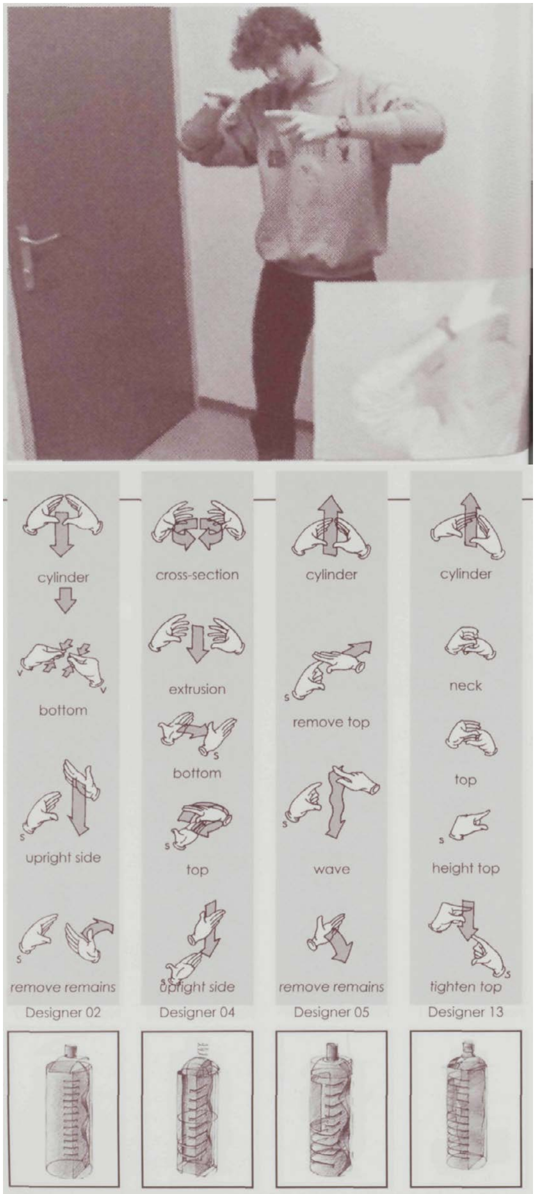


Figure 21: Hummels’ gestural design tools

2.2 MAIN FUNCTIONS

Here the different CAD-specific functions of the concepts are discussed. Each function will start with an explanation why it is used. Then the relevant gestures will be discussed, and the applicable feedback for these gestures are shown.

Utilising a 3D point grid

In order to design more accurately in VR, a 3D point grid can be used. Since the user will have their hands moving freely in the air, some reference point for the designed model needs to be present in the virtual world. A grid of points in all directions can be used by the designer to accurately define shapes. For example, a polygon tool could allow the user to select a number of points, after which the software creates a solid shape within these points. This method is also used by K. Goenka (2016) in his prototype software, as can be seen in Figure 22. Looking at his demo, a point grid proves to be a way to quickly and precisely design whilst in VR.

Utilisation of the point grid could be most accurately done by the user pointing their index finger. This way they can accurately select the points they want to use for designing their models. Haptic feedback can help in interacting with these points. If a haptic feedback device is placed on the user's index finger, small vibrations could indicate when the user has selected a point on the grid. This way, the user can get a better sense of distances whilst in VR, and work more quickly and accurately. A sketch of such a device is shown in Figure 23.

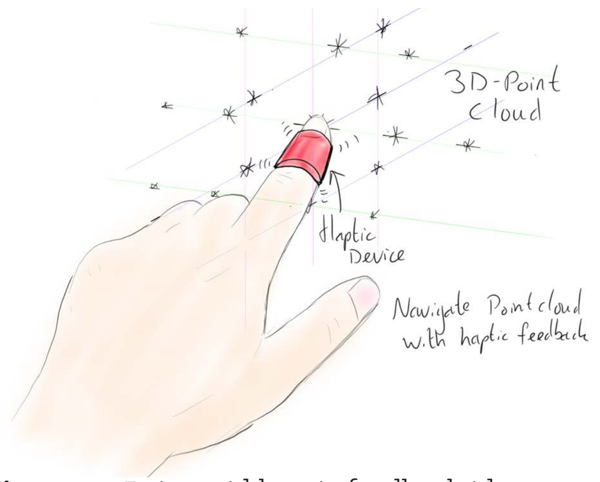


Figure 23: Point grid haptic feedback idea

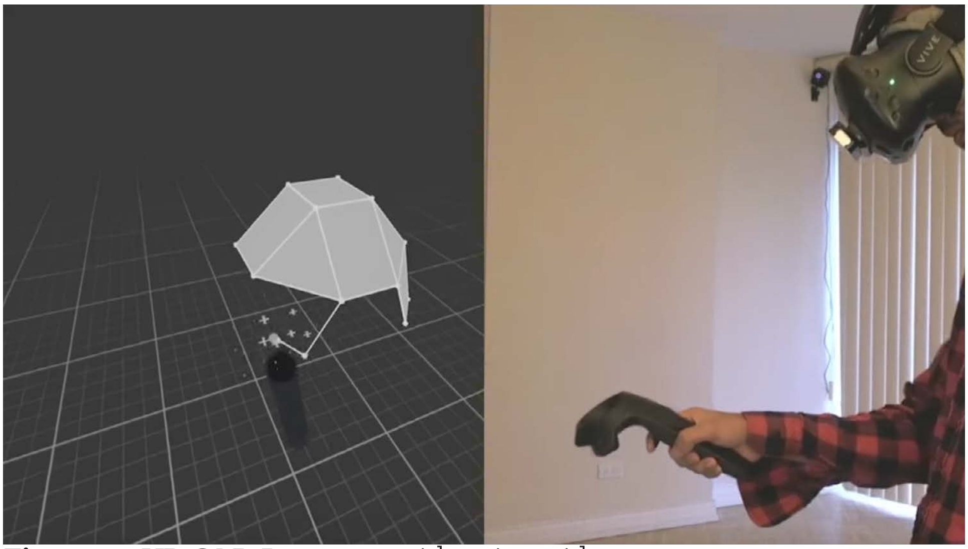


Figure 22: VR CAD Prototype with point grid

Scaling 3D models

The sense of scale is one of the strengths of working on 3D models in VR, as with the stereoscopic HMD objects can be shown on a true 1:1 scale. However, when working on smaller objects in VR CAD, or when the user needs to work on smaller detail on larger models, the ability to zoom in and out is essential. With the proposed point grid, zooming in on a model could also dynamically increase the density of points so more detailed work can be done.

In terms of the gestures suitable for this action, the grabbing of the object with both hands, and then moving the hands closer together or further apart could be an intuitive way of performing a zoom in or zoom out. The software could recognise the gesture that the user has grabbed the object on both sides with open hands, upon which the scale of the model can be adjusted (Figure 24). If the user then closes their hands, the software will once again freeze the model in place. While in the scalable state, the object could also be rotated (Figure 25).

Haptic feedback could help in performing this interaction. A haptic device placed in the palm of the user's hand could give a signal when the hand collides with the 3D object (Figure 27). The user then has a tactile way of knowing if they in fact grabbed the object.

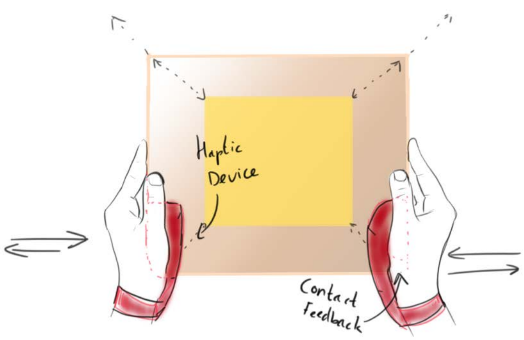


Figure 27: Example of haptic feedback device for this interaction

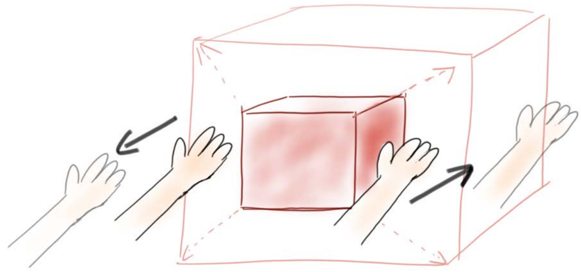


Figure 24: Expanding the model by moving arms apart

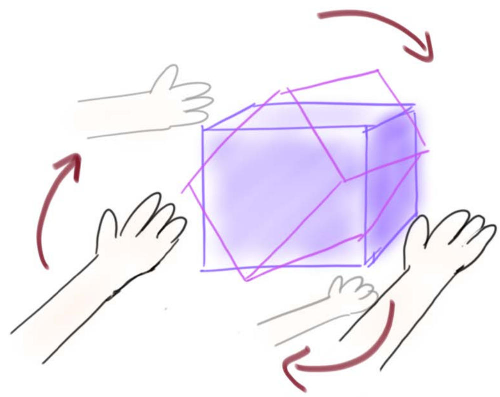


Figure 25: Rotating the model

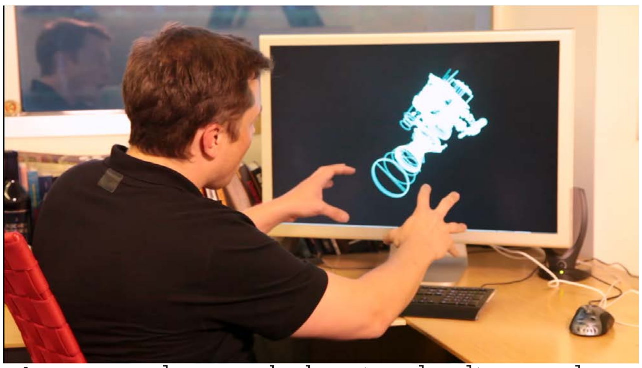


Figure 26: Elon Musk showing the discussed hand-CAD interaction using a Leap Motion

Adjusting 3D models

Because the basis of most CAD programs is the ability to create complex shapes by adjusting basic geometric shapes, this feature should also be present in the concept. With the interaction being hand based, the 3D model should be more malleable than traditional software like SolidWorks allows for. The user should be able to grab an object at both sides and stretch or shrink it, and they should be able to grab a corner of a polygon and change the shape all together (Figure 28). The point grid can be used to allow for this freedom and still have a degree of accuracy.

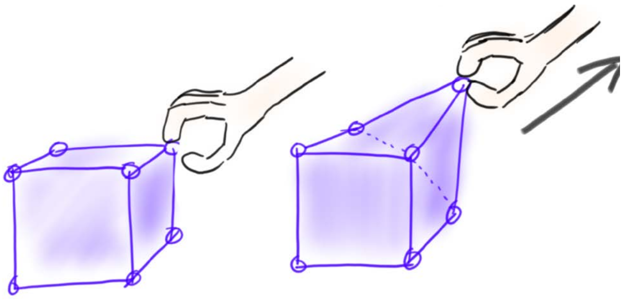


Figure 28: Adjusting the model by pinching at a point

For this interaction a pinching or grabbing gesture should be the most intuitive. Feedback can then be provided by limiting the movement of the user's finger. For example, when grabbing virtual objects of different sizes, the finger could be stopped at the appropriate point.

The different ways finger movement could be limited by a hand-based device are sketched in Figure 29. The first idea is based around rings that are placed on the users fingertips. These rings are connected to each other with a set of guide rails. Integrated in the rings is a system that can lock itself onto the rail, stopping finger movement. The second idea uses a device that is placed in the palm of the user's hand. This device has expandable flaps that can unfold towards the finger of the user. Then, when the user makes a grabbing motion, the fingers will be stopped as they hit the expanded flaps. The third idea uses an exoskeleton along the top of the hand. The rods are connected to the fingertips, and this way movement can be limited. This idea is very similar to the Dexmo.

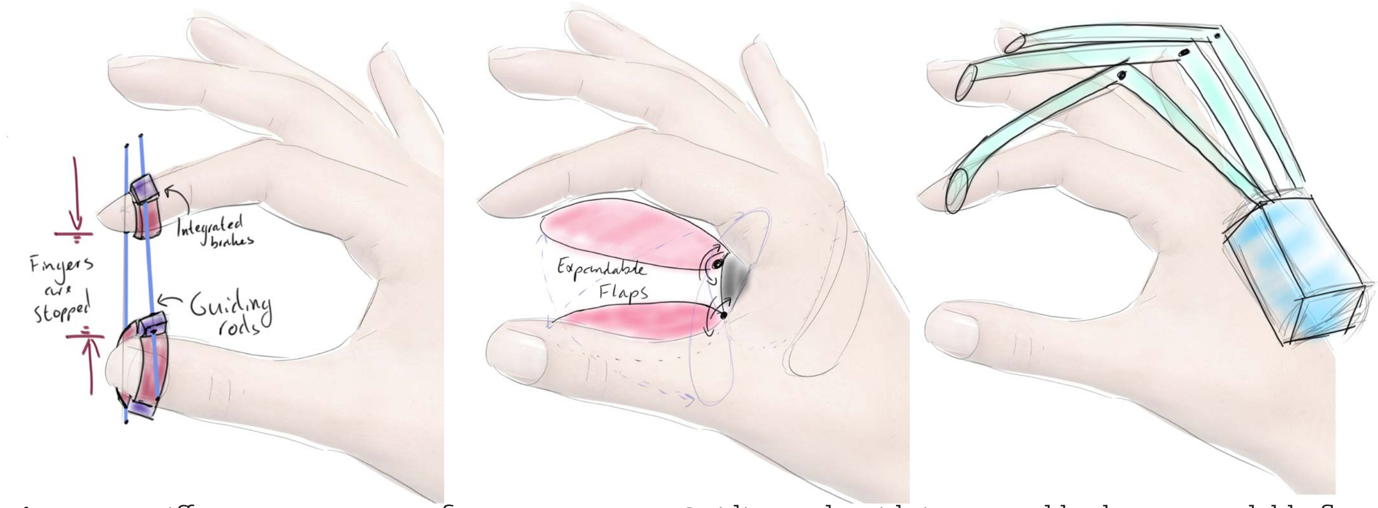


Figure 29: Different ways to stop finger movement: Guiding rods with integrated brakes, expandable flaps and hand exoskeleton

2.3 LIST OF REQUIREMENTS

Now that the main functions and type of interaction of the concept are known, a list of requirements can be drafted. The list shown here is based on previous findings and design choices, which are at the core of the project.

Focus on and the ability to provide useful haptic feedback
The feedback should focus on the three main functions of the concept, meaning the interaction with the point grid with the index finger, the scaling of object with both hands and the adjustment of objects with a pinching motion. These interactions are at the core of the design, and the concept should above all make sure useful feedback is provided.

Freedom of movement for the hand and fingers
For the user to be able to perform the gestures easily, pleasantly and intuitively, the product should allow for a high amount of freedom of movement. One of the strengths of the Manus glove is the freedom your hand has, which also adds to the immersion, so it would be suboptimal if this aspect is removed.

Ease of putting into use and use itself
The product should be easy to put on or attach to the Manus glove, preferably also while wearing an HMD. This is important because users of the product will most likely switch between being in and out of VR regularly, and if a considerable amount of time and effort is required to put the device into use, user satisfaction and adoption will suffer. The use itself should also be easy and intuitive, as the product should help the user with the CAD interaction, instead of making it more complex.

Making effective use of materials and components
One of the aspects of the assignment is to use haptic feedback components cleverly so that a effective, innovative, low-cost solution can be made. Therefore the product should be designed so that the components and materials are limited to just the essential.

Fits the Manus VR brand
The final product should fit the Manus' brand identity. Meaning the product should look minimalistic and high-tech, using mainly black colours with red accents (Figure 30).

Figure 30: Manus' design language

2.4 FIRST CONCEPTS

To explore these ideas hands-on, simple prototypes were made using K'NEX and rubber bands. These will be discussed in turn.

Concept 1

This prototype (Figure 31) was built for three finger use: thumb, index and middle finger. The part of the thumb serves as a base, and rods connected to the other fingers pivot around this base. Rubber bands make sure a pinching motion can be made, after which the prototype will return to its original state. The main goal of this prototype is to explore the freedom of movement of the fingers when using a three-finger system. It was found that a grabbing motion with three fingers is very easy to do, as well as the pinching of the index finger and thumb, and middle finger and thumb. Problem areas that were found are that it is hard to do a pointing gesture, with index finger stretched outwards and the other finger curled up, while using the device.

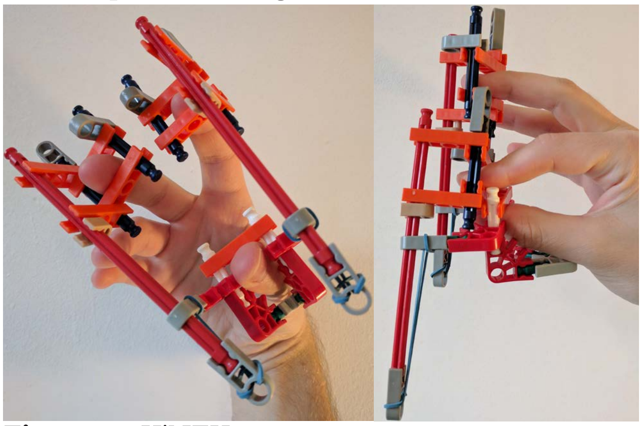


Figure 31: K'NEX prototype 1

Concept 2

The second prototype (Figure 32) was built to simulate feedback on all fingers but the thumb. Two shackle parts were built with the same amount of joints as the finger. These were connected to a rod that pivots around the base and again uses a rubber band to push back against the hand while grabbing. While this idea does provide tactile feedback along the entire finger, it also has its limitations. As the device is hand palm mounted, it will get in the way of closing the hand. Therefore it will be harder for the user to differentiate between gestures. For example a pointing gesture with the index finger stretched out and the remaining fingers curled up will not be fully possible.

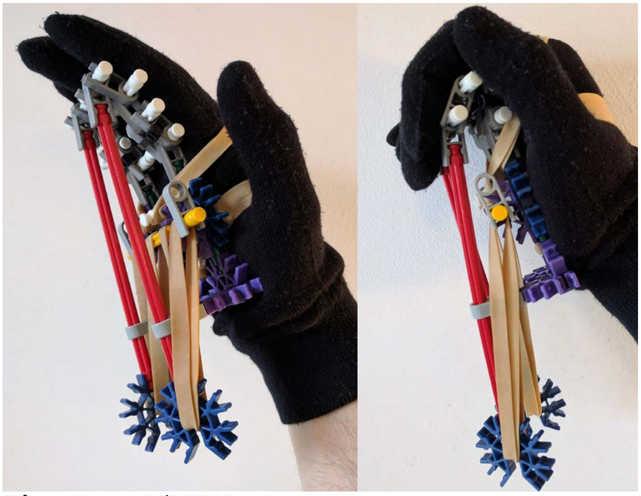


Figure 32: K'NEX prototype 2

Concept 3

The third and final prototype (Figure 33) is similar to the second prototype, with the difference being that the device goes on top of the hand instead of under it. In creating this prototype, it was difficult to achieve good freedom of movement of the fingers, as the rod system interfered when making a grabbing gestures. Building this prototype also showed the complexity of creating an exoskeleton type of device, both in terms of designing and prototyping, due to the large number of actuated rods and joints. In this form, it is also more of a stand-alone product, instead of an accessory to the Manus glove, as it could for example also replace the flex sensors in the glove.

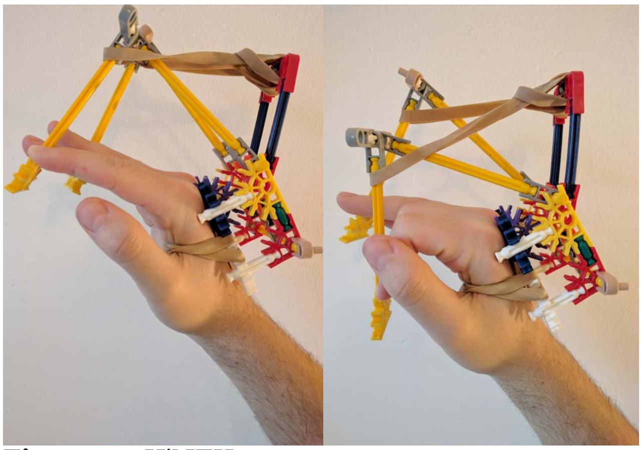


Figure 33: K'NEX prototype 3

2.5 CONCEPTS CONTINUED

To explore how these crude prototypes would translate to actual concepts, an additional design step was made. An evaluation was made on which components, on a basic level, could be used to achieve the effects shown in the previous chapter in actual product. This was done by creating basic 3D models of the different concepts, which also helped in getting a better feel of the parts necessary for the concept to work.

Prototype 1
In this concept the user places their thumb in the centre ring, and their index and middle finger in the top two openings. The guide rails that slide from the two fingers to the thumb allow for free movement on one axis, while a ball joint between the ring for the thumb and the part with the solenoid provides rotational freedom. This solenoid functions as a stopping mechanism for the rods, meaning that when it is engaged, the rods will be blocked. This will simulate the sensation of grabbing hold of an object for the user. Embedded in the index and middle finger rings are linear resonant actuators (LRA). These can provide haptic feedback to the fingertips of the user for the point grid interaction.

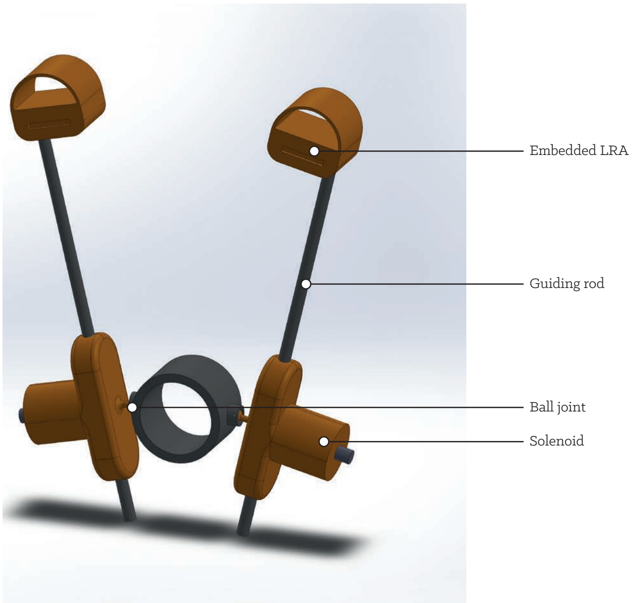


Figure 34: Concept 1 components

Prototype 2
This concept is placed on the inside of the user's hand, where each finger receives individual feedback. Guide rails from each finger slide through a pivoting stopping mechanism using a solenoid, similar to concept 1. LRA's embedded in each fingertip can provide haptic feedback to the user for the point grid interaction. An LRA embedded in the palm provides feedback for the scaling interaction.

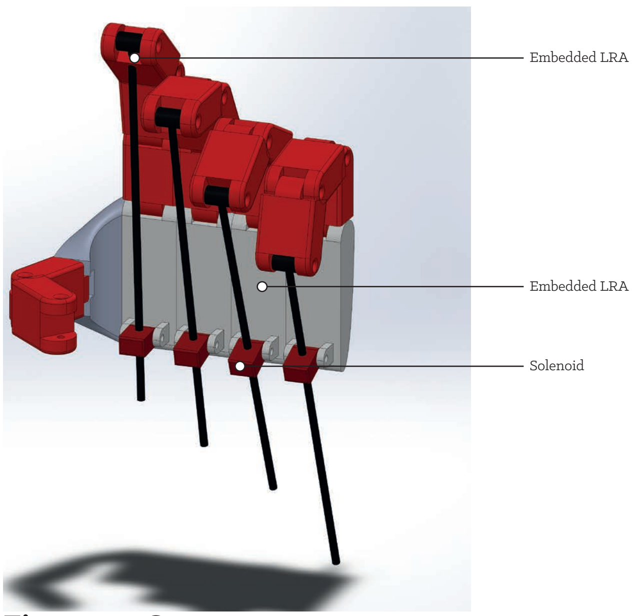


Figure 35: Concept 2 components

Prototype 3
This concept is placed on top of the user's hand, with each fingertip placed inside of the rings. Servo motors both in the base of the finger as well as at each 'knuckle' can provide resistance on each of the fingers individually, meaning the sensation of grabbing an object can be simulated. Embedded LRA in each of the rings provide haptic feedback for the point grid interaction, and an additional LRA on top of the hand for the scaling interaction.

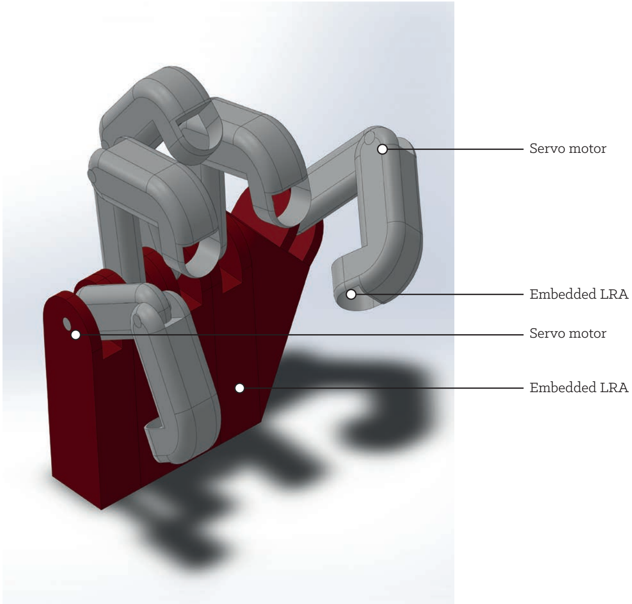


Figure 36: Concept 3 components

Conclusion
The project will continue with concept 1, as it matches best with the list of requirements. First of all the concept is most focussed on providing useful haptic feedback for the chosen interaction. Where concept 2 and 3 also provide additional feedback that is not necessarily required for the three main CAD functions, such as the feedback on the ring- and little finger. Concept one also provides the most freedom of movement, as it leaves both the palm and top of the hand free, in contrast to concept 2 and 3. This means the users fingers are more free to move, and gestures can be made more easily, such as closing the hand like a fist. This also plays in to the ease of putting the concept into use. Concept 2 and 3 will both require some sort of straps or other attachment mechanism for it to stay on the hand. Concept 1 can just be put on the user's fingers quickly. Concept 1 will also be easier and more intuitive to use, as the neutral position of the fingers and the guide rod system quickly makes it clear that a grabbing or pinching motion is the focus of the device.

Concept 1 also makes the most efficient use of materials and components, as both concept 2 and 3 require a larger amount of both. Especially concept 3, which requires a large number of servo motors. This also makes the devices more prone to defects, whereas concept 1 is a lot simpler in its construction and components. Therefore the project will continue with concept 1.

2.6 CHOSEN CONCEPT

Now that a concept has been chosen, additional design steps can be taken. In this chapter first some choices will be made to optimise the design, regarding mainly the ergonomics of and interaction with the concept. Then through iterative prototyping, flaws in the design will surface which can be improved upon. This chapter results in a complete prototype ready for user testing of the full experience.

The three interactions

To reiterate, the concept will first and foremost focus on the three CAD interactions described in chapter 2.2: Point grid, scaling models and adjusting models. In this concept, feedback for the first interaction is handled by an integrated LRM at the fingertip. Feedback for the final interaction (adjusting) is done by the stopping of the guiding rod using a solenoid. For the second interaction, scaling, no additional features have to be added to the concept, since this can be handled by the integrated vibrating motor in the Manus glove itself. This LRM is located on the back of the user's hand on can provide the feedback illustrated in Figure 26. It would be wasteful to add additional functions to the concept while the glove itself already features an adequate alternative.

The finger stopping mechanism

Changes have been made to the finger stopping mechanism and the concept in general (Figure 37). First of all the concept now only provides feedback between the index finger and the thumb. This was done because the addition of the middle finger provides no additional benefit to the beforementioned interactions. This also makes the concept simpler, since the two guide rails can be replaced by a single one. This single rod will be placed along the outside of the index finger and the nail of the thumbs, as this offers the best freedom of movement. This way the user can still point their index finger, open and close their hand and the hand palm itself is clear of obstructions. The stopping mechanism will also only stop the pinching movement of the user at a single point. The benefits of this is that instead of a variable stopping point, the concept can just have an on or off state for the blocking mechanism without any measuring mechanism keeping track of the distance between the fingers. While this offers lower fidelity than a variable stopping mechanism, the goal of the concept is not the provide realistic feedback of various objects, but only to provide useful feedback for the CAD interaction. Therefore a single stopping point will be sufficient as it clearly gives a signal to the user that they, in this case, grabbed their 3D model.

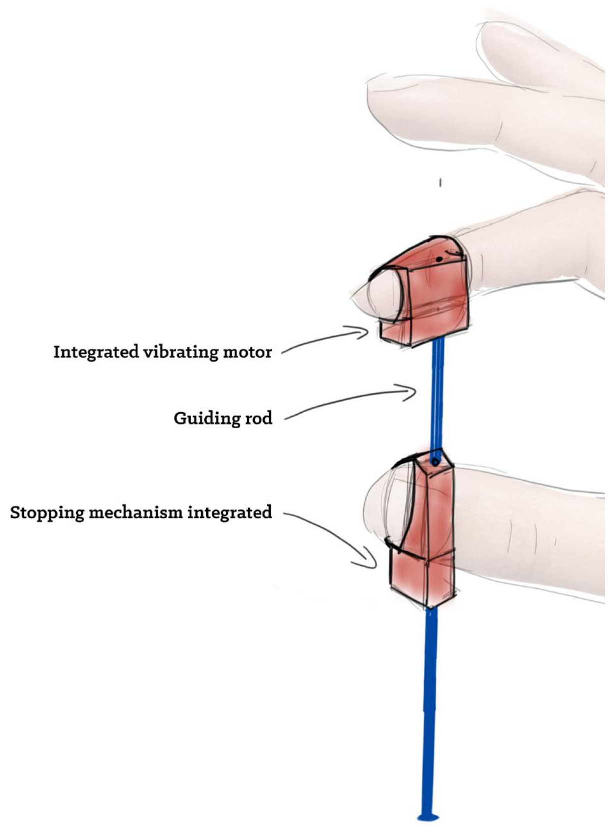


Figure 37: Overview of the new concept

2.6.1 Prototyping

The first prototypes that were built had the goal to determine how the different components could be integrated in the design, and which types of components were most suited for use (Figure 38). It consists of 3D-printed parts that can be placed on the index fingertip using a Velcro band. On the bottom of the part a mounting spot for vibrating motors was located, so that different motors could be compared in terms of the haptic feedback they can provide. By connecting the motors to an Arduino, different PWM signals and intervals can achieve different effects that can also be compared. A second iteration of this 'ring' decreased material thickness and general dimensions to fit the fingertip better, and a structural mount for the motors.

Parallel to these parts, tests were done to determine whether a solenoid could block the movement of a rod. First tests proved successful but a number of improvements were made. First off, the tolerances of 3D-printing meant some leeway was needed for the parts to fit properly. Secondly, the small amount the solenoid is able to extend its rod means that the distance between it and the guiding rod should be kept to a minimum.

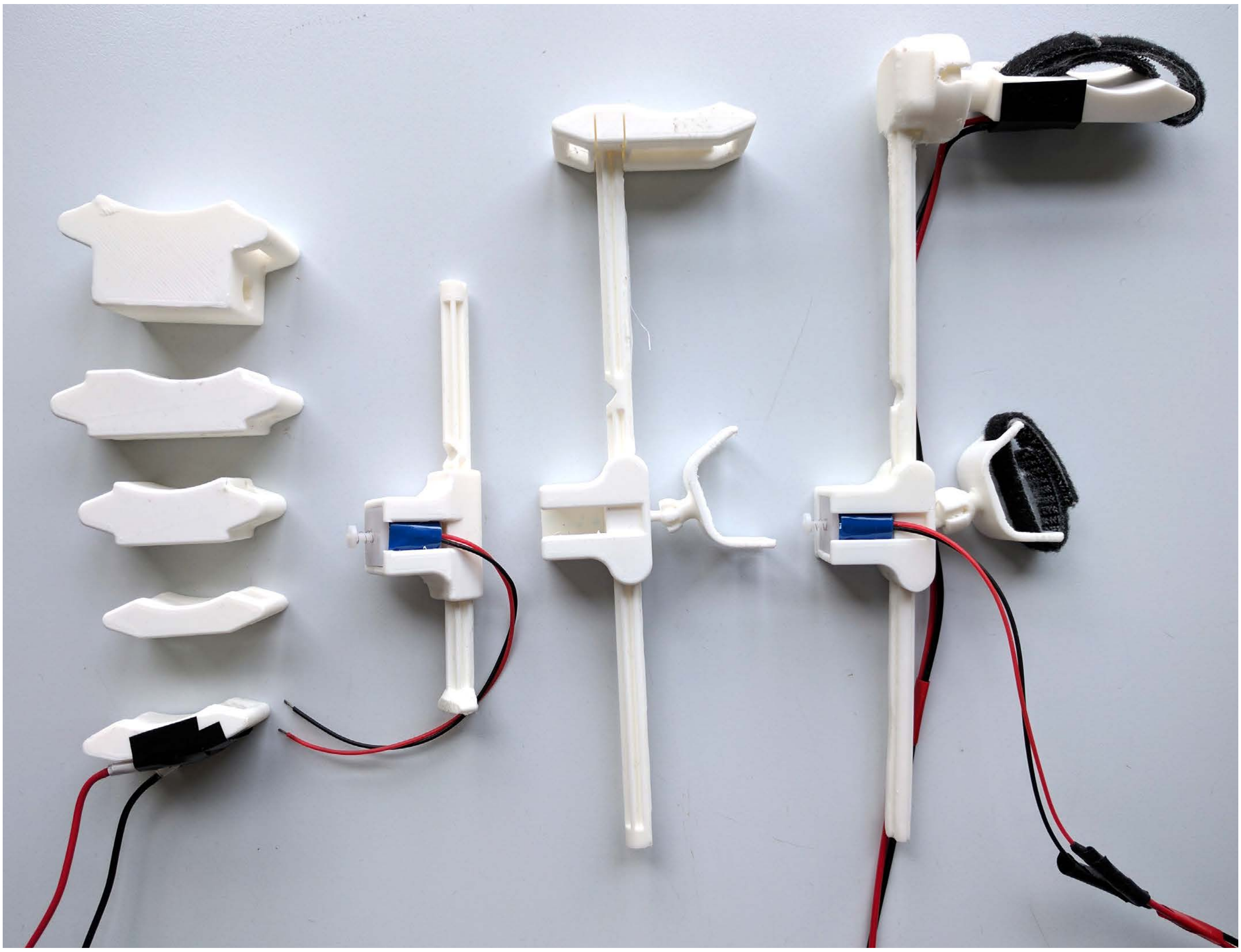


Figure 38: Different prototype iterations, from left to right

The next step was to integrate the stopping mechanism and the index finger part into a single prototype (Figure 39). First testing showed the following areas that need improving:

- A snap fit was used to attach the index finger shoe to the guiding rod, but this connection proved to be too weak so glue was used temporarily. Furthermore first use shows the ergonomics of this design make pointing with a straight index finger impossible because the fixed connection between the rod and the shoe make the part very stiff.
- The guiding rod that moves through the solenoid holder was given a flat edge that was supposed to make rotation the rod impossible, however this proved to be insufficient. Next versions of the rod will need a different shape so that rotation is not possible, otherwise the solenoid will not lock into the cavity on the rod.
- The way the rod connected forced the index finger in an unnatural position. By adjusting the index finger shoe more horizontal distance between the finger and thumb can be created, which is more comfortable for the user.
- The ball joint means the user's thumb can move freely. However the resting position of the thumb is not perpendicular to the solenoid holder, but at roughly a 45 degree angle. Therefore the ball joint will also be placed under an angle so the forces on the joint are more properly exerted.
- At this stage the prototype already features a number of wires leading outwards. By integrating these wires in the design they are less obtrusive to the user.

Figure 39: Prototype description

Prototyping continued

The next iteration of the prototype (Figure 40), improved upon the aforementioned issues. By making the index finger shoe rotate along its connection to the guiding rod, more freedom of movement for this finger is possible. As can be seen in Figure 41, the finger can now be pointed straight forward or curled up freely. Secondly, the guiding rod's new profile is cross-shaped so rotation of the rod in the solenoid holder is blocked, so the solenoid is always able to lock into the cavity. Then, by increasing the width of the index finger shoe, the horizontal distance between the index finger and thumb is increased, which leads to a more natural resting position for the hand while using the device.

The ball joint that connects the thumb shoe is now also placed under a 45 degree angle, so forces from the thumb are exerted along the direction of the joint. Finally, the integration of the wires was not possible in this iteration due to either printer settings or the model's dimensions.

Further improvements

Firstly, a new way of mounting the thumb to the device should be designed. The current solution allows for too much movement while the finger stopping mechanism is activated, as in this state the thumb is still able to move around the ball joint. This can feel unnatural or break immersion (D. Abbink, personal communication, March 2017), and a different design might allow for the same freedom in the unlocked state, but limits the thumbs more in the locked state. Smaller adjustments are increasing the print quality by adjusting the settings and taking the printer's properties into account more into the design so a model with a better finish and durability can be printed.

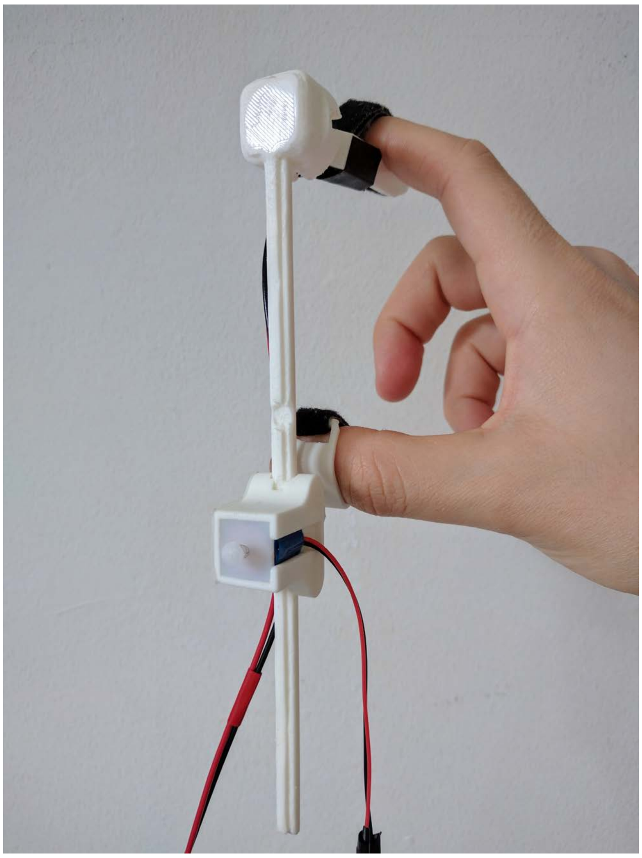


Figure 40: The protoype in its fourth iteration

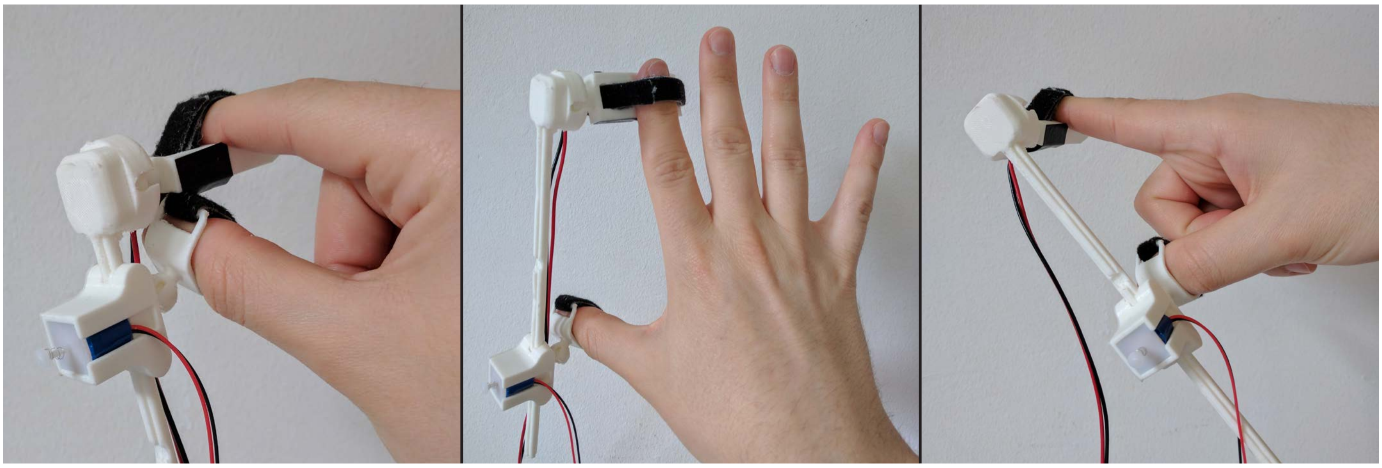


Figure 41: Demonstrating that the prototype allows for freedom of movement of the hand

2.6.2 Final Prototype

The last iteration of the prototype (Figure 42) implements the aforementioned improvements. To reduce the freedom of movement of the thumb while the user is making a pinching motion, the thumb is now placed inside of a ring that is fixed to the solenoid holder. Inside this ring there is a second ring that is shaped to fit the thumb and can freely rotate inside the outer ring. This implementation also decreases the distance between the stopping mechanism and the thumb, so the forces of the torque on the product while pinching is also reduced. The guiding rod is once again round, so the thumb, together with the solenoid holder, can freely rotate around it. This free rotation of the ring and rotation around the rod makes it that this iteration of the prototype has an even higher degree of freedom of movement for the fingers and hand, as demonstrated in Figure 43.

This version of the prototype is functional to a high enough degree that it can be used for user testing. It offers a good amount of freedom to the fingers and hand for the participant to perform tasks in a VR CAD environment, and implements the necessary components and functionality from the original design. However, in the next chapter an additional design step will be made to work towards a more finished product based on this design.

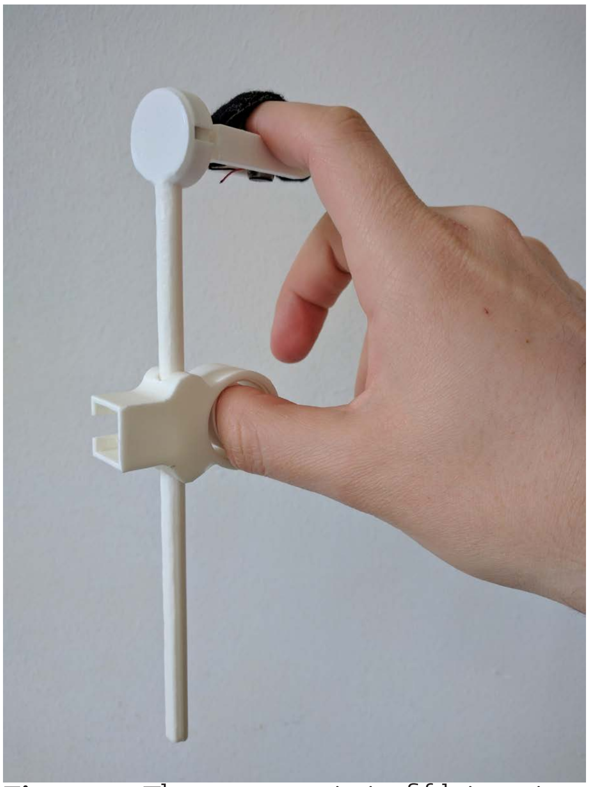


Figure 42: The prototype in its fifth iteration

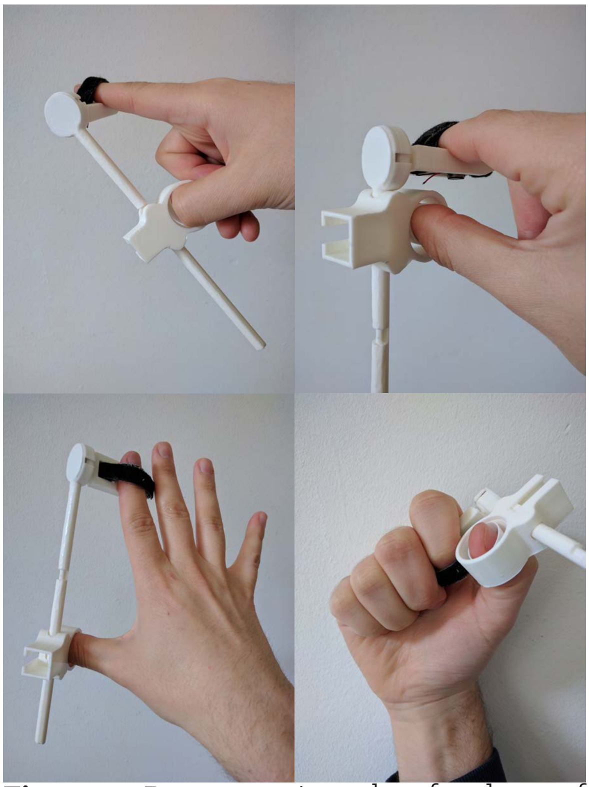


Figure 43: Demonstrating the freedom of movement of the final prototype

2.7 FINAL CONCEPT

In this chapter the final concept will be presented. A number of changes are proposed to the layout and the appearance of the product to improve both usability and aesthetics. This is done to show what the product could look like if it were ever brought to market. In this chapter the design choices that led to this design will be explained, while in the next part of the report the embodiment of this design will be discussed.

In this redesign, the main change is that the solenoid is moved to the index finger. This means that all electronics, such as the vibrating motor, battery and the PCB can be housed in this top part. It also means that the rod will no longer interfere while the user rests their hands on a desk or alongside their body for example.

The index finger is now also placed inside a ring that can freely rotate, as tests with the earlier prototypes showed that this already offers great freedom for the thumb, while not allowing movement in the locked state. This index finger ring can also rotate relative to the solenoid holder, to allow for the curling up of the index finger. This second ring for the index finger also provides more cohesion to the design, as both the thumb and index finger are now placed inside a ring.

The thumb ring is connected to the rod with a ball joint. This ball joint should be quite stiff, and have the sole purpose allowing a more natural position of the thumb relative to the index finger while pinching, also for different users with different hand sizes. The main freedom of movement should come from the rings and the rod along with the index finger that can rotate freely.

The previous chapter mentioned that a prototype was made that was usable for user testing. Therefore the design presented here will not be made into a functioning prototype. While it offers usability and aesthetic improvements, the functionality remains unaltered and therefore the previous prototype is adequate for testing purposes. A mock-up of this design will be made however to evaluate its appearance and ergonomics.

Figure 44: Final Concept

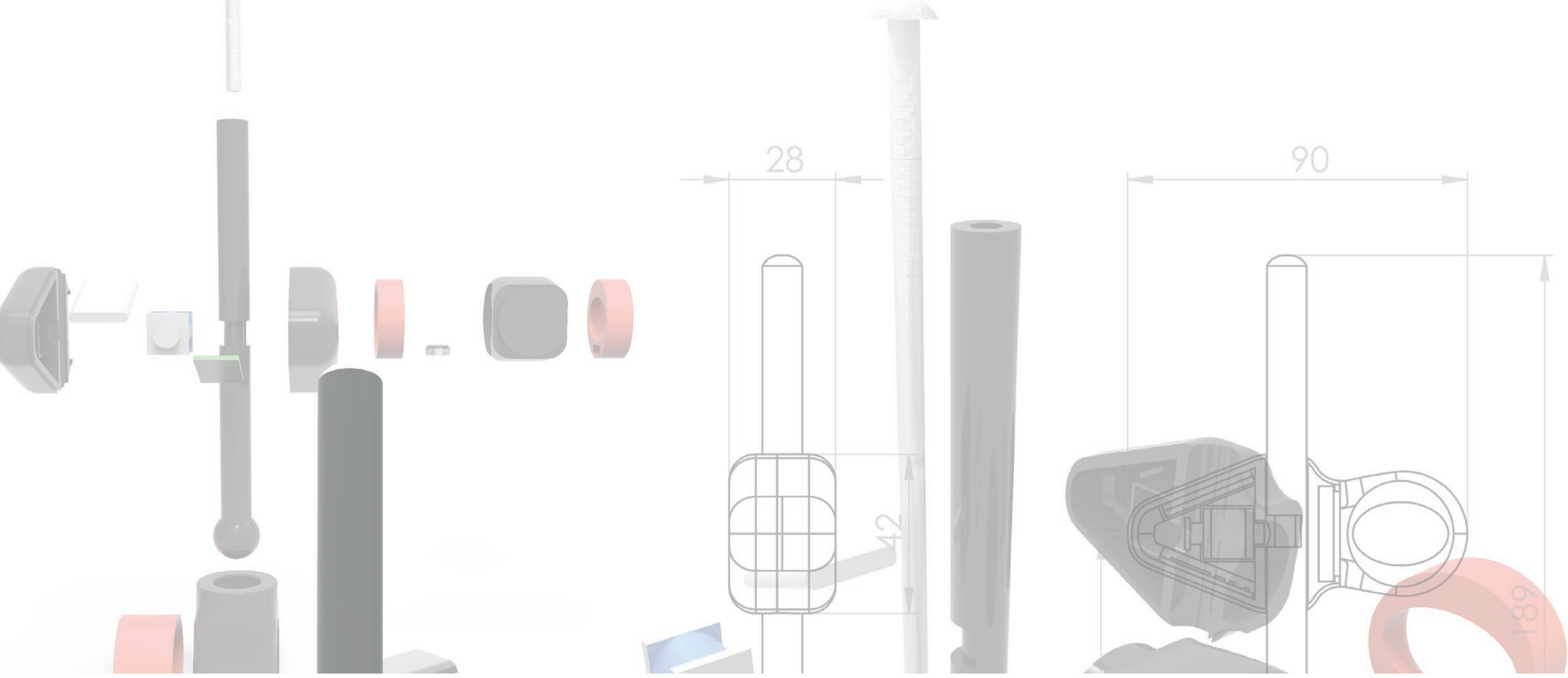
Figure 45: Final Concept while pinching

2.8 CONCEPTUALISATION CONCLUSION

This concludes the conceptualisation phase of this project. By further exploring the field of VR CAD a number of key functions could be determined. The three functions deemed most important for this application were established: the utilisation of a 3D point grid, the scaling and moving of 3D objects and the adjustment of 3D objects. From these three functions, interactions involving the user's hands were designed, and in turn relevant haptic feedback as well.

With a rough idea of the functions the haptic device should perform, a list of requirements could be created to guide the conceptualisation process. First ideas were immediately built into simple prototypes, which gave a good insight in the feasibility of these ideas. An additional design step for these ideas showed the pros and cons for each concept, leading to the decision to continue with the concept that was both the most effective and least complex.

This concept will provide tactile feedback between the index finger and thumb by placing both fingers in holders that are connected by a rod. While pinching these fingers, a solenoid can lock the rod giving the impression of pinching a physical object. Additional prototyping led to an evolution of the design, which through roughly five generations provided a prototype useable for user testing. A final design was also proposed which more closely matches the envisioned end product that could be put on the market.



PART 3: EMBODIMENT

Introduction

Now that a final concept has been proposed, a more detailed overview will be given for the inner workings of the concept. This means the different components that are used will be discussed, as well as how they will be assembled and produced. While this will not directly lead to a product that is ready for production, it does give more insight in what it would take to bring this product to market. Next to this a more detailed overview of the interaction and the added benefits of haptics will be given. Where in the conceptualisation chapter this was done in broad terms, this chapter will discuss the precise actions and reactions between the user and the product, keeping in mind the software that is used. This will be visualised in a state flow diagram. The goal of this chapter is also to serve as a basis for the validation part of this project, where the most important functionalities discussed in this chapter will be tested in a prototype.

3.1 THE HARDWARE

Components

In order for the design to function, a number of components are necessary. While some of these have been discussed during the conceptualisation phase, this section will give a complete overview of the components of the final design based on the exploded view shown in Figure 47. Measurement are provided in appendix B.

The guiding rod

The guiding rod consists of an inner an outer part, where the inner part is a metal rod and the outer part a plastic shell. This is done to add additional stiffness and strength to the design, which is necessary to counteract the pinching force of the user's fingers. If this rod were weaker, it could bend under this force which could damage the product. It could also give the wrong haptic feedback to the user, as the bending of the rod could give the impression that the user is not grabbing hold of something rigid. Therefore the rod should be as stiff as possible. The inner and outer rod are separate parts so the benefits of both materials can be used: the easier production of complex shapes in plastic, and the strength and stiffness of metal.

Battery, PCB, solenoid and casing

These are the main electronics of the design. The battery will provide power to the PCB and is rechargeable. The PCB is home to the microchips that make the products work. It features a microcontroller to control the solenoid and vibrating motor, wireless communication to communicate with the VR host computer (through the Manus VR dongle), and power delivery circuitry to power the solenoid, vibrating motor and to manage the charging of the battery. The solenoid is used to lock the product into place to provide tactile feedback, in the same way as the earlier concepts did. These components are all housed in the main casing. This consists of two parts in which the components can be placed and then closed.

The thumb ring

This consist of a red ring which fits the thumb, that is placed inside the thumb ring housing where it can freely rotate. The casing also is the socket for the ball joint connection to the guiding rod. The ring itself will be made of a soft, sponge-like elastomer, so it can fit a variety of thumb sizes comfortably.

The index finger ring and LRM

The ring itself consists of two parts, with a small slot to fit the vibrating motor. This way tactile feedback for interacting with the point grid can be provided to the index finger. A LRM is chosen as it provides more precise and stable vibrations compared to an ERM (eccentric rotating mass motor). This ring can be assembled with the LRM in place, and then mounted inside the index finger ring casing. This casing is connected to the main casing when its two halves are put together. It is then free to rotate relative to the main casing as to allow the index finger to curl up and straighten out.

Figure 46: Main casing internals

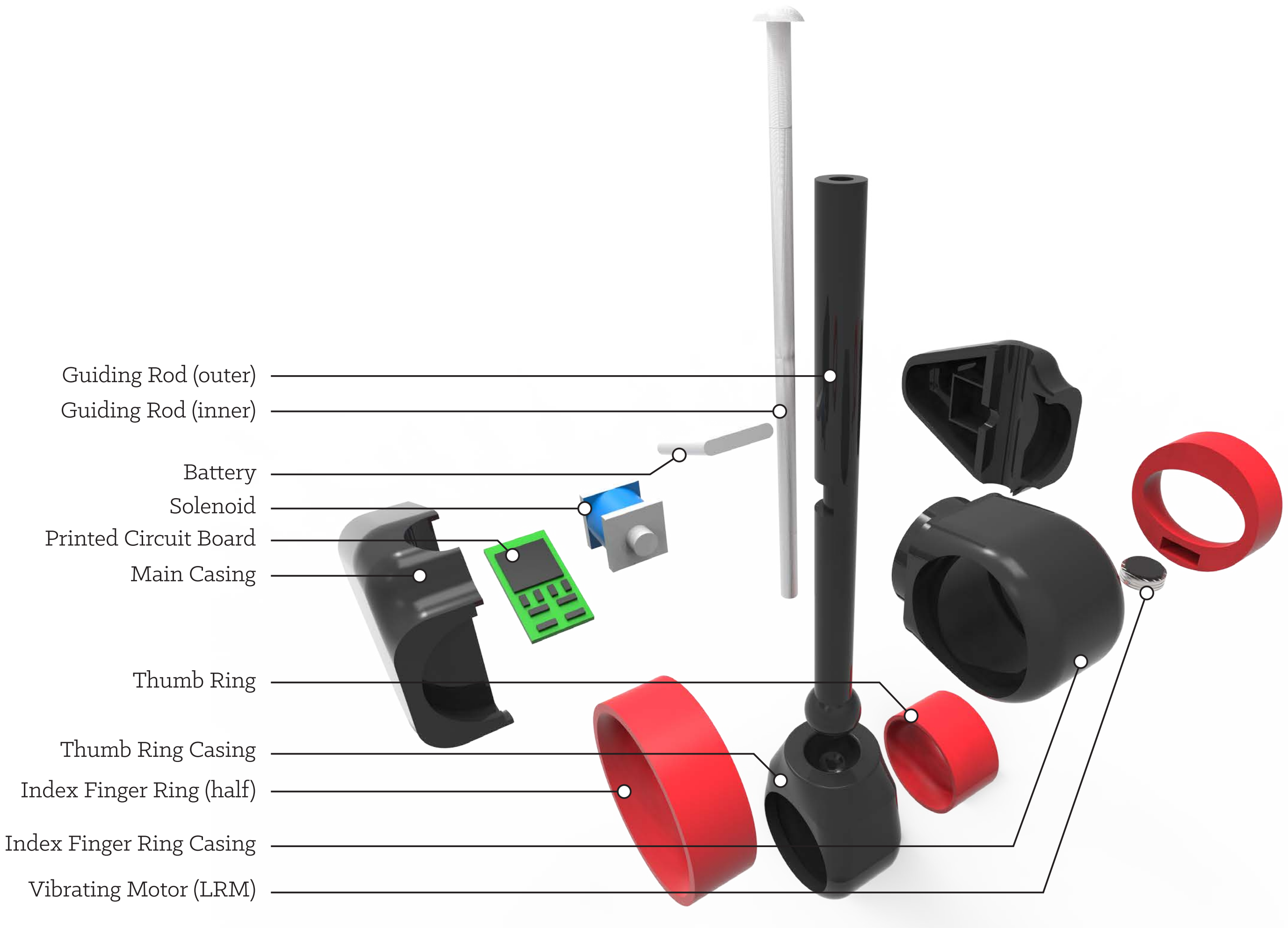


Figure 47: Exploded view showing the components

Production

To produce this product a number of processes are necessary. The plastic parts, the ring casings, main casing and outer guiding rod can be injection moulded in polypropylene or ABS plastic, while for earlier versions of the product, such as development kits, 3D printing can be used as the quantities will be smaller. This is also the case for the red rings, although they should be made of a softer elastomer. The inner guiding rod can be made of aluminium, and will need to be custom made for this product. The simplicity of the geometry of this part will most likely make this relatively affordable. The battery, solenoid and LRM can be off-the-shelf parts, with the main casing designed to precisely fit these parts. And finally the PCB will need to be custom made. For further development of the product a programmable microcontroller like an Arduino can be used, but for the final product a custom PCB will need to be designed with the functionalities mentioned in the Components section.

These parts can then be assembled. Figure 48 shows the different sub-assemblies of the product: the main casing, the guiding rod and the index finger and thumb rings. These sub-assemblies can first be assembled individually, after which the complete product can be put together.

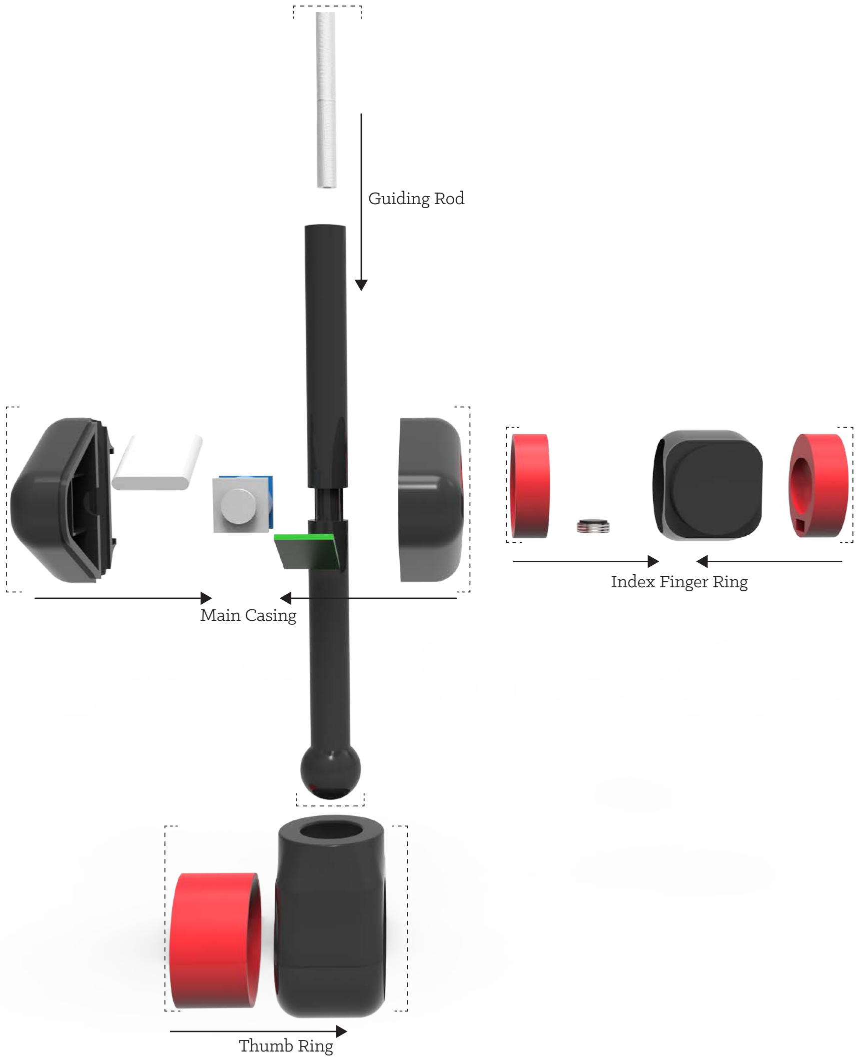


Figure 48: Sub-assemblies

3.2 INTERACTION & HAPTICS

Now that the hardware that will be used is established and embodied, the interaction and haptic feedback the product will have with the VR CAD application will be described. These interaction are based on the three main functions established in the conceptualisation chapter: a 3D-point grid, moving and scaling shapes, and creation and adjustment of shapes. This chapter will describe the types of interactions and haptic feedback that are created to enable the user to use these three functions. This is an overview of all the interactions that are envisioned for use with the product. A software prototype is also made that incorporates some of these functions for user testing, this will be discussed in later chapters.

Point grid interaction
Central to working with shapes within the VR CAD environment envisioned for this product and the Manus glove is the 3D point grid. It will offer the designer to ability to work quickly and precisely in a 3D space, as the vertices of the designs that are made will snap to the points on the grid. When scaling shapes the grid will scale along, adding or reducing the number of points for fine detail work or large adjustments respectively. Haptics are added to this interaction through the vibrating motor in the index finger ring: by hitting the points on the grid with the index finger, the user will feel a short vibration. This will make it easier and more intuitive for the user the identify the points on the grid, and to estimate distances based on tactile feedback in contrast to purely visual feedback.

Figure 49: Point grid interaction

Shape creation
To create a shape the user can extend their index finger as though they are pointing at something. The tip of the index finger then is similar to a mouse cursor, where it can select a point on the grid. With the hand the user can make a squeezing motion to start the shape creation. The Manus glove will recognise these gestures and the software in turn will create a shape. By moving the pointed finger to other points on the grid, the user will draw a 3D object, and by squeezing once more with the other hand, the created shape will be fixed.

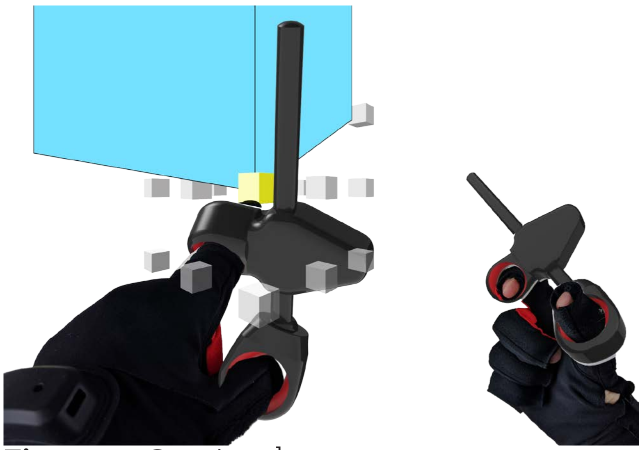


Figure 50: Creating shapes

Moving and scaling shapes

To move a shape the user can place their flat hand against the side of a shape. The vibrating motor will buzz briefly at the index finger indicating to the user that the action is recognised. Then, the shape will 'stick' to the user's hand, and they can move their hand in 3D space to move the shape that is attached. To release the shape, the user can close this hand, which will be recognised by the Manus glove and the software. The scaling of shapes happens in a similar fashion, as two flat hands can be placed at the sides of the shape. The shape will then snap in between these hands, while the user can move their hands apart or closer together to enlarge or shrink the shape.

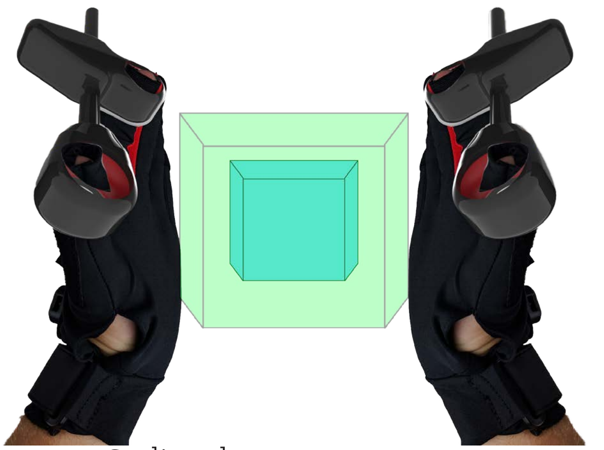


Figure 51: Scaling shapes

Adjusting shapes

The shapes in the VR CAD environment will consist of polygons, created by drawing triangles between vertices. The user can adjust these vertices to adjust the shapes they are working on. These vertices will show a small 'adjustment sphere' when the user approaches with their hand. The user can then grab these spheres by making a pinching motion with index finger and thumb. This action is recognised by the Manus glove, and the software in turn will active the solenoid lock. This way, when the user grabs this sphere, the solenoid will fall into its lock, blocking further movement of the index finger and thumb, and giving the impression to the user that they actually grabbed hold of the sphere. This sphere, and the vertex of the shape, is then locked between these finger in the VR world as well, where the user can move their hand to a different point on the grid and release it. Upon hitting a point on the grid with the sphere, the solenoid is disengaged, allowing the user to release their pinch and open their hand. While moving the vertex along the grid between the two fingers, the vibrating motor on the index finger will provide feedback similar to the shape creation process.

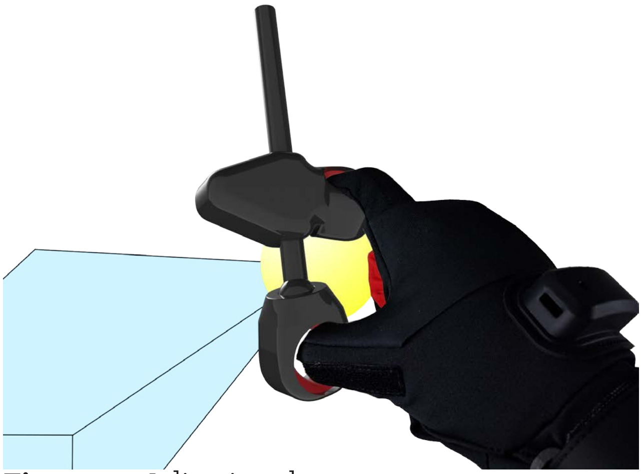


Figure 52: Adjusting shapes

State Flow Diagram

To visualise the interactions discussed above, a state flow diagram was made (Figure 53). In this diagram, the moving and scaling of shapes is left out. This is done because this functionality will also not be used in the validation chapter as it does not directly benefit from the haptics added by the product, as the locking mechanism will not be used.

In the diagram, the neutral state is always "Freely moving". This means the user is free to move around with hands and body in the virtual environment. From this state there are a number of options. When the user wants to create a shape, they move to a point on the grid, which they will hit. This enables the creation of shapes in the software if the user squeezes their other hand. The user is then returned to the freely moving state, only now they are creating the shape and changing its size while they move. When they then hit another point, finishing shape creation is allowed with a second squeeze.

The interaction is similar with the adjustment of shapes. When a adjustment sphere is hit, the solenoid lock is engaged, and a pinch at this sphere allows shape adjustment. Then the user is free to move and when they hit a point on the grid the solenoid is disengaged. If they move away from this point the lock is engaged once again, but if they release their pinch, the adjustment will finish. Meanwhile during all of the interactions, the index finger vibrating motor will vibrate shortly whenever a point on the grid is hit by the user, regardless of the state they are in. Also, in practice the user will almost always be in the freely moving state, as the different states are what happens in software in a split second.

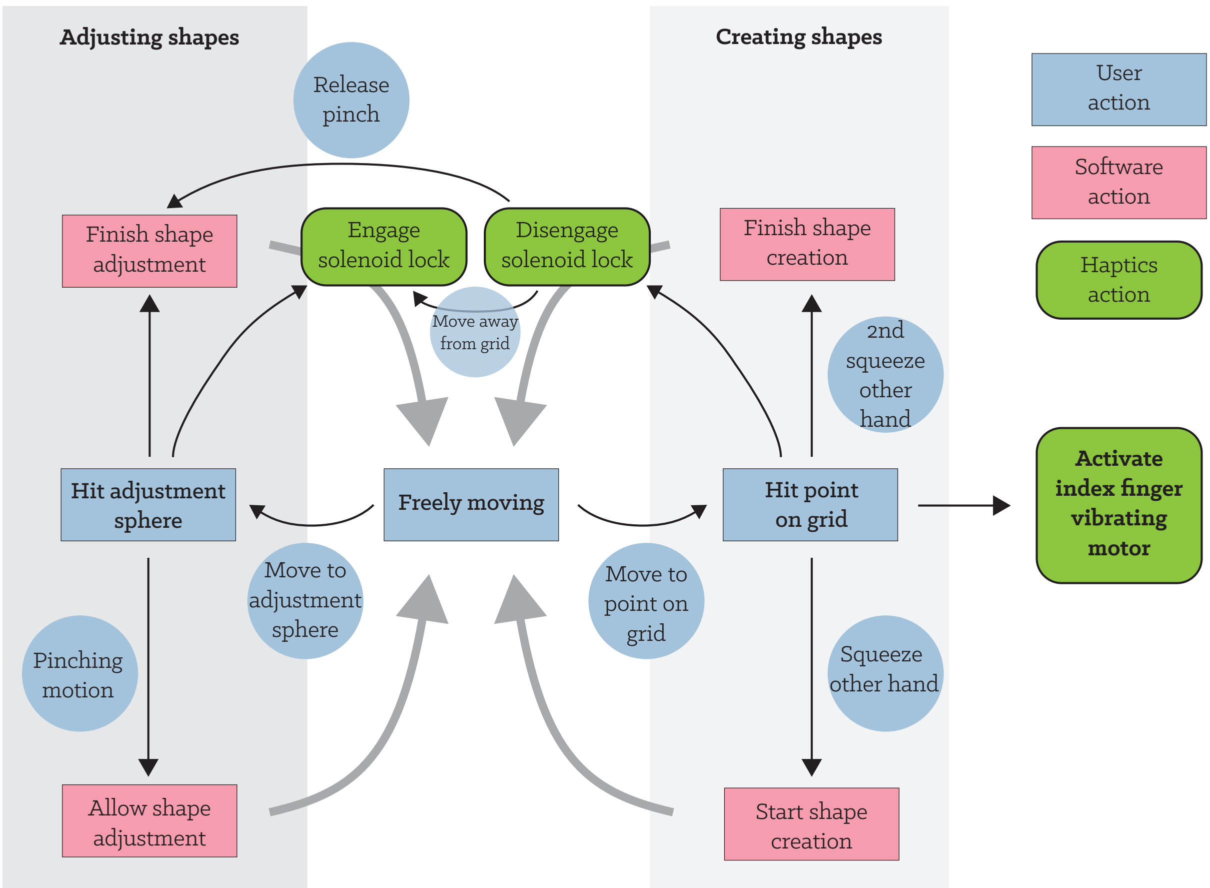
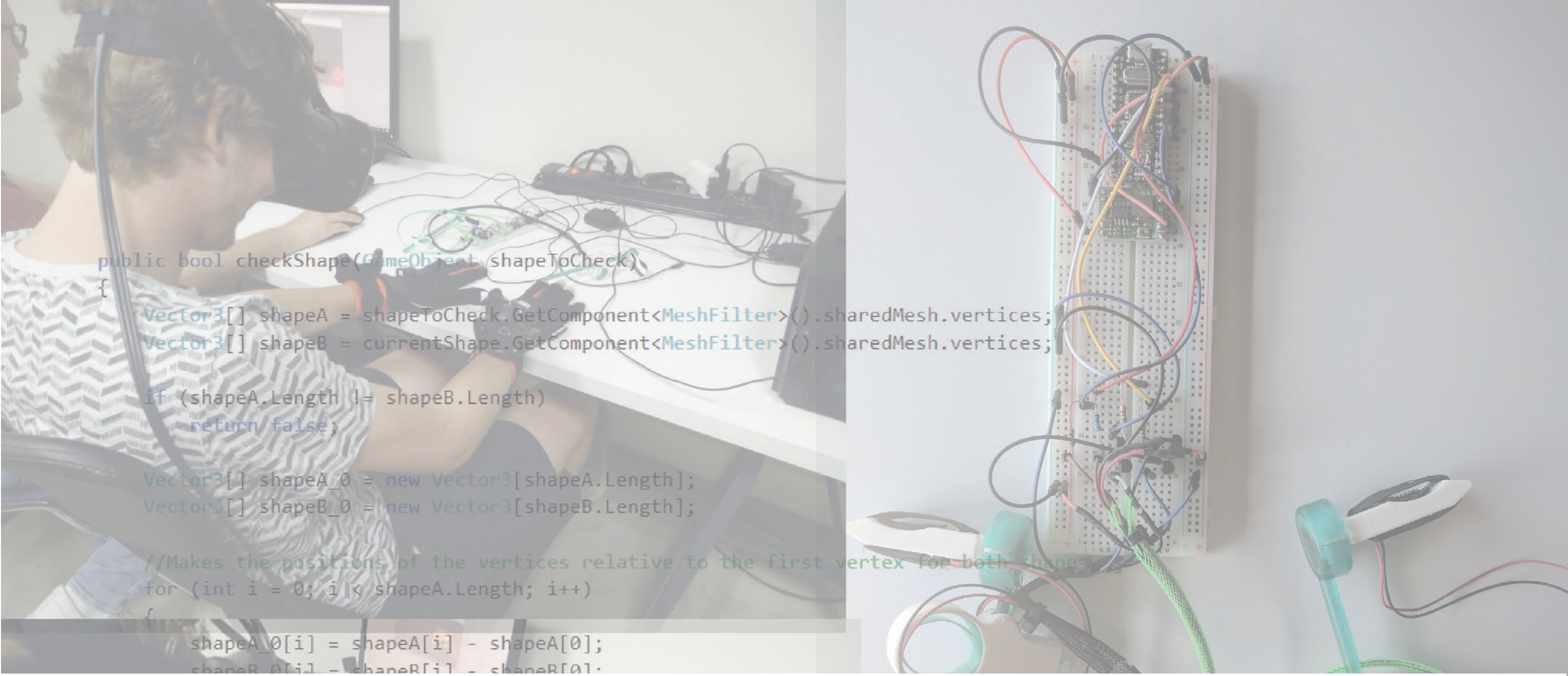


Figure 53: State Flow Diagram

3.3 EMBODIMENT CONCLUSION

This concludes the embodiment of the product within this project. It was shown which components would be necessary to make the concept, that was proposed in earlier chapters, feasible. And furthermore how these components could be assembled into the product. Naturally, additional steps would be required to bring the state of the design closer to production, but within the limitation of this project this chapter at the minimum gave a good impression of what it would take to continue development. The interaction was also described in detail and supplemented with a state flow diagram. The results of this chapter and the design choices that were made can now be translated to the prototype and user test that will evaluate the design in the validation chapter.



PART 4: VALIDATION

Introduction

The goal of this chapter is to validate whether the anticipated added benefits of the design are valid. This will be done by taking the most important aspects of the design from the embodiment chapter, and translating them to usable prototypes and user tests. First, the creation of these prototypes will be described, both in hardware and in software. The prototype created in the conceptualisation phase needs to be supplemented with components which also need to be controlled. This being a VR project, a virtual environment specifically made for testing purposes also needs to be made. With these in place, the design can be properly evaluated, as well as user tests that can be performed. Findings from these evaluations will lead to recommendations for the design.

4.1 SETUP

In order to validate the design, both a hardware and software prototype were built and integrated in order to represent and test the essence of the design. This chapter discusses the creation and integration of these prototypes and how they will be used for user testing purposes.

Hardware

The physical aspect of the prototype that will be used was previously explained in chapter 2.7, and consists of an assembled 3D printed device, however the electrical components that are used will be discussed here. In order for the locking mechanism to work, a small solenoid will be used. The solenoid holder was designed to precisely fit the used solenoid. When 5V is provided to the solenoid, the magnets inside will make the piston retract on one side and expel on the other side. This part of the piston will then slot into a cavity on the guiding rod and lock the device from moving. Secondly, a LRM vibrating motor is attached to the underside of the 'index finger shoe'. By providing 3V for a short amount of time, for example 30ms, tactile feedback can be provided to the user as described in chapter 3.2.

To control these components an Arduino Nano clone is used which is placed directly on a breadboard. This Arduino uses transistors as switches to provide the solenoid with 5V from a power supply directly, as well as 3V to the LRM's through a step down converter. It is loaded with code that listens to commands from the software prototype running on the computer over the serial port. When it receives certain commands, sent in the form of a single letter, it goes through a certain sequence. For example, when it receive the letter 'x', it will change its output on the solenoid pin for the right hand to "High", meaning 5V will go to the solenoid through the transistor. It will also give two short buzzes on the LRM by alternating twice between the high and low state on the right hand for 40ms.

```
void loop() {
    int lf = 10;
    Serial.readBytesUntil(lf, myCol, 1);
    if(strcmp(myCol,"x")==0){ //close LEFT solenoid and double buzz
      doubleBuzz(0);
      digitalWrite(solPinLeft, HIGH);
    }

void doubleBuzz(int side){
  if (side == 0){ //LEFT
      digitalWrite(vibPinLeft, HIGH);
      delay(40);
      digitalWrite(vibPinLeft, LOW);
      delay(50);
      digitalWrite(vibPinLeft, HIGH);
      delay(40);
      digitalWrite(vibPinLeft, LOW);
  }
```

Figure 54: Arduino code excerpt

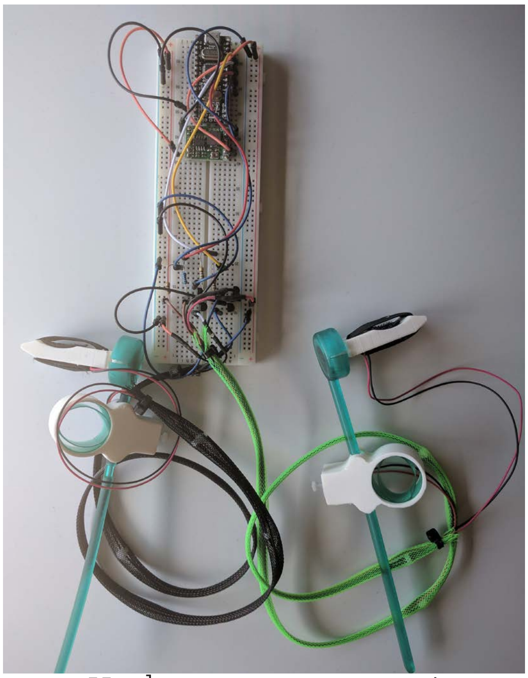


Figure 55: Hardware prototype overview

Figure 56: The prototype in use

Software

The second half of the prototype consists of the VR environment that was created specifically to validate the created prototype. This program was made using the game engine and development platform Unity, using the SteamVR plugin. This is the most used VR development platform with good support for the HTC Vive, meaning there is a good offering of tutorials and guides available online. Manus VR also has an SDK available for Unity that was used to incorporate the Manus gloves into the environment. Initial development was done using the standard Vive controllers, but with this SDK, the gloves could be implemented as well.

The program allows the user to create and adjust cubes, or more specifically hexahedrons, in a blank VR environment on a 3D point grid. The vertices of the shapes will snap to the grid that in turn fades in and out depending on the vicinity of the controllers or gloves. The available interactions are based on the interactions discussed in chapter 3.2. A full list of the functionality can be found in appendix C.

Important to the validation is the ability to perform a user test. This is implemented by having three premade shapes present in the program. The test can be started and stopped using buttons placed in the Unity editor's GUI, upon which the shapes will be shown in turn on a random but constrained location in the VR environment. The user can then be tasked with recreating the shown shape using the methods described above. While the test is started, a shape checking algorithm is executed that compares the premade shape with the user's shape. Upon successful recreation of the shape, the time needed and number of adjustments made are saved to a file on the computer.

The software used for the user test was built over the course of two months and encompasses 1300 lines of code. A detailed overview of the code and how it works is given in appendix D.

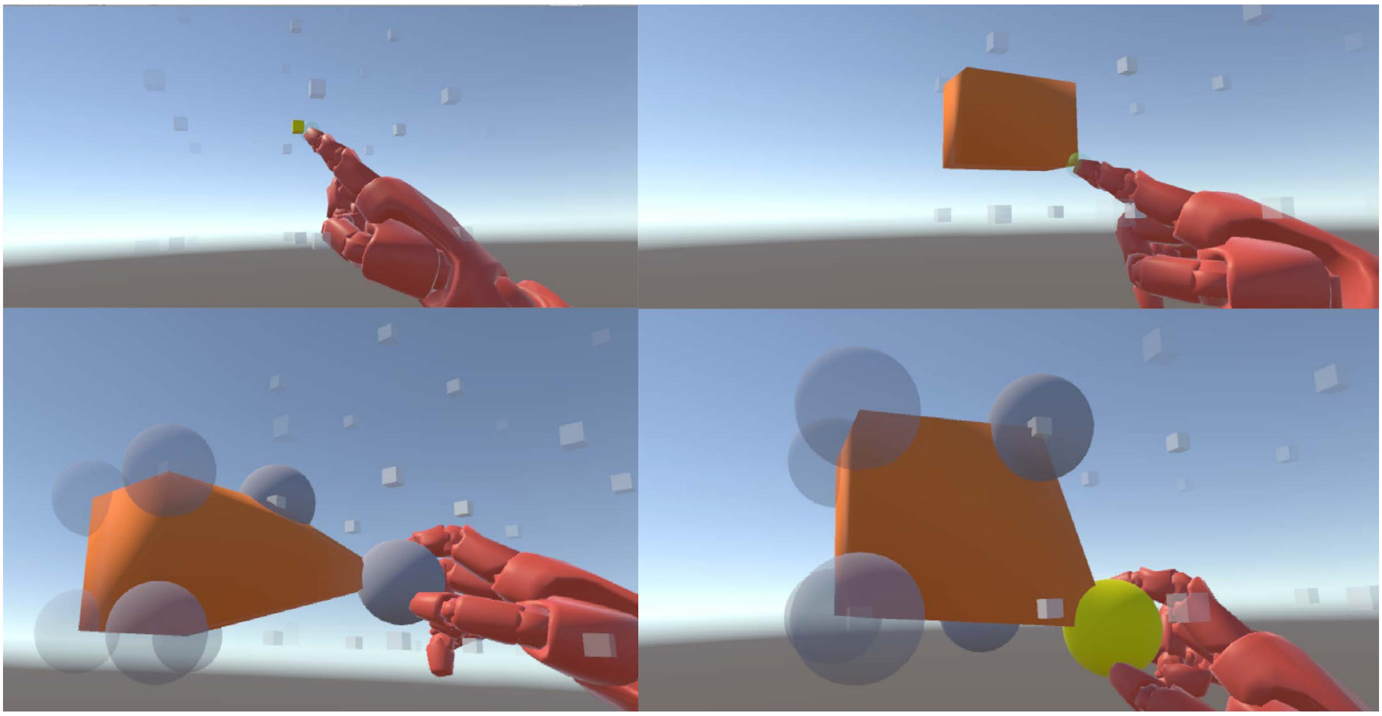


Figure 57: Screenshots from the VR test environment

4.2 THE USER TEST

In this chapter the user test will be described. Starting with the methods used and continuing with the results, the conclusions that can be made from these results, and a discussion about the results and the test in general. The apparatus used for the test is as described in the previous chapter.

Method

The test took place at Manus VR, where the demonstration room was used in which a VR computer and Vive setup is present. Participants were first explained the premise of the project and the main functionality of the design, as well as the functions of the program, and the corresponding controls and gestures. This was followed by the procedure of the test:

First, the participants were asked to familiarise themselves with the VR environment of the test. This was done with just the Manus Gloves, so without the prototype haptic device. They were asked to make shapes and adjust them to their own accord, where feedback was given if certain gestures were not performed correctly for example. When the participant was deemed ready, the test was started.

The first part of the test is performed without the haptic device, using just the Manus Gloves. The participant is presented with a premade shape (Figure 58) using the software's built-in functionality explained in chapter 4.1. It is explained that the goal is to recreate the shown shape by first creating a basic cube, and then adjusting the vertices until the shape matches. In addition to this the timer will start upon the creation of the basic cube, and the number of steps taken will be counted as well. This is done for each of the three premade shapes, while their order of appearance and position slightly varies between tests. After completing this test the haptic device prototype is put in use, after which the participant is free to practice shape creation and adjusting again before the start of the test to familiarise with themselves with the prototype. After this the second test will start, which is identical to the first test but now with the device in place (Figure 59).

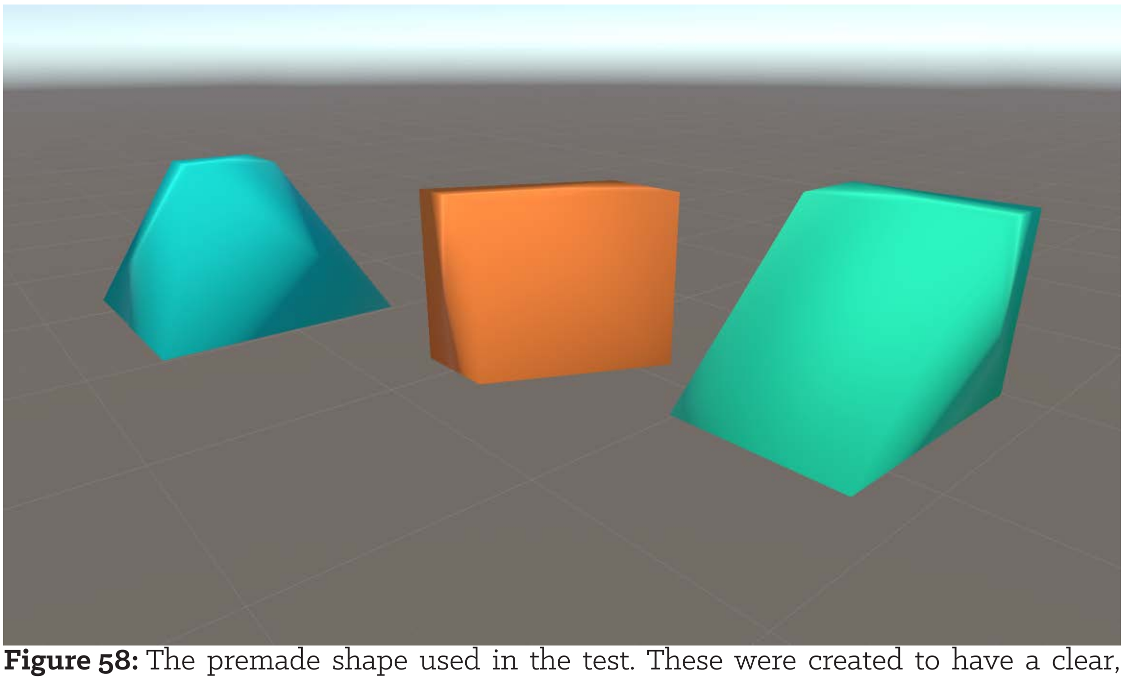


Figure 58: The premade shape used in the test. These were created to have a clear, distinguishable shape, so the participants could focus on the recreation.

Upon completing both tests, the user is asked to fill out a questionnaire. This starts with the general questions:

- How familiar are you with VR devices like the HTC Vive?
- Have you used the Manus VR Gloves before?

This is done to potentially see a difference in performance between people who are familiar with VR and those who are not. The questionnaire then continues with questions regarding the experience of the test, both without and with the prototype. These questions were selected from 'Measuring Presence' by Van Baren and IJsselsteijn (2004), which is a overview of presence measures described in literature. Not all questions are relevant for this research however, so the most applicable were selected, which are:

- I had a sense of acting in the virtual space, rather than operating something from outside (agree-disagree).
- How natural did your interactions with the environment seem?
- How aware were you of your control devices?
- How responsive were the control devices?
- How comfortable were the control devices?
- How well could you manipulate objects in the virtual environment?

By asking these question conclusions can be drawn regarding the immersion, intuitiveness, ease and comfort of the prototype. These questions where presented twice, once for just the gloves, one for the glove and the haptic prototype. A five-point Likert scale was used, with the axes going from strongly disagree to strongly agree, or similar labels. For example the question about responsiveness has labels from very unresponsive to very responsive. The questionnaire was performed using Google Forms, of which the results could be exported the Excel for further analysis.

Figure 59: A participant performing the user test with the prototype in use

4.3 RESULTS

The test was performed by eight people. Unfortunately, only the results from the questionnaire are valid to be evaluated, the reasons for which is shown in the discussion. The results (Figure 60) show that the main differences between the use of just the gloves or the gloves and the prototype is the awareness of the control devices, with a score of 3 and 4 respectively and the comfort, with 4,125 for the gloves and 3 for the prototype.

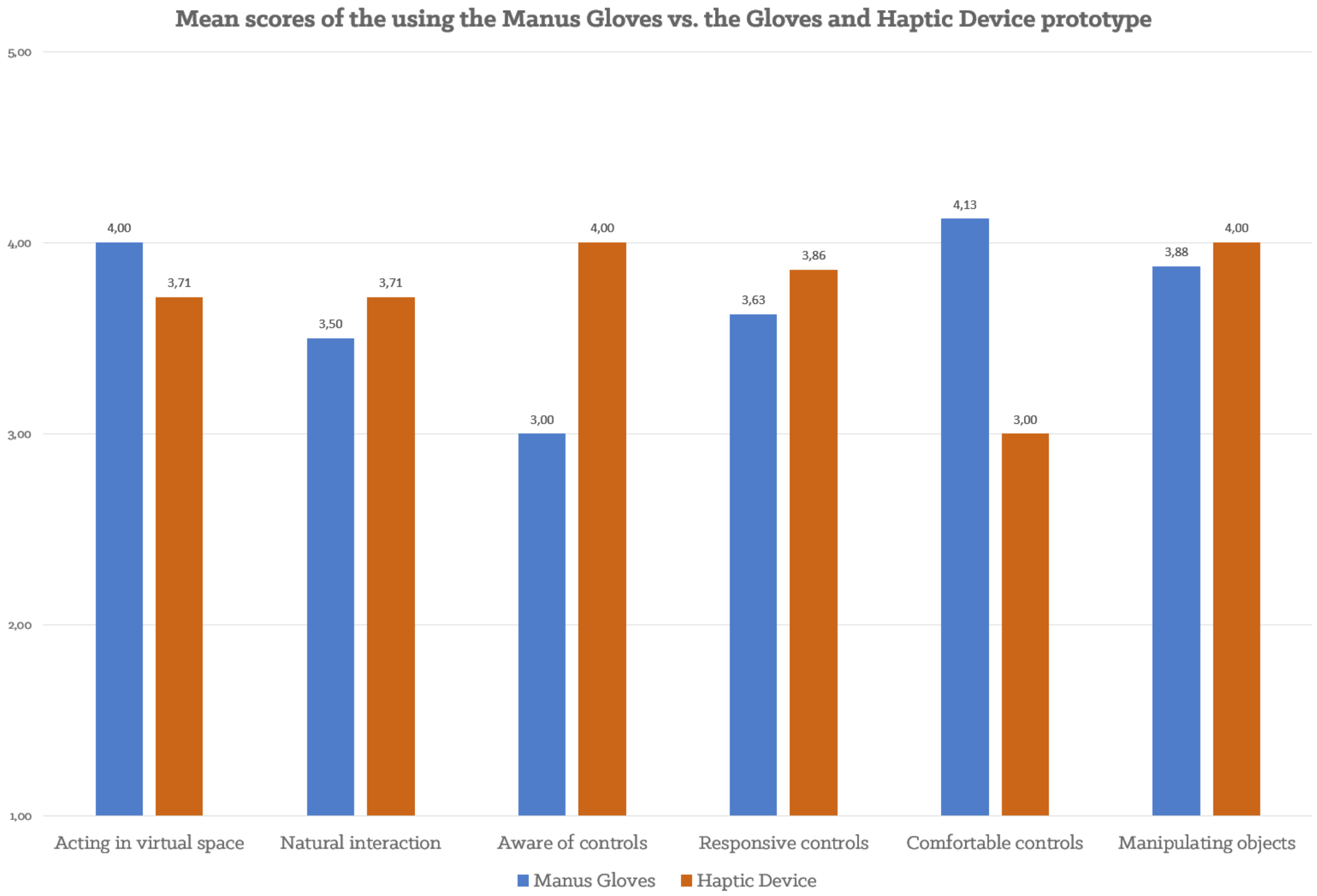


Figure 60: User test questionnaire results

Discussion

As stated earlier, it was not possible to accurately measure the time and steps the participant required to recreate the shapes. This has a number of reasons, which are both hardware and software related. The main issues were with the software. Due to the way the software was designed, namely using a HTC Vive with the controllers, the translation from the gestures made with the gloves to inputs for the program was unreliable. These gestures are programmed similar to the buttons on the controllers, which means that they are expected to be pressed once upon which the correct action happens in the software. The input from the gloves, and the way it is handled by program, is more 'loose' than the binary press of a button. For example, a gesture can be accidentally triggered twice by the user if they are not very aware of the position their fingers are in. This is due to the glove being implemented at the end of development, lack of experience in both Unity and working with the Manus SDK, and the gloves themselves also being unpredictable at times and somewhat lacking in clear documentation on its use.

The combination of these factors means that the software is quite buggy and unreliable in its use when using the gloves and not knowing precisely how the gestures should be made, what to do with both hands at any time and not knowing exactly in which order to perform the gestures. A more experienced software development team who is experienced in Unity and the Manus Gloves should be able to make a more reliable and user friendly VR test environment.

Next to this the hardware prototype also had issues. While the components and Arduino worked well in combination with the software, the rotation along the index finger was not smooth, and the thumb ring did not fit or remain on the thumb for some participants.

The combination of these factors meant that both shape creation and adjustment in the program were too unreliable to perform for the participants, which is why the choice was made not to track the time and steps at this point. If these issues were addressed the user test could be redone and a statement could be made about the speed difference the prototype makes. As it stands, this conclusions of this test will focus on the qualitative aspects of the test, drawn from the questionnaire as well as statement made by the participants. Because the participants did have enough time to familiarise themselves with the use of the program both with and without the prototype, and were given additional information where necessary, it is assumed that they were able to make an adequate assessment of the difference the prototype made.

Conclusion and Recommendations

The main conclusion that can be drawn from the user test is that the design needs to be as comfortable, ergonomical and unnoticeable as possible, as the scores for both awareness and comfort of the device were unfavourable for the prototype. This means the attaching of the product to the hand should be able to be done effortlessly and quickly, and after that stay firmly on the hand. It also means the moving parts should operate very smoothly with almost no friction, so the user will almost not notice the device is attached at all. Only then will the immersion and intuitiveness of the design really add to the overall experience. These steps were already taken when presenting the final design in the embodiment chapter, but as stated earlier the used prototype is based on an older version.

The remaining questions show less difference in the results. The prototype makes the interaction slightly more natural, responsive and easier to manipulate according to the results. This could be explained to the haptic feedback that was added at the fingertips, which made the environment easier to work in according the most participants. Participants also felt a bit less like they were acting in the virtual space while using the prototype (4 vs. 3.71). This could be explained in that the users were actively thinking about and trying the operate the prototype device, rather than letting themselves get immersed. The suggested improvements to the prototype could also alleviate this problem.

Participants were most vocal about the haptic feedback at index fingertip being very useful in working with the point grid system. Users described it as much more intuitive and quicker to work with the grid in this way, as it was easier to determine whether a point was selected correctly. Without the feedback, users often needed more time to find and select and point, and were reliant purely on visual information. Therefore this addition was deemed very useful.

5. CONCLUSION

This report showed the development of a haptic feedback device for VR CAD applications using the Manus VR gloves. Through an analysis of the VR market and VR haptics the search area VR CAD was found and chosen. This was supported by selection criteria which showed that it offered the most opportunities and was the best fit with the project, company and the student. Working from a number of key VR CAD functions, concepts were developed through iterative prototyping. This process resulted in a design that was functional and effective on delivering relevant haptic feedback. A final design was also presented that went beyond the concept and prototypes to show what a final version of the product could look like. A working integrated prototype was developed in both hardware and software which enabled the functionality of the design to be tested and evaluated. This resulted in a number of recommendations for further development. Concludingly, this project has brought forth an innovative addition to the continually developing field of VR haptic feedback. And while the application within this project was purposefully very specific, continued development using elements from the design could lead to a possible solution for one of the main challenges of VR: realistic feedback.

6. REFLECTION

There were a number of aspects I wanted to get out of this project, both to show what I have learned over my time at IDE, and what I still want to work on. First of all I am very happy that I was able to do my project within the field of VR. This was something I wanted to do when first thinking about my graduation project, and looking back it was a very engaging field that matched really well with my personal interests. It was also very interesting to experience a Dutch tech start-up company from the inside, and to see the impact a relatively small team can have on the global market.

I was also able to do the aspects of IDE that I enjoy the most, namely designing itself, and combining it with electronics and software and making prototypes thereof. This project really lend itself well into doing just that. I was able to integrate rapid prototyping in my design process, challenge myself with the electronics of my prototype and improving my soldering skills, and taking on the large challenge of independently building my own VR environment in Unity which in the end required over a thousand lines of C# code.
Furthermore I was able to show the wide variety of skills I acquired during my time at IDE, such as CAD work in SolidWorks and making renderings, and also graphic design in the lay-out of my report, creating diagrams and figures and photoshopping my poster for example. Also being able to design, set-up and perform a user test, and of course the key skills of ideation and conceptualisation. And, more generally, I learned a lot from working independently on a project of this scale and taking the responsibility for the outcome of the project in my own hands.

There are also a number of aspect that could have been executed better. For example, the embodiment chapter is quite short and additional steps could have been taken to come to a more defined design. This also applies to the IDE theory, which I could have used more explicitly. Also, the problems in performing the user test could have been anticipated sooner, but problems with the hardware and software prototype meant that the test needed to be postponed a number of times. While I do not regret making the software prototype since I learned a lot, it did take a large chunk of time in the project which could have been spent otherwise. I also could have sought more cooperation with experts at the TU and Manus to improve my design, as my project was executed very much on my own.

However, in the end I am satisfied with the result I was able to deliver, and I hope this is also the case for the company, the TU Delft and my mentors.

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APPENDIX A: THE COMPANY'S FEEDBACK

To further asses the search areas, they were discussed with the company. This led to new insights and information which is discussed below and based on personal communication with R. van Deventer (January 19, 2017).

Education
Many interesting applications can be thought of using VR in an education environment. In practise however, mainly due to budget constraints, many educational intuitions are hesitant in using VR, according to Manus VR.

Training
This is a very up and coming market, with many business working on training programs in VR and a large number of businesses that are interested. It also has a very wide number of applications for different professions.

Design
The main point of discussion was about VR sculpting. The conclusion was that while very promising and interesting, it would lead to more of a software development projects as opposed to a product design project. Due to the nature of this project and the assignment, that is not the preferred path.

Healthcare
The market for specialised healthcare will be hard to develop a product for, as the requirements are very strict and cooperation will be difficult and slow. More accessible could be the therapeutically and mental healthcare, for example to design for a certain phobia treatment.

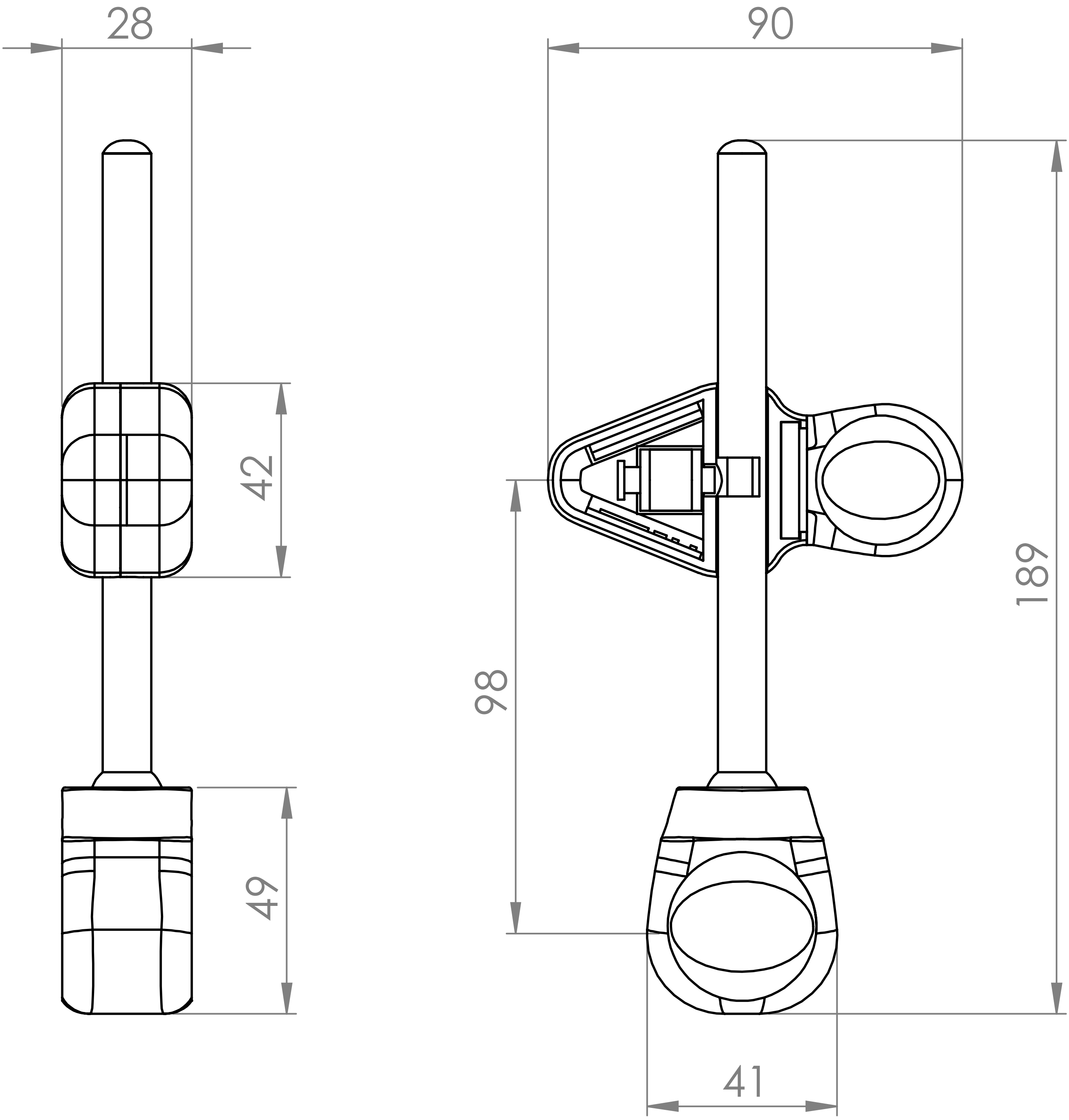
Entertainment
Manus VR thinks consumers VR will remain a small market for at least two more years. Therefore it will not be lucrative to design a product for home VR entertainment. What could be interesting is that arcade halls and amusement parks are looking at VR to offer their customers unique experiences. For this type of application a product could be designed that is very specific, for example especially made for a certain game.

Business
Many businesses are looking at VR to attract customers and visitors at conferences for example, where VR is mainly used for its wow-factor or to differentiate from the competition. Some car dealerships are using VR to let customers experience different configurations of a car before in their showrooms.

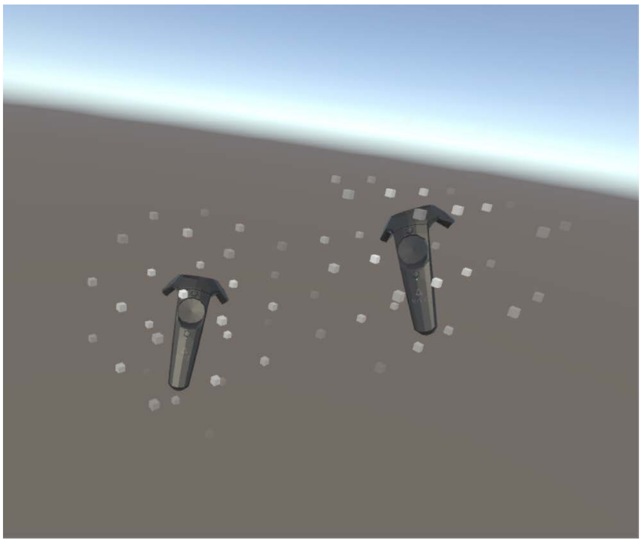
Science
Interesting application could be thought of, but these are generally very specific and probably not very lucrative.

Justice system
Using VR in the justice system is still very new and untested. It is also a difficult market to get into, so it might be difficult to develop something that can actually be sold.

APPENDIX B: MEASUREMENTS



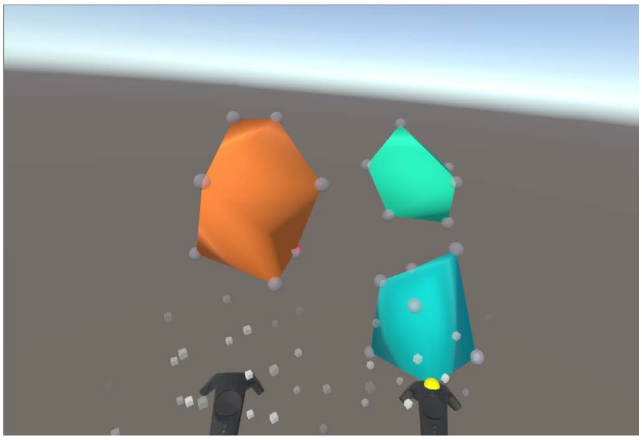
APPENDIX C:
PROTOTYPE SOFTWARE FUNCTIONALITY



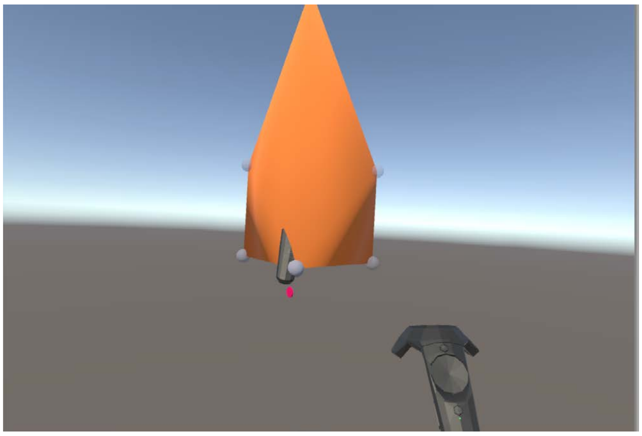
A 3D point grid system. This grid will fade in and out depending on the vicinity of the controllers, meaning the user is not overwhelmed with points, but only the relevant ones are shown.

Drawing a cube from one corner point to the one opposite, using the 3D point grid system. The controllers will snap to the points on the grid when they get close, meaning the user can always make shapes with exact dimensions. The cube is drawn in real-time, meaning the user always has a good sense of the dimension of the shapes they are creating.

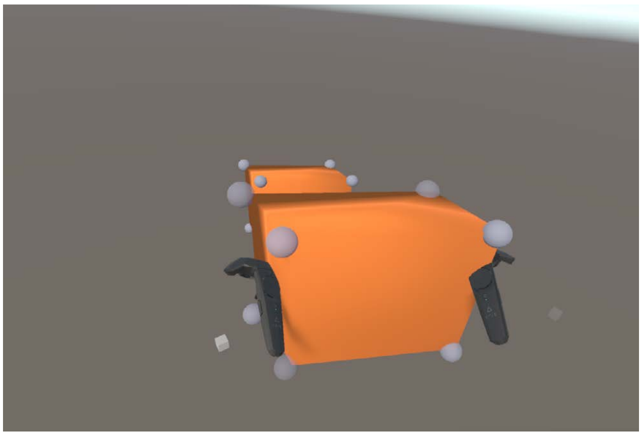
Adjustment of the vertices of the created cube. The user can grab a vertex and move it to another point on the grid, where they can release it, creating a new shape. This also occurs in real-time.



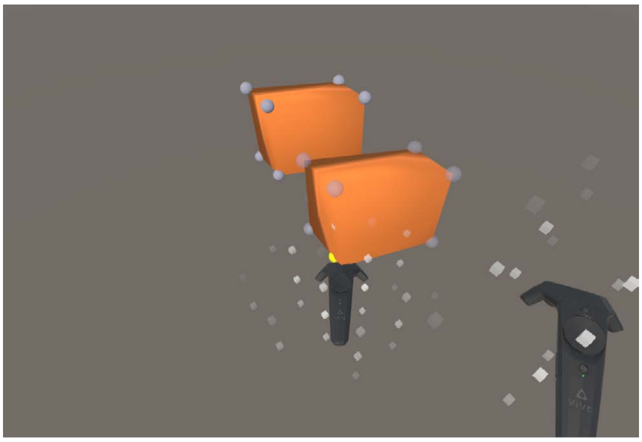
Creation of multiple shapes. The software allows for the creation of multiple shapes in the same session. Each of these shapes can be individually adjusted as well.



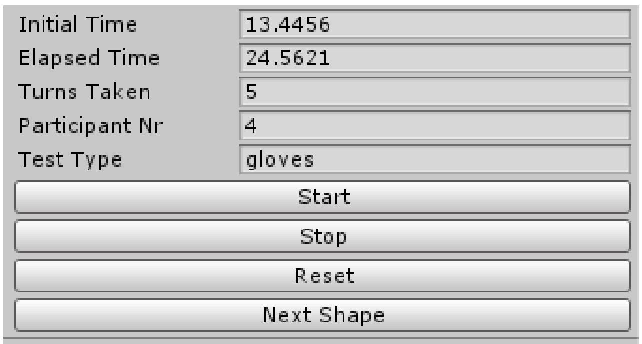
Moving shapes. The shapes can grabbed with one hand and moved to a new location. This feature can be useful to the user as they can move the grid and shapes itself instead of the user moving themselves if they do not want to. While the code is present in the software, the feature is disabled because of irrelevance to the user test and the instability of the feature.



Scaling shapes. The user is able to grab the shapes with two hands, and upon moving their hands apart the shape will scale up. While the code is present in the software, the feature is disabled because of irrelevance to the user test and the instability of the feature.



Shape recreation and verification. In the user test, participants will be asked to (re)create certain shapes in order to test the added value of the product. Working scripts are in place in the current prototype the check whether a created shape matches a premade shape. The time elapsed and number of steps taken in adjusting the shapes or saved to a file on the computer for easier data analysis.

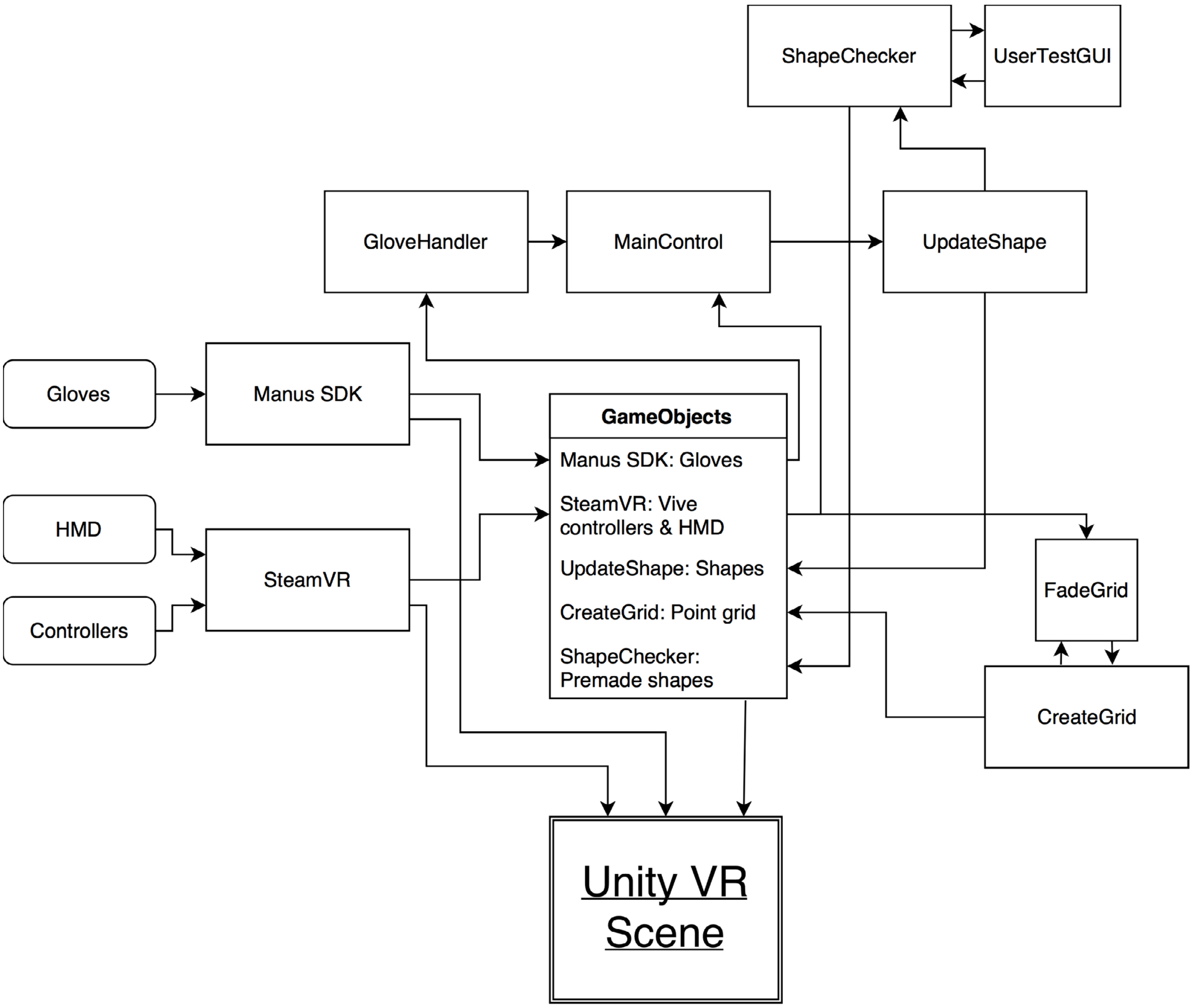



```
void Awake()
{
    if (Instance == null)
    {
        Instance = this;
    }

    try
    {
        stream = new SerialPort(COMport, 9600);
        stream.ReadTimeout = 5;
        stream.Open();
    }
    catch
    {
        print("COM port not available");
    }
}

public void WriteToArduino(string message)
{
    if (stream.IsOpen)
        stream.Write(message);
```

Arduino integration allowing communication with the haptic feedback device. The program allows for commands to be sent to an Arduino in order to trigger the different types haptic feedback of the prototype. For the finger stopping actuation with the use of a solenoid, the Arduino gets a command to engage the solenoid when the controller is near one of the vertices of a created shape. This means that when the user grabs the sphere that is located at this vertex it will feel like they are actually grabbing the sphere. This can also be done for vibration at the fingertip while travelling along the points on the grid.

APPENDIX D: PROTOTYPE SOFTWARE CODE

An overview of the way the software works is schematically, and somewhat simplified, shown below. Unity works based on Gameobjects placed in the virtual world, so all classes interact and manipulate these objects in some way. In term of inputs to the program, shown on the left, there are the Manus gloves that are interpreted by the Manus SDK and the HMD and Vive controllers interpreted by SteamVR. These have their corresponding object in the Gameobjects list, as well a connection with the Unity VR scene directly: for example the position of the HMD controls the camera in the scene. These two SDK's are not specifically made for this prototype, while the remaining classes are.



MainControl and GloveHandler

The class MainControl receives the inputs from the user, both from the Manus gloves as well as the Vive controllers. It can then call on methods in other classes to for example make or adjust shapes in the UpdateShape class.

```
//Shape creation
if (activeHand == "left")
{
    if (snapToGrid & gloveHandler.Instance.IsFistRight())
        if (updateShape.Instance.currentShapeIsFixed)
        {
            CreateShape();
            gloveHandler.Instance.GloveOnHold();
        }
        else
        {
            FinishShape();
            gloveHandler.Instance.GloveOnHold();

        }
}
private void CreateShape()
{
    Debug.Log("Creating Shape");
    updateShape.Instance.addShape();
    tempPosition = snapPoint;
    updateShape.Instance.currentShapeIsFixed = false;
    IsNewShape = true;
}
```

It makes sure that the correct methods are called, depending on the button pressed or gesture the user makes, and the state the program is in as explained in the state flow diagram (Figure 53). For the input from the gloves there is a separate class GloveHandler, that receives the state of each joint on each finger on both hands, and can determine whether certain gestures are made.

```
public bool IsPointingLeft()
{
    //Pinky, ring and middle finger slighty bent, index finger strechted and thumb bent as well
    if (avgBendPinkRingMiddleLeft > 0.2 & avgIndexBendLeft < 0.1 & avgThumbBendLeft > 0.2)
        return true;
    else
        return false;
}
```

UpdateShape

UpdateShape is responsible for the creation and adjustment of shapes, as well a spawning the “adjustment spheres”. It receives position data from MainControl based on where the user wants to make a shape, and draws a cube where the vertices are defined based on the position where the shape was created, and the live position of the controller or glove. This is updated live until the MainControl class give the command to fix the shape.

```
public void createMesh(GameObject shape, Vector3 startPos, Vector3 endPos)
{
    Vector3[] vertices;
    Vector3 v1 = startPos;
    Vector3 v2 = new Vector3(endPos[0], startPos[1], startPos[2]);
    Vector3 v3 = new Vector3(endPos[0], endPos[1], startPos[2]);
    Vector3 v4 = new Vector3(startPos[0], endPos[1], startPos[2]);
    Vector3 v5 = new Vector3(startPos[0], endPos[1], endPos[2]);
    Vector3 v6 = endPos;
    Vector3 v7 = new Vector3(endPos[0], startPos[1], endPos[2]);
    Vector3 v8 = new Vector3(startPos[0], startPos[1], endPos[2]);
    vertices = new Vector3[] { v1, v2, v3, v4, v5, v6, v7, v8 };

    MeshFilter filter = shape.GetComponent<MeshFilter>();
    Mesh mesh = filter.mesh;

    mesh.Clear();
    mesh.vertices = vertices;
    mesh.triangles = triangles;
    mesh.RecalculateNormals();
    mesh.RecalculateBounds();
}
```

CreateGrid

CreateGrid creates the point grid when the program starts. It does this by spawning tiny cubes along the three axes. These cubes are hidden by default but once a controller or glove is near, a trigger will activate and they are added to a list corresponding to that device. The distance between the cubes in the list and the device is then calculated, and the transparency of the cubes is adjusted accordingly, until they are too far away and are removed from the list. These calculation are done in the FadeGrid class.

```
int numCubes = 10;
int delta = 10;
for (int z = -10; z < numCubes; z++)
{
    for (int y = -10; y < numCubes; y++)
    {
        for (int x = -10; x < numCubes; x++)
        {
            var clonePos = new Vector3((float)x / delta, (float)y / delta, (float)z / delta);
            var cubeClone = Instantiate(cube,
                clonePos + emptyObject.position, Quaternion.identity);
            cubeClone.parent = emptyObject;
            cubeList.Add(cubeClone);
        }
    }
}
```

```
var center = leftControllerCenter.transform.position;
foreach (GameObject cube in nearCubesLeft)
{
    var distance = Vector3.Distance(center, cube.transform.position);
    float alpha = 1.0f - distance / 0.2f;
    var material = cube.GetComponent<Renderer>().material;
    var color = material.color;
    material.color = new Color(color.r, color.g, color.b, alpha);
}
```

ShapeChecker

The ShapeChecker class does calculation and gathers data for the user test. UserTestGUI is added so an interface is available while performing the test. ShapeChecker can compare the shapes that are created by the user with the premade shapes that are present in the program. It compares the vertices of the created shape with the premade shape by first making their positions equal. Then each of the vertices are checked whether they are identical. When this is the case, the method will return true. ShapeChecker also gathers data from the user test: it count the elapsed time and number of steps taken per shape. This is written to a file on the computer for easier data analysis.

```
public bool checkShape(GameObject shapeToCheck)
{
    Vector3[] shapeA = shapeToCheck.GetComponent<MeshFilter>().sharedMesh.vertices;
    Vector3[] shapeB = currentShape.GetComponent<MeshFilter>().sharedMesh.vertices;

    if (shapeA.Length != shapeB.Length)
        return false;

    Vector3[] shapeA_0 = new Vector3[shapeA.Length];
    Vector3[] shapeB_0 = new Vector3[shapeB.Length];

    //Makes the positions of the vertices relative to the first vertex for both shapes
    for (int i = 0; i < shapeA.Length; i++)
    {
        shapeA_0[i] = shapeA[i] - shapeA[0];
        shapeB_0[i] = shapeB[i] - shapeB[0];
    }

    for (int i = 0; i < shapeA_0.Length; i++)
    {
        if (shapeA_0[i] == shapeB_0[i])
            continue;
        else
            return false;
    }
    return true;
}
```