Designing a Haptic Palm Strap for the SenseGlove

A Master Thesis by Jasper Henny
Designing a Haptic Palm Strap for the SenseGlove

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Master Thesis by Jasper Henny

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# Glossary

This chapter contains a comprehensive list of all terminology used throughout this report, compiled in a lookup table.

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<th>Terminology</th>
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<tbody>
<tr>
<td>Bimanual (interaction)</td>
<td>(An interaction) Using both hands</td>
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<tr>
<td>Concept (Product)</td>
<td>A design of a product that is developed sufficiently enough to evaluate its intended functionality in comparison to other concepts</td>
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<tr>
<td>Contact feedback</td>
<td>Haptic feedback that requires the component that provides the feedback to be in contact with the skin</td>
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<tr>
<td>Cutaneous</td>
<td>Of/ on the skin</td>
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<td>CV90</td>
<td>An anti infantry vehicle named Combat Vehicle 90</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>The directions and angles any individual joint in the human body can naturally move to</td>
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<tr>
<td>DINED</td>
<td>A database of human measurements, moderated by the Delft University of Technology</td>
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<tr>
<td>Force feedback</td>
<td>Haptic feedback in the form of a force exerted on the user</td>
</tr>
<tr>
<td>Haptic(s) (feedback)</td>
<td>The sensations one can feel through their sense of touch, and its related field of science</td>
</tr>
<tr>
<td>Haptic Interface/ Glove</td>
<td>An electronic device that communicated with its wearer through Haptic feedback</td>
</tr>
<tr>
<td>Harris Profile</td>
<td>A design tool used to choose between branching paths in the design process (usually product concepts or sub-solutions)</td>
</tr>
<tr>
<td>Interaction Prototyping</td>
<td>A design tool used to test and evaluate interactions with a theoretical object (that has yet to be designed)</td>
</tr>
<tr>
<td>Lab Study</td>
<td>A study with a virtual and physical setup,</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
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<tr>
<td>Linear Resonant Actuator</td>
<td>A vibration motor that provides vibrations by oscillating a tiny mass through a voice coil</td>
</tr>
<tr>
<td>LRA</td>
<td>Abbreviation of Linear Resonant Actuator</td>
</tr>
<tr>
<td>Morphological Chart</td>
<td>A design tool used to combine sub-solutions and component ideas into full concept</td>
</tr>
<tr>
<td>PCB</td>
<td>Abbreviation of Printed Circuit Board</td>
</tr>
<tr>
<td>Phalange</td>
<td>A finger digit</td>
</tr>
<tr>
<td>Physical Reality</td>
<td>The physical world as experienced through a human’s innate senses</td>
</tr>
<tr>
<td>Printed circuit board</td>
<td>A combination of connected electronic components using conductive tracks etched on a sheet of copper laminated on a non-conductive plate</td>
</tr>
<tr>
<td>Scopus</td>
<td>The largest database of peer-reviewed scientific research papers, curated by Elsevier</td>
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<tr>
<td>Steering Mechanism</td>
<td>An umbrella term for mechanisms used to control the path of a vehicle, including joysticks and steering wheels</td>
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<tr>
<td>Synchronised</td>
<td>In unison</td>
</tr>
<tr>
<td>Tactile</td>
<td>Related to the sense of touch</td>
</tr>
<tr>
<td>Tactile feedback</td>
<td>Haptic feedback on the skin</td>
</tr>
<tr>
<td>Vibrational feedback</td>
<td>Haptic feedback in the form of localised vibrations on the skin</td>
</tr>
<tr>
<td>Virtual Reality</td>
<td>An entirely artificial experience in a fully computer generated environment</td>
</tr>
</tbody>
</table>
Executive Summary

This document details a lab study into bimanual synchronised haptics, followed by the design of a product that can be used in combination with the SenseGlove to provide their wearer with haptic feedback based on how they operate a steering mechanism in Virtual Reality.

The Dutch Ministry of Defense approached SenseGlove B.V., a company specialised in haptic gloves, to develop a Proof of Principle of the potential of haptic gloves in combination with Virtual Reality as a replacement for their high fidelity combat vehicle simulators. This project was split into two parts, a kinematic arm that can block the user’s motions so a person can no longer move their physical hands through digital objects, and a tactile palm strap that provides haptic feedback to the palm of the user to convey the motion of a digital steering mechanism. The kinematic arm was designed internally, and the tactile palm strap was taken as the focus of this graduation project.

An explorative Literature Study was conducted to find the ideal locations for haptic feedback on the human palm, as well as their corresponding types. These feedback locations and types were evaluated using a method called Interaction Prototyping. Based on the results of this study, a Lab Study was set up to evaluate three types of haptic feedback on the palm of the user. For this Study, a prototype haptic interface was made that could provide all three types of haptic feedback.

The outcome of the Lab Study was inconclusive because of a low sample size and many confounding factors. While the results were unsuitable to base a feedback choice on, the confounding factors resulted in valuable Design Challenges. The choice to go for vibrotactile feedback was made based on other factors such as cost, ease of production and company preference. The design challenges formed the basis for the Ideation Phase.

Product Ideas were generated using various creative techniques, and a Morphological Chart was made to condense the ideas into three Product Concepts. One Concept inspired by competitive gloves, one Concept inspired by damping materials, and one Concept inspired by the fingers of the user. Through the aid of a Harris Profile, the choice was made to further embody the concept inspired by the fingers of the user: The Finger Folds.

The Finger Folds form a modular addition to the SenseGlove that can easily be connected and disconnected from the company’s flagship product. It consists of four modules that each provide haptic feedback to the ideal region on the palm of the user independently of one another. Each module is connected to a finger, which automatically aligns the product and keeps the haptic feedback consistent during use, no matter how extreme holds their fingers or folds their hand. Signal consistency is maintained through constant skin contact. The modules can easily be attached to or detached from a Hub that is located between the SenseGlove and the back of the user’s hand. This Hub handles the information communication between the SenseGlove, Virtual Reality and each of the modules.
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A Lab Study into Bimanual Synchronised Haptics
Foreword

This document would not have existed without the aid of a vast amount of people, in amount both large and small. This work not only builds on a large collection of research papers, but also on the shoulders of participants in lab studies and interactions with prototypes.

The project initially started in September 2018 as a proof of concept from SenseGlove B.V. to the Dutch Ministry of Defense. During the project, the focus shifted to an internal project for SenseGlove B.V. itself.

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...and everyone at SenseGlove B.V.
Haptics and VR

This chapter introduces Virtual Reality, the role of haptic feedback and its potential applications. It then introduces a company, named SenseGlove B.V., and describes its vision on haptics. Next, their client is introduced, followed by a problem definition. The chapter concludes with an explanation of the approach used for research into Synchronised Haptics and the subsequent design of a product that allows for Bimanual Synchronised Haptic feedback based on the user’s actions in Virtual Reality.
What is Virtual Reality?

Introduction

Virtual Reality (VR) is an experience within a fully immersive, three dimensional environment that is entirely computer-generated and software defined. When a person wears specialised electronic equipment, such as a Virtual Reality Headset, they perceive a completely different reality that is separated from physical reality through visual and audio feedback.

Applications

Virtual Reality is widely regarded as a promising technology, and has many potential applications. Some of those applications include gaming, product design, architecture, city planning, research into human psychology and PTSD, and training for situations that pose a high risk for the people involved, such as warzones, outer space or complicated surgeries.

Figure 1: Artist Impression of someone using Virtual Reality as an organizational tool (https://arpost.co/2017/11/27/business-virtual-augmented-reality-apps/, 2017)
Control
While Virtual Reality can be seen and heard through a dedicated headset, interacting with a digital environment in an immersive manner is still a challenge. Companies like HTC, Oculus and Valve developed their own multipurpose controllers that can be used to interact with virtual reality in much the same way a remote controller can be used to interact with a television. Examples of such controllers include the HTC Vive controller, Oculus Touch and SteamVR Knuckles.

Haptics
Other companies dive deeper into human-computer interfaces by allowing people to ‘touch’ Virtual Reality with their products. The user can’t physically touch Virtual Reality, but the ‘illusion of touch’ can be created through haptic feedback. Example products include the SenseGlove, VRGLv, HaptX Glove, Dexmo, Hi5 VR Glove, Tactical Haptics’ Reactive Grip Motion Controller and Elitac’s Tactile Feedback Glove. Products like these are collectively called ‘haptic interfaces’.

*Figure 2: Haptic Interfaces, going clockwise from the top: Sense Glove, VRGLv, Manus, Teslasuit, Dexmo and HaptX*
What is Haptic Feedback?

Introduction
If visual feedback is what you see with your eyes and audio feedback is what you hear with your ears, haptic feedback is what you feel through your sense of touch. Its corresponding field of science is called 'haptics', and is about perceiving and manipulating objects through your sense of touch and proprioception. A common example of haptic feedback is the vibrational feedback that a smartphone uses to notify their user. ("haptic | Definition of haptic in English by Oxford Dictionaries", 2019).

The Illusion
Virtual Reality inherently lacks the feeling of touch. While the body transfer illusion can be used to give people a sense of presence in Virtual Reality, there is no corresponding illusion that can be used to provide people with a sense of touch. In the context of this report, haptic feedback is created by a separate electronic device called a haptic interface. These products reverse the roles, and touch the user where and when the user would expect to touch a virtual object. This way, the user can be 'tricked' into thinking they are touching objects that are part of a digital environment.

Figure 3: Artist Impression of someone handling a virtual drill with a haptic glove
SenseGlove B.V. (2019)
Feedback Categories

Haptic feedback can be divided into contact feedback, and non-contact feedback. Contact feedback is applied directly to the user’s skin. This category is divided into force feedback and vibrational feedback. Force feedback can be of the tactile variety (brushing, stretching or displacing skin) or of the kinesthetic variety (in which parts of the user’s body are pushed, pulled or locked in place. A different, harder to classify type of haptic feedback is electrical stimulation that directly actuates the user’s own muscles through the user’s skin. The Teslasuit is an example of a product that provides haptic feedback in such a way. ("Teslasuit - full body haptic suit", 2019).

Non-contact haptic feedback is experimented with by companies such as Ultrahaptics, which are using localised ultrasound or air vortices to create invisible shapes for the user to feel. These shapes can give tactile cues about the shape, size and texture of virtual objects, but it can not provide force feedback to restrict the user’s motions. ("Ultrahaptics - Discover a new type of haptics", 2019).

![Haptic Feedback Categories](image)

**Figure 4: Haptic Feedback Categories**

Applications

At the moment, haptic feedback can only be used to convey rough shapes and motions, but as technologies advance and designs develop, so too do the applications of haptic feedback. In combination with Virtual Reality, haptic feedback can be used to improve the realism of training simulators for assembly lines, surgeries and combat vehicles. It can aid designers by allowing them to touch their CAD models, and is already used for research into human psychology.
An introduction to SenseGlove B.V.

Introduction
SenseGlove B.V. is a startup company co-founded by Gijs den Butter and Johannes Luijten. The company believes that Virtual Reality will change the way people interface with the digital world. Their goal is to make the digital world feel real. To achieve that, they want to provide their clients with a sense of touch in Virtual Reality. According to the company, this sense of touch does not need to be perfectly realistic, but it does need to be sufficiently immersive. (“SenseGlove B.V.“, 2019).

Making the Digital feel Real
The flagship product of this company is the SenseGlove: a haptic interface that is worn like an exoskeleton around the hand. The business model of SenseGlove B.V. revolves around selling this glove as a training aid for specific scenarios, like assembly line training or learning how to operate a combat vehicle. To prevent having to develop a specialised virtual scenario for every client, the company is integrating as many possible haptic interactions into the SenseGlove as possible. These interactions can then be used in all scenarios.

The product
The SenseGlove has 24 Degrees of Freedom and tracks the wearer’s fingers, hand and wrist in 3D space so their hand in VR acts identical to their hand in physical reality. The SenseGlove provides the wearer with two kinds of haptic feedback. Passive force feedback is provided to the wearer’s fingers to create the sensation of grasping soft or solid objects through custom brakes built into the knuckles of the device. Their patent-pending brakes allow the wearer to touch objects with variable stiffness, such as stress balls or eggs. Tactile vibrational feedback is provided to each of the wearer’s fingers through buzz motors, to cue the wearer, create illusory textures for the wearer to touch, and to create the illusion of vibrations in digital objects such as handheld drills. (“SenseGlove B.V.“, 2019).

*Figure 5: SenseGlove B.V.’s flagship product: The SenseGlove.*
SenseGlove B.V. (2019)
An introduction to the Ministry of Defense

The problem

The Research & Development Office of the Dutch Ministry of Defense is constantly looking into potential applications for Virtual Reality. One such application is to replace their current high fidelity combat vehicle simulators with Virtual Reality in combination with a workstation consisting of haptic interfaces connected to VR. Their current training simulators are expensive and need to be exact replicas of the vehicles they are working with. If the ministry updates their vehicles they also need to replace the corresponding simulators.

The solution

Switching from physical to virtual simulators could cut costs significantly for the Ministry of Defense. A virtual reality setup with corresponding haptic gear is much less expensive than a high fidelity simulator in terms of acquisition, and if the simulation needs to be replaced or updated, this can be done much more easily by replacing just the virtual environment instead of the entire physical installation. It is also much easier on maintaining the equipment, and a single physical setup can be used for multiple varieties of combat vehicles. The main issue with replacing the high fidelity simulators with Virtual Reality, is that haptic interfaces are currently not yet at a level where the required simulations can be made sufficiently realistic for the people that need to train with those simulators.

Proof of Principle

This is why Captain van Dort of the R&D Office of the Dutch Ministry of Defense contacted SenseGlove B.V. with a design brief. The Ministry would like to see a proof of principle from the company in the form of a new haptic interface that can convey the virtual interior of a physical combat vehicle in a sufficiently immersive manner. For the purposes of this project, the Ministry has provided a 3D model of Combat Vehicle 90 (CV90) as the digital environment the haptic interface needs to emulate. This is because the CV90 simulators at the Ministry’s TACTIS simulation center are slated for replacement.

Figure 6: CV90 exterior.
Working in the CV90 Interior

Introduction
In order to convey the virtual interior of a physical CV90, it first needs to be analysed. The interior of the CV90 is a complex multi-dimensional interior featuring many possible interactions for the user, including buttons, levers and a steering mechanism. The interior is cramped and does not allow for much freedom in the movements of the user.

Context
For this project, the gunner position within the CV90 was provided as the area to develop the proof of principle for. It features, among others, a scope for the gunner to look through, a steering mechanism to aim the main gun with, and a dashboard with various screens and buttons. In consultation with Captain van Dort, it has been decided that entering and leaving the gunner’s position, as well as the gunner strapping themself into the CV90’s seat belt, are outside the scope of this project. These are the least important parts of the training.

The purpose of the simulator is to train the gunner in operating the gun and its corresponding dashboard. Therefore, interacting with the steering mechanism and the dashboard are the main parts of the interior that the proof of principle should be able to emulate. For the proof of principle, the anthropometric data of the designer should be used for the design of prototypes, instead of that of a gunner.

Figure 7: The gunner position in the interior of the CV90
Approaching the Challenge

Converting the entire gunner’s position to VR in terms of both kinesthetic and tactile haptic feedback is too big of an assignment for a single thesis. This is why the project must be scoped down.

Direction

There are two potential design directions for this project. One direction is the kinematic side of the project, where a kinesthetic end-effector is developed that blocks the motions of the user if they attempt to move through digital objects in VR, like the dashboard of the CV90. The other direction is the tactile side of the project, where the focus lies on developing a haptic interface that can teach the gunner proper, synchronised, steering behaviour without relying on a physical steering wheel.

From a research point of view, the bimanual synchronised haptic feedback required to make a steering mechanism feel immersive, is far more interesting than the end-effector. Bimanual interaction with VR, especially in combination with haptics, is a very recent field of science. As a result, very little research has been conducted on the subject so far. This direction for the project could lead to interesting results that can be used by SenseGlove B.V. for the development of future products. The kinematic arm on the other hand, can more easily be realised by the company itself, using established kinematics and components that are very similar to the ones used in the current design of the SenseGlove.

In consultation with SenseGlove B.V. the decision was made that the company would design the kinesthetic end-effector for the proof of principle internally, and that the design of a haptic interface for the tactile feedback regarding the steering mechanism would be the main focus of this thesis.

Assignment

The assignment has been defined as follows:

“Design a haptic interface that complements the SenseGlove and provides the wearer’s palms with a sufficiently immersive physical handling experience of a virtual steering mechanism through haptic feedback”
Scope

To narrow the scope of the project down even further, the design of the haptic interface mentioned in the assignment will focus only on making the rotation of the virtual steering mechanism feel as immersive as possible. Pivoting the steering mechanism is outside the scope of this project in terms of prototyping, but will be taken into account in terms of the design of the haptic interface itself. The haptic interface should cooperate with the SenseGlove and the kinematic end-effector that is in development for the Ministry of Defense as well. This kinematic end-effector will be named the SenseArm from this point forward.

The setup for the envisioned combined Proof of Principle for the Ministry of Defense is as follows:

In physical reality, there is a pair of SenseGloves, a pair of SenseArms, and a pair of new haptic interfaces that convey the motion of the steering mechanism to the palms of the user. Additional equipment includes a chair for the user to sit on, and a full VR setup featuring a headset, trackers and a lighthouse system to track the trackers in 3D space, as well as the cables and converters necessary to power the SenseGloves, SenseArms and additional haptic interfaces.

In virtual reality, there is a 3D model of the CV90 interior, two 3D models of the user’s hands, and a fully interactive steering mechanism.

![Figure 8: An anonymous gunner rotating the steering mechanism in the CV90 interior](image)

Approach

The approach used for this project is a modification of the Basic Design Cycle, as explained in “Product Ontwerpen: Structuur en Methoden” by Roozenburg and Eekels, with a larger focus on Analysis, Simulation and Evaluation. A schematic overview of this process can be seen in Figure 7, below.

To design a product that provides bimanual haptic feedback to improve a user’s accuracy in handling a virtual steering mechanism the most suited type of haptic feedback, and its corresponding location on the palm, need to be identified first.
Analysis
A preliminary research is executed to find the most suitable types of haptic feedback and their corresponding locations on the human palm through Literature Research on Human Anatomy, Haptics and the State of the Art. The feedback locations from this preliminary research are tested and validated through Interaction Prototyping.

Simulation
Based on this preliminary research, a haptic interface is designed and constructed through iterative prototyping. This prototype provides the feedback from the preliminary research at the corresponding locations on the human palm. This feedback is then tested in a lab study to analyse which of the proposed feedback types and locations have the largest positive influence on the performance and experience of the participants.

Decision
The results from the lab study are used to create a set of Recommendations, a corresponding set of Design Challenges and a Program of Requirements for the design of a haptic interface that complements the SenseGlove, and can provide the wearer with bimanual haptic feedback based on the user’s actions.

Synthesis
The Recommendations are used to identify the main design challenges that need to be tackled to design a haptic interface that complements the SenseGlove and provides bimanual haptic feedback to the palms of the wearer. The results from the lab study are used to decide on a type of haptic feedback. The design challenges are solved through Ideation for this type of haptic feedback, and the solutions are combined into three concept Palm Straps.

A choice is made between these concepts for further development. The final result is the design of a matching pair of haptic Palm Straps integrated into the SenseGlove that provide haptic feedback to the palm to convey the motion of a virtual steering mechanism.

Evaluation
Finally, the design of the Palm Straps and the project as a whole are evaluated.

Figure 9: Approach
An Explorative Study on Synchronised Haptics

This chapter starts with an explanation of what bimanual haptics entails and why it is important for interactions with Virtual Reality. It then details findings from multiple explorative studies on the most common locations for haptic feedback on the human palm, with its corresponding types of haptic feedback. These studies are based on research papers on haptics, SenseGlove B.V.’s competitors, Interaction Prototyping and human anatomy. Finally, this chapter details potential design conflicts between the Palm Strap and the SenseGlove itself, and provides a preliminary Program of Requirements for the final design of the Palm Strap to adhere to.
What is synchronised haptics?

“When interacting with virtual objects through haptic devices, most of the time only one hand is involved. However, the increase of computational power, along with the decrease of device costs, allow more and more the use of dual haptic devices.”
- Anthony Talvas

Setup

Bimanual haptics is a new field of science and has not yet been commonly studied. In order to get a better understanding of bimanual haptic feedback based on bimanual interactions with digital objects in Virtual Reality, a small literature study was conducted with the aid of Scopus. Two papers in particular contain interesting findings in this field:


Findings

Bimanual haptics is about the interaction between a virtual environment and a person using both of their hands to manipulate that environment. This type of interaction is different from one-handed interactions (or unimanual interactions) with Virtual Reality, both in terms of the cognition and anatomy of the user, as well as in terms of haptic feedback and the digital environment in VR. (Talvas, Marchal & Lecuyer, 2014).

Bimanual haptics is not simply unimanual haptics with a copy or mirror of the haptic feedback on the second hand. There is always a dominant hand, and a non-dominant hand. Bimanual tasks are things that people do commonly in real life, even for actions that were thought to be unimanual. For example, while writing a signature on a sheet of paper, one hand is used to control the pen, while the other is used to keep the paper in place. There are also tasks that cannot be performed unimanually, like opening a jar or using a bow and arrow. (Talvas, Marchal & Lecuyer, 2014).

According to various studies, the bimanual perception of symmetric shapes, and bimanual perception of stiffness is more precise than unimanual perception. Bimanuality features additional benefits such as increased accuracy and faster completion of tasks. Brain studies suggest that neural pathways exist specifically for the coordination of both hands during bimanual tasks. Several studies also showed that it is easier to follow the relative position between the hands rather than their individual position relative to a 3D space. (Talvas, Marchal & Lecuyer, 2014) (Gil, Ciáurriz & Díaz, 2018).

In terms of VR, digital objects that can be handled with two virtual hands in a realistic or immersive manner have proven to be difficult to implement. In practice, while objects can be felt in both hands through haptic feedback, so far they can only be interacted with by one hand at a time. This can create situations where one hand moves an object away from the other hand, but the user keeps perceiving the object with both hands because of haptic feedback. This is a challenge that SenseGlove B.V. is working on internally.
Conclusions

Bimanual activities are an intrinsic part of physical reality and can add a new layer of immersion to interactions with digital objects in Virtual Reality. To make these interactions feel immersive, haptic feedback is required on both hands. This haptic feedback does not need to be symmetrical, but it does need to be synchronised.

Synchronised haptics, in this context, is bimanual haptics where the user receives reactive haptic feedback on either hand based on the actions of the other hand, with minimal latency. For synchronised haptics, clear correlation between the haptic feedback on both hands is necessary.

Operating a steering mechanism is a bimanual task. In order to accurately teach this task to aspiring gunners in the CV90 interior in VR, the user needs to feel the steering mechanism rotate in their hands. Studies suggest that the brain has neural pathways specifically for bimanual interaction with objects and that the user’s spatial awareness off their hands relative to each other is heightened compared to one hand relative to a 3D space. Therefore, it is necessary to teach the gunner the proper posture and motion in regards to the movement of their hands, as it could prove difficult to adjust erroneous steering behaviour once it has been learned.

SenseGlove B.V. is developing digital objects that can be manipulated by two hands simultaneously in VR. Unfortunately, these objects are not yet operational. As a result, for the Lab Study on synchronised haptics, featured in the next chapter, a digital model of the CV90’s steering mechanism had to be used that can only be operated by the participant’s dominant hand. The participants were not told about this, and they were asked to treat the virtual steering mechanism as a real steering mechanism and steer with both hands.

Taxonomy

To understand bimanual haptics in the context of steering mechanisms, an understanding of grasping and prehension is required. The hand, and in particular its fingers, is a versatile tool that can manipulate objects (and other tools) in a large variety of ways.

Grasping Taxonomy

The current design of the SenseGlove provides haptic feedback only to the fingertips of the wearer. This design choice was made because of the many mechanoreceptors that the skin on the fingertips contain. These mechanoreceptors are what allow the skin to sense haptics. A more detailed study of the mechanoreceptors in the hand can be found in the Anatomy Section of this chapter, starting on page 22.
To facilitate grasping objects in VR, the SenseGlove team has added colliders with collision detection to just the fingertips. The palm currently plays no role in grasping digital objects. This decision makes collision detection and grasping recognition easier in Virtual Reality, but creates an issue in the physical world.

The exclusive focus on the fingertips leads to a scenario commonly observed by the SenseGlove team where the wearer of a Senseglove attempts to grasp objects with their fingertips alone, and succeeds where they would drop the object in real life. This type of grasping, called precision grasping, is suited to objects such as pencils or tiny stress balls, but not for objects such as water bottles, hammers or steering mechanisms. The latter type of prehension requires a power grasp. (MacKenzie & Iberall, 1994)

Figure 10 below shows the various classifications for prehension that were identified by Cutkosky and Howe. While wearing a SenseGlove, the users commonly attempt prismatic or circular precision grasps, while a steering mechanism should require a prehensile prismatic power grasp. Based on observations of a gunner aiming with a steering mechanism in the CV90 interior, a medium wrap should be the default resting position for the hand, while the adducted thumb grab should be used to press the buttons on the steering mechanism to fire the main guns.

![Grasping Classifications](image)

**Figure 10: Grasping Classifications by Cutkosky and Howe**

(MacKenzie & Iberall, 1994)
Anatomy

Setup
The Proof of Principle that the Ministry of Defense commissioned, the haptic Palm Strap for the SenseGlove, is a tool for teaching its wearer certain behaviour through tactile feedback on the palm. This means that interacting with the anatomy of the user’s skin, and how the skin perceives motion, are important aspects of the design. A preliminary literature study was conducted using SCOPUS, with the goal of learning about how the human skin senses haptic feedback and which locations are best used to perceive it. This literature research also looked into the effects of teaching people physical behaviour through haptic feedback.

Findings
While some research has been done on how the human skin perceives tactile haptic feedback, the amount of research papers on portraying motion through tactile haptic feedback is very slim. As a result, little information was found on the subject. However, there are areas of the palm that are better at perceiving certain shapes than others. The human skin uses four kinds of mechanoreceptors to perceive haptic feedback. These receptors, their locations and what they perceive can be seen in Figure 18, below. (MIHELJ, 2016).

Figure 11: Functional properties of skin mechanoreceptors (MIHELJ, 2016, p.169)
Rotating a steering mechanism should provide directional tactile feedback. If this directional feedback needs to convey a certain velocity, it becomes increasingly difficult to sense the shorter the window for tactile feedback becomes. Ogrinc, Farkhatdinov, Walker & Burdet, (2018) have researched this phenomenon and have come to the conclusion that coupling the directional tactile feedback with vibration magnitude allowed their participants to more easily distinguish between tactile patterns on the wrist in terms of direction and speed.

In rehabilitation and haptics, there is a distinction between guiding the user’s physical motions and cueing the user’s physical motions. Guiding is done by moving the limbs of the user for them, which is often used to build up muscles during various kinds rehabilitation. Cueing is done by providing haptic feedback to the user’s limbs to entice the user to move their limbs on their own. While haptic cueings seems to have no downsides, excessive use of haptic guiding, in case of advanced driver-assistance systems, can impede the development of driving skills (Wada, 2018).

Conclusions

As can be seen in the Figure 11 above, the human fingertips are suited for identifying both small, large, sharp and smooth edges. This makes them ideal for feeling the shape of the steering mechanism, and matches the findings from the Interaction Prototyping study. This functionality is already included in the SenseGlove itself, and according to SenseGlove B.V. is sufficient tactile feedback to convey shapes and sizes. Therefore, the Palm Strap should only focus on providing haptic feedback about the motion of digital objects, not about holding on to a digital object.

The pacinian corpuscles can sense slip, vibration and acceleration, but are stretched out across the length of the palm instead of the width, and as such are less useful for conveying motion from the top to the bottom of the palm and vice versa. The ruffini corpuscles sense skin stretch, but along the length of the palm as well. Adding directional haptic feedback cross the palm in these areas would therefore add little to the design of the Palm Strap.

Meissner’s corpuscles can sense slip and tremors, and the merkel’s discs can sense local shape and pressure. The slip has a fast adaptation, but the shape has a low adaptation speed. This means that the areas of the hand where these mechanoreceptors overlap are well suited to a brushing type of haptic feedback that does not have an immediately obvious shape. The area of the palm next to the base of the fingers would be a good location for this feedback and matches the findings found in the Interaction Prototyping study/

The other area where these mechanoreceptors overlap, the base of the thumb, is less suited as a feedback location because it can fold over the center of the palm, leaving very little room for a feedback mechanism of any kind. Whether brushing cutaneous feedback or vibrational cutaneous feedback is superior as directional haptic feedback should be investigated in the Lab Study on Synchronised Haptics in the next chapter.

To teach proper steering motions to aspiring gunners in the Dutch Ministry of Defense, haptic cueing should be used instead of haptic guiding.
Feedback locations and types

Introduction

Haptic feedback can be used to create the feeling of motion on the human palm in various ways. Examples include stretching or displacing the user’s skin, or brushing over it with a deformable material. Another option is to expose the skin to a series of sequenced impulses that fire from one side of the palm to the other. These impulses can either be brief increases in localised pressure on the skin, or short vibrations.

In order to determine which of these types of haptic feedback are most suitable for conveying motion, and what their corresponding locations should be on the human palm, four studies were executed. Literature Research and an analysis of the State of the Art were used to find the rough feedback locations. Then, the SenseGlove itself was analysed to find conflicting areas with the SG geometry. Finally, these locations were evaluated using Interaction prototyping.

Research Papers

Setup

Scopus was used to search for research papers on the subject of synchronised and bimanual haptics, using the keywords listed in Appendix A: Keywords. From these papers, the ones that document feedback locations on the palm and the types of feedback provided are skinned and the relevant parts of their setup, findings and conclusions are documented.

Findings

Approximately 30 relevant papers were found on Scopus about haptic feedback to the hand. None of these papers mention attempts at simulating motion or the direction of motion on the user’s palm, but there are three research papers that describe the location and type of haptic feedback they provide to the user’s palm.

*Designing a 2x2 Spatial Vibrotactile Interface for Tactile Letter Reading on a Smartphone* by Chu & Peng, (2018) describes four flat vibration motors attached to the back of a smartphone to generate spatial tactile feedback on the palm of the user. According to their research, a 3 cm distance between motors and a 200 ms vibration time are appropriate for their system. The locations of the vibration motors can be seen in Figure 10, below.
**Figure 12: feedback locations from literature research**

*Haptic Stimulation Glove for Fine Motor Rehabilitation in Virtual Reality Environments*, by Borja, Lara, Quevedo & Andaluz, (2018) details a prototype built for stimulating the median and ulnar nerves of the hand’s palm using vibration motors. Feedback is provided to the palm of the hand if the hand comes into contact with a virtual surface. The vibration motors are located at the fingertips, and in a rough circle on the user’s palm. The paper does not mention why these locations were chosen for the vibration motors. The locations of the vibration motors and a picture of the product can be seen in Figure 10, above.

*Haptic Feedback to the Palm and Fingers for Improved Tactile Perception of Large Objects*, by Son, B. and Park, J. (2018), shows the design of a custom cutaneous feedback interface that uses a servomotor to apply haptic force feedback to the palm. The device uses a crank-slider mechanism that uses a small volume, because of the palm’s complex deformation when the thumb is folded over the palm. Four of these devices were placed on the palm in the following locations outlined above in Figure 10. The researchers based these locations on the division of the palm according to the crease, and placed at least one actuator in each region.
Conclusions

Most of the papers found through scopus about haptic feedback on the hand only focused on research on haptic feedback to the fingertips. The few papers that do mention haptic feedback to the palm area, seem to focus on conveying shapes, instead of motions. Still, it is interesting to note that all of these papers try to cover the entire palm area with two regions. One region near the base of the fingers, which matched the one found from the Interaction Prototyping study, and one area closer to the heel of the hand. This second area is more difficult to implement because of the palms anatomical complexity when it comes to deformation as a result of folding the palm. Both of these areas can be seen in Figure 11, below.

![Figure 13: potential feedback regions on the palm area.](image)

The potential feedback area on the left of the palm area, the pink area in the visual above, was described in the Interaction Prototyping study as an area where the shape of the held object was felt, but not its motion. For the area on the right of the palm area, near the base of the fingers, the perception of shape and motion were opposite, with motions being felt clearly and shapes hardly at all.

If force feedback to the fingertips of the user is sufficient haptic information for the user to feel the steering mechanism, only the area on the right in the visual above should be used to convey motion on the user’s palm area.
State of the Art

Setup
SenseGlove B.V.’s competitors develop haptic gloves with functionalities that overlap with the SenseGlove. Their respective flagship products were analysed in terms of the type and location of the haptic feedback they provide to the user’s palm area. This analysis was executed much like a literature study, through online promotional material, research papers, specifications provided by the respective companies on their own websites, and through informal interviews with people that used these haptic interfaces at conventions.

The competitors’ gloves analysed for this research are the VRGluv, HaptX Glove, Dexta Robotics’ Dexmo, the Hi5 VR Glove, Elitac’s Tactile Feedback Glove, UltraHaptics and Manus’ Haptics+ Module.

Findings
None of the competitor’s haptic gloves provide directional haptic feedback to the palm. Of the mentioned gloves, only two provide haptic feedback to the palm at all, and one to the wrist. All the other devices only provide haptic feedback to the fingertips, either through tactile vibration feedback or force feedback. An overview of the haptic interfaces and their feedback locations can be found in Figure 14 and Figure 15, below.

<table>
<thead>
<tr>
<th>Device</th>
<th>Tactile Force Feedback</th>
<th>Tactile Vibration Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRGluv</td>
<td>Multiple locations on each finger</td>
<td></td>
</tr>
<tr>
<td>HaptX Glove</td>
<td>Palm and Fingers (grid, haptic bladders)</td>
<td></td>
</tr>
<tr>
<td>Dexta Robotics' Dexmo</td>
<td>Fingertips (active)</td>
<td></td>
</tr>
<tr>
<td>Hi5 VR Glove</td>
<td></td>
<td>Wrist (rumbler)</td>
</tr>
<tr>
<td>Elitac’s Tactile Feedback Glove</td>
<td></td>
<td>Fingertips and heel of the palm (vibration motor)</td>
</tr>
<tr>
<td>Manus’ Haptics+ Module</td>
<td></td>
<td>Fingertips (not specified)</td>
</tr>
<tr>
<td>GloveOne</td>
<td></td>
<td>Fingertips and the center of the palm (vibration motor)</td>
</tr>
<tr>
<td>Avatar VR</td>
<td></td>
<td>Fingertips, the heel and front of the palm (vibration motor)</td>
</tr>
<tr>
<td>SenseGlove</td>
<td>Fingertips (passive)</td>
<td>Fingertips (buz motor)</td>
</tr>
</tbody>
</table>

Figure 14: Feedback types and locations from competitors’ gloves
HaptX is the only company with a haptic glove that can provide directional haptic feedback to the palm area. It can do so by activating haptic bladders in sequence across the skin of the user’s palm. Elitac and Avatar VR are the only other companies that provides haptic feedback to areas on the hand that are not the fingers, through vibration motors. Their promotional material does not explain why they chose these locations on the palm, or what purpose those vibration motors serve.

UltraHaptics is a company that does not use a haptic glove to provide feedback to the hand. Instead, their flagship product, the Stratos, uses a 256-transducer array to create the sensation of touch in mid-air through ultrasound. The Stratos can convey rough shapes, but only from one direction, making the technology unsuited for conveying haptic feedback to the palm of the hand when the hand is closed or grasping a virtual cylinder.

Whether the Stratos can make their user feel motion through the skin on their palms is currently unknown.
Conclusions

Most haptic gloves that are currently on the market or in development only provide haptic feedback to the fingertips of the wearer. HaptX is an exception and uses a grid of haptic bladders all across the user’s palm and fingers to apply haptic feedback in the form of localised pressure. It has not, however, been designed nor implemented with the explicit intent to convey motion to the palm area. Avatar VR’s glove is the only haptic interface that provides vibrotactile haptic feedback specifically to the area of the palm near the base of the fingers. Their website and promotional material does not explain why they chose this feedback location.

Directional haptic feedback on the palm of the hand through skin stretch, brushing or vibrotactile feedback is an entirely new field of haptics on the Virtual Reality Glove market.
Conflicts with the SenseGlove

Setup
The new design for the Palm Straps should cooperate with or extend the functionality of the SenseGlove. The SenseGlove already has palm straps, which can either be replaced by the new design, or be extended by it. Internally, SenseGlove has started the development of a replacement Palm Strap that is more ergonomic and comfortable for the user to wear. This concept Palm Strap is called the Linda Palm Strap; named after its designer: Linda Plaude.

For the research portion of this project, the current SenseGlove palm straps will be used since it is easiest to prototype for these palm straps, and these palm straps are still on sale with the official SenseGloves. For the redesign portion of this project, the Linda Palm Straps will be used as the base for the new palm strap design.

A SenseGlove was measured and evaluated and its specifications and information communication protocol were provided by the company.

Findings

The SenseGlove is an exoskeleton for the hand, worn as a glove. It consists of a housing on the back of the hand that acts as a container for the main PCB of the device. Five identical kinematic arms linked to this PCB through flexible internal PCBs connect to each of the wearer’s respective fingers.

The SenseGlove provides haptic feedback to the fingertips only, in one of two forms: tactile vibration and passive force feedback. The vibrational feedback is provided by tiny Linear Resonant Actuators, or LRAs, located within each of the five arms of the exoskeleton.

The glove does not currently provide haptic feedback to the palm of the wearer, although a thumper motor within the main housing of the SenseGlove is in development.
Passive force feedback is provided to the fingertips through the exoskeleton's kinematic arms, that act as end-effectors. Each arm consists of a mechanism with a dyneema wire pulled through it. The further the wearer curls their finger, the longer the wire is extended, as shown in Figure 18, below. The knuckles of the SenseGlove hold a braking mechanism, that can stop the dyneema wire from extending, blocking the arms in place and preventing the user’s finger from curling further.

![Figure 18: a schematic overview of the extension of the dyneema wire, drawn in red](image)

The current iteration of the SenseGlove features velcro palm straps across the hand of the user to keep the exoskeleton in place. Neither the current palm strap, nor the Linda Palm Strap currently in development feature any electronics and are incapable of providing haptic feedback to the wearer. The current device takes up a large amount of space on the skin of the wearer’s hand, as shown in Figure 19, below.

![Figure 19: space on the hand taken up by the glove](image)
The Linda Palm Straps that are currently in development take up a similar area on the hand, as can be seen in Figure 20 below. These new straps are made of a combination of velcro and plastic and are much easier to don and doff than the current model. The hand of the wearer is nested in a semi-rigid housing that is lined with a deformable plastic layer with soft spikes in a continuous pattern for extra grip on the wearer’s skin.

*Figure 20: Linda’s redesign of the Palm Strap*

*Figure 21: Close up of the pattern used by the soft plastic lining of the Linda Palm Strap*
Conclusions

The passive force feedback exerted on the fingers can be used to make the wearer feel the general shape of a steering mechanism only. It cannot make the user feel motion or precise shapes or edges.

The current design of the velcro straps does not cover the area of the palm at the base of the fingers, but covers the palm area alongside it. The area where the fingers connect to the palm has been identified as a promising location for two types of haptic feedback based on the Interaction Prototyping and Literature Research earlier in this chapter. The velcro strap running across the palm will be used as a base or mount for a haptic interface for the Lab Study.

For the final design in this project, the Linda straps will be used as a base. While the velcro straps and the plastic housing can be modified to create room for haptic actuators, the straps in particular are aligned in an optimal way across the palm in regards to the folding anatomy of the human hand. Therefore, changes to the location of the velcro straps should be as small as possible in any redesigns.
Interaction Prototyping

Setup
Interaction Prototyping is an evaluation method that is based on observing a focus group while they interact with a prototype product as though it were the end product. Within this project, it was used to determine how the employees and interns at SenseGlove B.V. perceived the steering mechanism from the CV90 in terms of tactile feedback on their palms. How would they translate what they felt into haptic feedback, and was there a difference between the dominant and non-dominant hand?

A prototype steering mechanism was 3D printed using the corresponding 3D model from the digital interior of the CV90. Ten employees and interns at SenseGlove B.V. were asked to rotate the steering mechanism while an observer grasped the center of the steering mechanism and provided counter-forces to the motion the participant tried to make. The participants were asked to describe where on their palm they felt the steering mechanism, and how they felt its movement on or through their skin.

![Image](image_url)

*Figure 22: prototype steering mechanism for the interaction prototyping sessions*

Findings
During the interaction, the distinction was made between pulling the steering wheel counterclockwise and pushing it clockwise, to see if there were differences in what the participants perceived. Both interactions were performed with the dominant hand doing the pulling or pushing, and the non-dominant hand moving along. The findings can be seen in Figure 23, below.
All participants felt constant pressure on their fingertips during each of the interactions. Pressure on the top or the bottom of the hand was only felt when motions were initiated with loose hands, or when the rotational limit of the steering mechanism was reached (roughly 30 degrees clockwise and counterclockwise). Pressure was felt at these areas because of the geometry of the handles of the steering mechanism.

During the motions, directional information was felt on the area of the palm near the area where the fingers connect to the hand. In discussion with the participants, there are two potential ways to describe this motion in terms of haptic feedback: a brushing motion along the palm or sequenced vibrations.

The Interaction Prototyping study also looked into holding the steering mechanism, and pivoting it forwards and backwards. Only the feedback felt during the rotation of the steering mechanism is relevant within the scope of the project.

Conclusions

The SenseGlove should provide constant passive force feedback to the fingertips of the user while they are rotating the steering mechanism.

When the rotational limit of the steering mechanism is reached in VR, the user should receive haptic feedback to make them perceive this limit, to either the top or bottom of the hand, depending on which limit is reached.

The direction the steering mechanism is moving in can be felt on the palm of the hand in a very specific area: the ‘ridge’ on the palm near the base of the fingers. Whether brushing feedback or a sequence of vibrational feedback is better suited to conveying this information is analysed further in the Lab Study in the next chapter.

While all participants described this directional feedback on their palm at the same area, they did not describe the same intensity across both hands. Therefore, further analysis on whether haptic feedback on the dominant alone is enough, is performed in the Lab Study in the next chapter.
Conclusion

Based on the conclusions from the various exploratory studies executed in this chapter, the following feedback locations and corresponding feedback types should be compared in the Lab Study in the next chapter, as illustrated in Figure 24, below.

![Figure 24: The feedback locations for the Lab Study](image)

The area for the brushing (far left) and vibrational feedback (far right) is based on the Interaction Prototyping study and reinforced by the literature researches on both research papers and anatomy. It shows no conflicts with the current design of the velcro straps of the SenseGlove.

The force feedback on the sides of the hand (middle) is based on the Interaction Prototyping study alone, and has not been mentioned by the literature studies. It has been mentioned by all of the participants of the Interaction Prototyping study, however, and is the only feedback observed that conveys the limit of the rotational angle of the steering mechanism. It also shows no conflicts with the current design of the velcro straps of the SenseGlove.

The State of the Art analysis only returned interesting results in Avatar VR’s glove. Its locations were reinforced in part by the Interaction Prototyping Study. The other competitive gloves either provide feedback to the fingertips alone, other areas of the palm (near the wrist) or the entire wrist at once.
Prototype Design

Approach

In order to evaluate the feedback locations and their corresponding feedback types, a prototype Palm Strap has been developed for use in a lab study on bimanual haptics. This prototype has been designed using an approach called Iterative Prototyping.

With a short set of Requirements as a basis for the design, five design challenges were identified. Ideas were generated rapidly to solve these design challenges, and for each challenge a mock-up or prototype was created as quickly as possible. These mock-ups and prototypes were then used to evaluate those solution to the design challenges, making changes to the design where necessary. Every iteration of a solution to a design challenge is an improvement to the overall design.

After a few iterations the design matches the requirements, and the components are combined into a single design and prototype.

Requirements

1. The prototype must provide vibrotactile feedback, brushing feedback and pushing feedback, all to the correct locations on the human hand.
2. The prototype must provide haptic feedback based on the actions of the wearer in Virtual Reality.
3. The prototype must be robust enough to withstand repeated use during the lab study.
4. The prototype needs to be modular so components can be switched out when they are not required for a test, and can be replaced if they break or fail.
5. The actuators that provide the haptic feedback must be in contact with the skin of the wearer at all times.
6. The prototype must be worn together with a SenseGlove, and must not interfere with its functionality.
7. The prototype must be as easy to don and doff as the SenseGlove itself

Design Challenges

The most important design challenges revolve around providing the correct haptic feedback at the correct location at the correct time, and integrating the prototype with the SenseGlove on a physical, electronic and digital level.

Each type of haptic feedback was identified as a separate design challenge in terms of its actuation and location. The physical integration with the SenseGlove is also an important design challenge, as it acts as the mount for all of the feedback actuators. The timing for each type of haptic feedback became part of the electronic and digital integration of the Palm Strap with the SenseGlove, which is the final design challenge.
The design challenges and their iterative solutions are as follows:

Vibrotactile Feedback Module

The major design challenges for the vibrotactile feedback are keeping the LRAs in their correct location during use, keeping the LRAs in direct contact with the user’s skin at all times, and preventing resonance with and transference of vibrations through the housing of the LRAs.

To keep the LRAs in contact with the user’s skin at all times, they would either need to be attached to the skin directly, or be pressed onto the skin while they are suspended in specialised housing that connects them to the SenseGlove. To circumvent the design challenges regarding modular housing for the LRAs completely, the decision was made to place the LRAs at the correct location on the palm with double sided tape, with their wires looping back between the user’s fingers and over the back of their hands.

This solves the issues of the vibrations of the LRAs traveling through the housing or the rest of the Palm Strap, and prevents resonance with the housing and the rest of the Palm Strap. While it does introduce extra steps in the donning and doffing of the product, it solves the issues of aligning the LRAs for each user, and keeping them aligned properly during each test.

*Figure 25: LRAs taped to the skin of the participant with double sided tape*
Brushing Cutaneous Feedback Module

The largest design challenges for the cutaneous brushing feedback were attaching and detaching the haptic actuator from the rest of the Palm Strap, and providing the intended feedback to the skin. This module has gone through two iterations, and each iteration improved on both design challenges.

Iteration 1

The first iteration was 3D printed and required the velcro strap of the SenseGlove to be pulled through small slits in the design. The slits were fragile and pulling the velcro straps through them was a difficult process, increasing the time it took to don or doff the glove significantly.

A 3D printed beam was used to provide the haptic feedback to the palm. This beam was oriented along the palm of the hand, and could be moved forward and backward by a servomotor. The beam was rigid and uncomfortable on the skin, making it ill-suited as a haptic actuator. It also did not move far enough to provide a perceivable motion across the palm.

The moving parts of the first iteration were too loose for repeated use, meaning the servomotor would eventually disconnect from the beam that moved across the palm.

Figure 26: Iteration 1 of the brush and its connection to the SenseGlove. The weak connection to a servomotor broke on the right side of the prototype. The slider was kept in place between the mount and the servomotor. The brushing beam was barely registered by the user.
Iteration 2

The second iteration was short-lived, and featured a change to the mount for the servomotor and a different brush. A velcro strap was looped around the 3D printed base, so attaching and detaching the module from the SenseGlove could be done by simply pressing the velcro straps of the module and the SenseGlove against one another.

This solution proved to be too unstable for regular use. The Velcro connection would twist or otherwise unalign the base for the servomotor, meaning the brush could not consistently provide its feedback to the correct location on the palm of the user. It also felt rickety, potentially taking away from the credibility of the device in the eyes of the user.

The housing for the brush could be directly attached to the servomotor. The brush itself was taken from a pencil eraser and cut to size.

![Iteration 2 of the brush holder, with pencil eraser.](image)

Iteration 3

The third iteration of brush module was also 3D printed, but the geometry was changed significantly. A base was 3D printed that needed to be attached to the velcro strap on the palm of the user only once, and did not interfere with donning and doffing the SenseGlove at all.

Two ‘feet’ were printed for a servomotor, that could be slit onto the 3D printed base for scenarios that require this kind of haptic feedback. The servomotor was kept in place through the tapping nature of the design of the base and the feet, and the coarse surface finish of the 3D printed parts. This way, the brush module could easily be added to or removed from the Palm Strap for the various scenarios.

The pencil eraser holder from the second iteration was replaced by a smaller version that was easier to 3D print. While haptic feedback across the palm is desired in a linear motion, a circular motion on the same plane that indents the palm slightly can be used as a substitute if the object that indents the palm is deformable enough. A pencil eraser is rigid enough to
communicate a clear direction of motion across the skin, while also being deformable enough not to irritate the skin.

The holder contained a hole on the side with which it could be connected to the extruding gear of a servomotor. The holder was printed in two identical sides, which were glued together using superglue. The eraser did not fit perfectly inside the holder at first, but this issue was resolved by wrapping a thin layer of masking tape around the eraser instead of 3D printing the holder again. The switch was made to Batan B2122 servomotors to actuate the brush because those servomotors were readily available as prototyping materials at the SenseGlove workshop.

![Figure 28: Iteration 3 of the brush and its connection to the SenseGlove](image)

**Pushing Cutaneous Feedback Module**

For the pushing scenario, force feedback to the sides of the hand is desired. Ideally, this force feedback would be applied in a linear motion towards the side of the hand. In order to provide this linear motion with a servomotor, a crankshaft mechanism is required.

To circumvent the need for a complicated crankshaft mechanism with many moving parts, an arm was attached to the servomotor that could provide the necessary feedback in a circular motion. Because of the size of the radius of this circular motion, and the short distance travelled by the end of the arm from their starting position to their ending position, the motion of the haptic actuator approaches a linear motion.
This arm went through three iterations, with only a minimal change between iteration 2 and 3. The servomotor that moves the arm is too weak to harm or inconvenience the user by moving the arm too far towards the human palm. The arm will indent the skin ever so slightly, but then the servomotor will stop its motion in that position. The resulting sensation for the user is a slight pressure at the intended location on the side of the hand. In its neutral position, the arm of the servomotor does not touch the skin of the user, but is suspended a 1-3 mm above it.

**Iteration 1**
The first design for the arm had a very small amount of surface area, which was insufficient to provide the intended cutaneous feedback for the user. The size of the arm was too small, and the geometry of the connection with the servomotor was too complicated for rapid prototyping.

**Iteration 2**
The second iteration of the arm solved the lack of surface area by separating the arm into two components: an arm and a surface area. The end of the arm could slide into the surface area, and the two could be permanently connected with super glue. This iteration lacked a way to fasten the arm to the servomotor, however.

**Iteration 3**
The third iteration was 3D printed in various lengths to account for different hand sizes amongst participants. A reliable way to prevent the arm from separating from the servomotor during use was to create a hole in the arm through which a screw could be fastened into the main gear of the servomotor itself. The arm was tapped onto this main gear by force, carving small lines into the 3D printed material, keeping the arm from rotating while the servomotor wasn’t.

The first set of servomotors provided by SenseGlove B.V. for prototyping purposes contained many broken servomotors. To retain consistency in the design, all servomotors used to solve the design challenges of the prototype were replaced by Batan B2122 servomotors, which were readily available as prototyping materials and served their purpose without issue.

![Figure 29: Iterations 2 (left) and 3 (right) of the arm. Minimal changes were made.](image-url)
Physical connection to hand and SenseGlove

In order to connect the servomotors for the pushing scenario to the SenseGlove a mount or baseplate is required. The geometry of the baseplate is based on the geometry of the baseplate of the SenseGlove itself, so they can be aligned and connected easily. This new baseplate has gone through two iterations.

The holes and slits in the baseplate align perfectly with those on the SenseGlove. The velcro straps that allow a user to wear a SenseGlove can be pulled through these slits to keep the second base plate locked in place while the SenseGlove is worn.

The baseplate for the prototype features additional slits, holes and recesses. The large recesses on either side of the baseplate are meant to hold the servomotors for the pushing module. The holes next to the recesses can be used to fasten these servomotors to the baseplate using M3 nuts and bolts. These recesses and holes protrude out from the sides of the SenseGlove, so they do not interfere with its geometry, cabling and functionality, and have been aligned so the pushing module can provide its feedback at the correct location.

**Iteration 1**

The first iteration of the baseplate featured additional small slits that aligned with the slits in the baseplate of the SenseGlove. The idea behind those slits is that pulling a velcro strap through them aligns the baseplates with each other and keeps them locked in place while worn.

During testing two issues with these baseplates arose. The additional slits for the velcro straps introduced time consuming and frustrating extra steps to the donning and doffing of the SenseGlove that involved bending and pulling a velcro strap through multiple slits.

The recesses and holes on the side of the baseplate were not aligned properly with the geometry of the intended servomotors. In combination with the slight expansion of 3D printed material compared to CAD models, the servomotors did not fit snugly into the baseplate.

**Iteration 2**

The second iteration brought the amount of slits for the velcro straps down to a minimum to facilitate donning and doffing the SenseGlove. The baseplate of the palm strap and of the SenseGlove are also connected through double sided tape to keep the baseplate from moving around. The padding between the user’s hand and the SenseGlove was moved to the new baseplate instead, also attached with double sided tape.

At this point in the design, the decision was made to switch to a different set of servomotors, all Batan B2122 models, because the old set was malfunctioning. To accommodate the new servomotors, the recesses on the side of the baseplate needed to reduced in size and their corresponding attachment holes needed to be moved.
Iteration 3

A lot of material can be saved in the design of the baseplate for the palm straps by cutting material from the center of the baseplate. This iteration was never 3D printed because the 2nd iteration was functioning properly, and the rigidity of the baseplate would have decreased if material was removed.

Figure 30: Iterations 1 (left) and 2 (right) of the baseplate. The second iteration shows the servomotors with iteration 3 of the arms attached.

Electronic and digital connection to Unity and SenseGlove

The largest hurdles in terms of electronic and digital integration of the prototype with the SenseGlove were cable management, electronic component management and the communication between the SenseGlove and the palm strap.

Electronic component management

The following electronic components were required for the prototype to function properly:
- One Arduino Uno
- Six C10-100 LRAs (Precision Microdrives)
- Six DRV2605 Haptic Drivers with built-in haptic libraries
- One TCA9548A I2C Multiplexer
- Three Batan B2122 servomotors

These components were first connected through a breadboard and many short wires, to test if the setup worked or needed tweaking. While this version of the prototype worked properly, it was not suitable for repeated use in a user study. The connecting wires and the components themselves could come off too easily, and the setup was too fragile for transport.
A second iteration was made where the connections were soldered onto a protoboard directly, completely replacing the need for wires in-between components. Header pins were soldered onto the protoboard to act as mounts for the various electronic components, holding them in place tightly.

Figure 31: The Protoboard
Cable management

The wiring that connects the actuators (the servomotors and LRAs) to the protoboard are too short to run a user study without severely hampering the degrees of freedom of the user. To prevent damage to the device and confusion on the user’s part, the protoboard should be kept away from the user. This however, introduces the issue of the wiring being too short. To solve this issue, longer cables were soldered to act as connectors between the soldered protoboard next to the computer and the haptic actuators on the user’s hands.

The first cables used for this solution were UTP 5e twisted pair cables that were 220 mm long. This length was required to bridge the distance between the user and the computer running the digital side of the prototype. This first iteration featured unshielded cables, which worked fine for the LRAs, but introduced a new problem for the signals for the servomotors. Because the wires were unshielded, the signals ‘bled over’ to each other, resulting in situations where a single servomotor was sent a signal, and all of them were actuated. To solve this issue, a new set of shielded cables was stripped and outfitted with header pins.

Figure 32: Iteration 1 (left) and iteration 2 (right) of the cables.
Communication between arduino and unity

The SenseGlove communicates with a computer program named Unity in two ways. It sends information to Unity regarding its own location and the positioning of its parts. Unity returns information on which components of the SenseGlove should be actuated based on the information it receives.

In order for the palm strap prototype to function, it needs to receive information from Unity as well, and that information depends on the motions of the SenseGlove. The Unity side of the interaction was handled by SenseGlove internally, but can be summarised as follows:

1. The motions of the user’s hands are analysed by Unity to determine the intent of the user.
2. This intent is converted to a corresponding string in a look-up table.
3. This string is sent to Arduino.

From there, the arduino of the palm strap prototype takes over.

1. The string is received by Arduino.
2. A switch case determines which haptic feedback the palm strap should provide based on the received string.
3. The arduino writes values to the haptic actuators (in this case the LRAs and servomotors in the palm strap prototype), which in turn activate and execute the corresponding haptic feedback.

Many iterations were required to get the communication between Unity and Arduino to work seamlessly. The most recent version of the Arduino code can be found in Appendix B: Arduino Code.
Combined Prototype

Figure 33: the left handed half of the Palm Strap prototype pair.

The final iteration of the prototype combines the latest iteration of all of the design challenges mentioned above into a single product that can be used concurrently to a SenseGlove. It features modular components that can be swapped in and out as needed. An exploded view of the product can be found in Appendix J: Exploded View of Lab Study Prototype.
A Lab Study on Synchronised Haptics

This chapter describes an empirical study on synchronised bimanual haptic feedback through matching haptic Palm Straps with integrated actuators. This synchronised haptic feedback is provided to the user’s physical hands based on their movement of a virtual steering mechanism. The insights gained from this study form the basis of the design for a new haptic interface in the form of a palm strap that is integrated with the Sense Glove.
A Lab Study into Bimanual Synchronised Haptics

Introduction

Bimanual Haptics is a new field of research, and as a result few research papers have been written on the subject. How haptic feedback provided to one hand of a participant, based on the actions of their other hand, can influence the participant’s behaviour and their immersion in Virtual Reality, is a largely unexplored area.

A lab study has been set up and executed to study the effects of three types of bimanual haptic feedback applied to the palm areas of the hands of each participant. In the study this haptic feedback is provided in response to the actions of the participants while they play a simple video game in Virtual Reality.

Method

This research is a confirmatory research using within subject design. The participants are asked to perform the same task in Virtual Reality six times. During each iteration of the task, the participant receives one of three types of haptic feedback on either one or both of their hands based on their actions in a virtual environment. The goal of the study is to measure the variance of the participant’s ability to follow a predetermined path with both of their physical hands while performing the tasks, while they experience these types of haptic feedback.

The expected outcome of the study is that providing feedback to both of the participants’ hands (bimanual feedback) leads to a clearer correlation between the participants’ hands and will increase their accuracy in following the predetermined path, compared to providing the haptic feedback to only one, or none of the participants’ hands.

Research Question

“Does adding haptic feedback to both of the participant’s hands, based on their actions in VR, improve their accuracy in terms of moving their hands along a predetermined path more than adding that feedback to only the dominant hand of each participant, and no haptic feedback at all?”

Participants

The participants are eleven students and staff members from the faculty of Industrial Design Engineering at the Delft University of Technology. All participants are male and right-handed.
Device

A prototype haptic interface was designed and built for this study. The prototype consists of a modular palm strap that can be integrated with the geometry of the SenseGlove. This prototype can be used to deliver three types of haptic feedback to the hand of the user:
- Force feedback to the sides of the hand
- Vibrational cutaneous feedback to the palm of the hand
- Brushing cutaneous feedback to the palm of the hand

For this research, two SenseGloves are connected to their respective Prototype Palm Straps. The participants wear these combined products during the study, which allow them to interact with Virtual Reality by grabbing onto it with their hands.

Setup

Physical Setup

During the test the participant is seated on a chair in the middle of an area defined by an HTC Vive Lighthouse System. The chair is fixed in place so the participant can’t move it during the test. The virtual environment in which the video game takes place, is centered on this chair so the participant starts in the ideal starting position relative to a virtual steering mechanism.

Next to the chair, outside of the participant’s reach, is a table with a laptop on it. This laptop has an open google forms questionnaire for the participant to fill in after each scenario. On this table are also a roll of double sided tape and a pair of scissors. These apparatus are required to attach part of the Palm Strap Prototypes to the participant’s hands (the LRA module).

The participant is wearing an HTC Vive Headset and two SenseGloves, each with a matching Palm Strap prototype. Both SenseGloves have a tracker mount, which holds a corresponding HTC Vive Tracker so the computer can track and log the locations of both SenseGloves.

The SenseGloves are connected to a PC through a device sold by SenseGlove B.V. called a LinkBox. The Palm Straps are connected to the same PC through shielded wires, a soldered protoboard and an Arduino.

The PC runs the video game the participants play during the test in Unity. Unity translates the video game to Steam VR, which places the user in Virtual Reality. The SenseGloves and the Arduino operating the Palm Straps communicate with each other through Unity.
Figure 34: The Physical part of the setup

Virtual Setup
In Virtual Reality, the room is calibrated by centering the room on the user at the start of the experiment. The user is not meant to move around the area in VR, and is encouraged to stay seated on their physical chair during the lab study. The participant is located in a digital environment consisting of a plain room with a gray floor and gray walls. There is no ceiling, and a light blue sky can be seen if the participant looks upwards.

Directly in front of the participant’s stomach is a virtual steering mechanism, which is identical in shape and scale as the steering mechanism used in the CV90 interior. This steering mechanism has collision detection and can be grabbed and rotated by the participant by using the provided SenseGloves.

In front of the user at eye level is a metallic grey bar. While looking at this bar in front of them, the participants can not see the steering mechanism because it is positioned outside of their line of sight.
Attached to the metallic bar is a dark grey reticle that can be moved along the bar by rotating the steering mechanism. Rotating the mechanism clockwise moves the reticle to the right, and rotating the mechanism counterclockwise moves the reticle to the left. This motion is absolute, not behavioural, meaning that every angle of the steering mechanism corresponds to a specific location of the reticle on the bar.
Video Game
During the video game, 15 targets are spawned on the metallic bar in sequence on either the middle, the left or the right end of the bar. The objective for the participant is to move the reticle to the center of each target and keep it there for a brief period of time (0.2s). This is done by grabbing onto the steering mechanism and rotating it to ‘aim’ the reticle. If a target is not aimed at quick enough, it will fade away and disappear.

This video game is part of the experiment to distract the participants from moving the steering mechanism consciously. By giving them a task to focus on, the participants’ natural steering behaviour can be analysed. The virtual steering mechanism can rotate 30 degrees clockwise and 30 degrees counterclockwise from its starting position, just like the actual CV90 steering mechanism can.

*Figure 35: The Virtual part of the setup*

*Figure 36: The minigame used for the experiment.*
Rotating the steering mechanism clockwise moves the reticle to the right, rotating the steering mechanism counterclockwise moves the reticle to the left.
Variables

The independent variables in this research are the types of haptic feedback the user receives from the prototype palm straps based on their actions. The three types of haptic feedback (pushing, brushing and vibrotactile feedback) are divided into six scenarios for the participants to experience.

During the Pushing scenario, force feedback is provided to the sides of both hands when one hand is moved, to nudge the participant into moving their hands along with the rotation of the steering mechanism. The push is made in the direction the hands are moving.

During the Vibrotactile LRA scenarios, the participant receives vibrotactile feedback on the palm in sequence through three vibrotactile actuators. The LRAs vibrate in sequence with the desired motion of the hands, when the participant moves one of their hands. The servomotors for the pushing scenario provide pushing feedback to the side of the hand if the steering mechanism hits its rotational limit, letting the user know that their hand should not move further.

During the Brush scenarios, the participant receives brushing cutaneous feedback on the palm in the direction of motion of the hand, when the participant moves one of their hands. The servomotors for the pushing scenario serve the same function in these scenarios as they do in the Vibrotactile LRA scenarios.
### Scenarios:

<table>
<thead>
<tr>
<th></th>
<th>Unimanual</th>
<th>Bimanual</th>
<th>Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Control</strong></td>
<td><strong>Push</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No haptic feedback is provided by the palm strap</td>
<td>Force feedback is provided to the sides of the hands to push each hand in the direction it is already moving</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Brush</strong></td>
<td><strong>Brush (b)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cutaneous feedback is provided to a hand in a motion opposite to the current motion of that hand</td>
<td>Cutaneous feedback is provided to both hands in a motion opposite to the current motions of the dominant hand</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td><strong>Vibrotactile (LRA)</strong></td>
<td><strong>Vibrotactile (LRA) (b)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vibrotactile feedback is provided to a hand in a sequence opposite to the current motion of that hand</td>
<td>Vibrotactile feedback is provided to both hands in a sequence opposite to the current motions of the dominant hand</td>
<td></td>
</tr>
</tbody>
</table>

### Locations:

1.  
2.  
3.  

*Figure 37: Feedback Types and Locations*
Objective Variables
The objective dependent variables are the angular deviation and temporal correlation between the hands. These variables can be calculated from the xy positions of the hands over time. These locations are logged in a .csv file by Unity every 20ms, relative to the center of the virtual steering mechanism.

The angular deviation between the hands is a measure of how well the participant can keep their hands in a straight line through the center of rotation of the steering mechanism. The temporal or cross correlation between the hands is a measure of how simultaneous the hands move; or in other words, how much one hand lags behind the other. The closer to zero these numbers are, the more accurate the user’s positioning of their hands on a virtual steering wheel is during the steering motion.

![Figure 38: Angular deviation (left) and Temporal Correlation (right)](image)

The angular deviation between hands is calculated by converting the x and y coordinates of each hand to polar coordinates, and then transforming one of the hands until both hands are in the same quadrant on a circle with as its center the center of rotation of a steering mechanism. Then, the angle of the right hand is subtracted from the angle of the left hand to calculate the difference, or the angular deviation, between the hands.

The following equation was used to calculate the cross correlation of the participants’ hands. This formula returns a value R that is the correlation between the two signals at a phase shift of Tau.

\[
R_{xy}(\tau) = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})(y_{i+\tau} - \bar{y})
\]

\[
= \frac{1}{N} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 \sum_{i=1}^{N} (y_i - \bar{y})^2}
\]

*Equation 1: the equation for the temporal correlation between the paths travelled by the hands of the participants*
R is the correlation between two functions or data sets, x and y. N is the amount of data points in the data set, in this case the amount of samples. x-dash and y-dash are the means of x and y, and Tau is the offset that R is calculated for, or the lag between one signal and the other. In this experiment, x is the angle between the left hand and the center of rotation of the steering mechanism, while y is the angle between the right hand and that same center of rotation.

To calculate the lag between hands, Tau is changed incrementally to loop the two signals of the hands past each other. This results in a table of values for the cross correlation between the two signals. Each of these values corresponds to a specific phase shift Tau. The value for Tau at which this correlation has the highest value, is the lag between hands in samples. dividing Tau by the sampling rate (50 Hz) returns the lag between hands in milliseconds.

The higher the correlation and the lower the phase shift, the better the scenario is ranked. Nelson-Wong describes this equation and its applications in more detail in their research paper “Application of Autocorrelation and Cross-correlation Analyses in Human Movement and Rehabilitation Research.”

Subjective Variables
The subjective dependent variables are the perceived steering realism and the perceived synchronicity between hands. These variables are measured for each scenario in a questionnaire on a seven point scale that the participant fills in after each scenario.

The value the participants rate the perceived realism is a measure of how realistic the steering motion itself feels for each participant. The rated perceived synchronicity between hands is a measure of how connected the hands of the participant feel to one another, compared to how connected they would have felt if the participant was holding a physical steering mechanism.

Figure 39: Perceived steering realism (left) and perceived synchronicity between hands (right)
Procedure

The procedure for the experiment is as follows:

Setup
1. The procedure for the experiment is explained to the participant
2. The participant signs one of the provided forms of consent
3. The participant fills in the first page of the google forms questionnaire
4. The participant sits down on the chair
5. The participant dons the SenseGloves and prototype Palm Straps with aid of an examiner
6. The examiner turns on the Vive Trackers and puts an HTC Vive on the participant’s head, adjusting its straps until it fits the participant comfortably
7. The examiner starts the simulation in Virtual Reality
   a. The digital environment is centered on the user in VR (the HTC Vive headset is used as the marker for the center of the room)
8. The examiner asks the participant to grab onto the virtual Steering Mechanism
9. The examiner asks the participant to familiarise themself with the steering mechanism and how it controls the reticle
10. The examiner randomises the feedback scenario orders for this participant
11. The **Scenario** and **Questionnaire** procedures below are repeated 6 times, followed by the **Wrap Up** procedure.
   a. Setup
   b. Scenario 1
   c. Questionnaire 1
   d. Scenario 2
   e. Questionnaire 2
   f. Scenario 3
   g. Questionnaire 3
   h. Scenario 4
   i. Questionnaire 4
   j. Scenario 5
   k. Questionnaire 5
   l. Scenario 6
   m. Questionnaire 6
   n. Closure
Scenario
1. The examiner prepares the scenario
   a. The examiner selects the next scenario in Unity
   b. The examiner makes sure the correct feedback modules are equipped on the Palm Strap prototype for the selected scenario
   c. The examiner asks if the participant is ready for the experiment
2. The examiner starts logging the locations of the participant's hands in Unity
3. The examiner spawns the first target for the participant to aim at
4. The participant aims at the provided targets, destroying them
5. A new target is spawned when a previous target has been destroyed or has faded completely
6. When 15 targets have been destroyed or have faded, the scenario is ended
7. The examiner removes the HTC Vive headset from the head of the participant

Questionnaire
1. The examiner reads the questions on the questionnaire out loud and fills in the answers, unbiased, for the participant
2. The participant answers the questions on a 7 point scale
   a. The examiner provides visual aid when the questions involve visuals by presenting the visuals on the laptop to the participant
3. The examiner places the HTC Vive headset on the head of the participant again
4. The examiner opens the next page on the Questionnaire

Wrap Up
1. The simulation is closed in Unity
2. The examiner removes the HTC Vive from the head of the participant
3. The participant takes off the SenseGloves and prototype palm straps with aid of an examiner
Data

General

The data from the experiments has been analysed within subjects and across all eleven participants. Visualisations of the data per participant have not been included in this chapter for the sake of brevity, but can be found in Appendix C: Data per Participant.

In all graphs, both in this section of the report and in Appendix C: Data per Participant, the feedback scenarios have been ordered from the smallest amount of haptic information provided to the palm of the participant (left) to largest amount of haptic information provided to the palm of the participant (right). The graphs have been made in Matlab. The functions used for these graphs can be found in Appendix D: Matlab Code.

![Image of haptic feedback scenarios and order]

**Figure 40: Scenario order from least to most information (left to right)**
*From left to right, the scenario order is Control, Push, Unimanual Brush, Unimanual LRA, Bimanual Brush and Bimanual LRA.*

Within each participant, there is no clear correlation between the amount of haptic feedback provided to the hand and any of the dependent variables. Within participants, there also does not seem to be a clear preference for any of the scenarios. None of the dependent variables consistently score significantly closer to the ideal values than the control scenario does. Similarly, there does not seem to be a preference for Unimanual or Bimanual scenarios.
Participant 6 and participant 10 do show trends in their subjective variables and angular deviation respectively, in terms of the amount of haptic information provided to the palm. However, none of the other variables for any of the other participants show this trend, which means that there is no clear correlation between the amount of haptic information provided to the palm and the dependent variables.

![Perceived Realism and Synchronicity for participant 6](image1)

**Figure 41: Subjective measures for participant 6 with trend line**

![Angular Deviation for participant 10](image2)

**Figure 42: Angular Deviation for participant 10 with trend line**

Although eyeballing the above visual might suggest that for participant six there is a correlation between the amount of haptic information provided to the hand and the subjective variables, none of the subjective variables for the other participants suggest that this correlation exists. The same is true for participant 10 and the correlation between haptic information provided to the hand and the angular deviation between hands.

During the experiment, it became clear that the participants did not always interpret the haptic feedback correctly. Various participants mentioned that they did not expect the brushing feedback to feel the way it did. Some participants also mentioned that they were uncertain about what triggered the haptic feedback, further explaining that they assumed the trigger was either hitting the targets or missing them in the case of the LRA and Brush scenarios. The participants that mentioned the servo motors on the sides of the hand always interpreted the haptic feedback it provided, and its meaning, correctly.
Subjective Variables

Realism

Figure 43: Rated Realism per scenario across participants

Figure 43 above shows the perceived realism per scenario across all participants in a modified error bar plot. The colored ‘+’ markers indicate the values the participants rated their perceived realism for each scenario. The black ‘O’ markers are the mean values per scenario across all participants. The black vertical line shows the range of values the realism was rated for each specific scenario across all eleven participants. The ideal value for perceived realism for each scenario is a value of 7. The worst value is a 1.

As you can see from the Perceived Realism graph above, there is no clear correlation between the amount of information provided to the palm of the participant, and the mean rated realism per scenario.

None of the means of any of the scenarios are significantly different from each other, making it impossible to select one of the scenarios as the best scenario in terms of rated Realism. The bimanual and unimanual scenarios are also statistically identical.

The LRA scenarios have the best ranges of values out of all scenarios, but on a 7 point scale they are not significantly different from the other scenarios.
Perceived Synchronicity

![Perceived Synchronicity per Scenario](image)

**Figure 44: Rated Synchronicity per scenario across participants**

The perceived Synchronicity for each scenario across participants uses the same legend as the perceived Realism. Compared to the perceived realism, the rated Synchronicity shows larger deviations in its given ratings, however, these variations are still too small to be significant. The ideal value for rated synchronicity is 7. The worst value is 1.

From eyeballing the graph it looks like the bimanual scenarios, in terms of their respective means, are an improvement over the unimanual scenarios. However, even between the largest shifts, the Unimanual and Bimanual Brush scenarios, the difference in rated Synchronicity is still insignificant.

Participant 4 rated all scenarios, aside from the control scenario, at 7 in terms of perceived Synchronicity. This explains the extended range of all scenarios compared to the rated Realism above.
Objective Variables

Angular Deviation

![Combined Angular Deviations for all Participants](image)

*Figure 45: Normalised absolute boxplot of the angular deviation for each scenario across participants*

Figure 45 above shows the concatenated angular deviation for all participants as a box plot. The ranges of values above have been normalised towards each participant’s respective starting position, and the values have been made absolute so the participants do not cancel each other out in terms of positive and negative angular deviation.

Per participant, a positive angular deviation signifies that the right hand is further along its path than the left hand, while a negative angular deviation indicates the opposite. In Figure 46 only the absolute deviation is shown, not its direction. As you can see in the above graph, there is no clear correlation between the amount of haptic feedback provided to the palm and the angular deviation per scenario across participants.

The ideal scenario in this boxplot would have as few outliers as possible (unimanual brush) while also having as small a range as possible (unimanual LRA) and as small a spread as possible (Unimanual LRA). The ideal median (the red line) would be as close to 0 as possible.

Judging from the boxplot in Figure 45, the unimanual LRA scenario scores best on most of the mentioned criteria mentioned above. However, statistically speaking, the deviations between spread and range, as well as the deviations between the medians of each boxplot, are insignificantly small. Furthermore, a median angular deviation between the hands of 10 degrees is a very small deviation for holding a steering mechanism.
Figure 46: Lag (or Phase Shift) per scenario across participants

Figure 46 above shows the lag between hands per scenario. A positive lag indicates that the right hand was leading the left hand, while a negative lag indicates the opposite. The colored ‘+’ markers are the values of the lag for each participant. The black ‘O’ markers show the mean lag per scenario across all participants, and the vertical black lines show the range of values for each scenario. The ideal value for the lag would be as close to 0 ms as possible. The Unimanual Brush scenario has a larger range because of an outlier.

The control scenario has the shortest range, but the bimanual LRA scenario is closest to the ideal mean. Statistically speaking, however, because of the low sampling rate (50Hz), these means are not significantly different from one another. The largest deviation is less than 20ms (which is 1 sample) and this could just as likely be a measuring error.

Like with the previous variables, no clear correlation between information density and the mean lag per scenario presents itself. The bimanual scenarios do score slightly better than their unimanual counterparts in terms of their means, but as mentioned above, these means are not significantly different.
Correlation

Figure 47: Cross Correlation per scenario across participants

The temporal-, or cross-correlation per scenario is a measure of how synchronised the motions of the participant’s hands are during the various scenarios. The higher the mean correlation is, the more the hands moved in parallel across the rotation of the steering mechanism, and the better the scenario scores. In the above graph, the colored ‘+’ markers indicate the peak correlation for each participant for each scenario. The black ‘O’ markers indicate the mean peak correlation per scenario, and the vertical black lines show the range of peak correlations among participants per scenario.

As you can see in the above graph, each of the means are correlated more than 85%, which is very high. While the Unimanual LRA and Bimanual Brush scenarios both have a correlation of above 90%, statistically speaking the mean peak correlations of each scenario are not significantly different from one another.

Again, there is no clear correlation between the amount of information provided to the palm of the participant and the mean cross correlation between hands. There is also no clear correlation between the amount of haptic information and the range of peak correlations per scenario.
Discussion

As can be seen from the data, there is no single type of haptic feedback that scores significantly better than any of the other types of feedback within participants nor across participants. This includes the control scenario where no haptic feedback was provided aside from what the SenseGlove provides to the fingertips.

There is no clear correlation between the dependent and independent variables, and there also does not seem to be a clear correlation between the amount of haptic feedback provided to the palm and the dependent variables.

Within participants there is too much variation in the data for there to be clear correlations or an objectively better scenario. Across participants, the data shows no significantly different values.

This means that in terms of haptic feedback to improve the participant’s experience and performance on handling a virtual steering mechanism, the SenseGlove alone is good enough: no additional haptic feedback is required.

The answer to the Research Question therefore, is that the bimanual scenarios did not significantly improve the accuracy of the participants in terms of moving their hands along a predetermined path compared to the unimanual scenarios nor the control scenario in which no haptic feedback was provided aside from the feedback to the fingertips provided by the basic SenseGlove.

In terms of the angular deviation and lag, there is very little to no room for improvement for any of the scenarios. The mean values are insignificantly small, with a mean angular deviation around 10° and a mean lag of less than 20ms. The mean cross correlation between hands is extremely high for all scenarios, with all values exceeding 85%. This is likely because of muscle memory and experience in handling physical steering mechanisms.

While no scenarios scored significantly better or worse in terms of rated Realism and Rated Synchronicity, the mean values for each scenario were the average of the scale, or lower. For both variables, there is a lot of room for improvement.

The data of the dependent variables being so variable suggests that the haptic feedback was interpreted incorrectly by the participants because of various confounding factors.

First of all, the meaning of the haptic feedback was not explained to the participants in advance. When participants spoke about the haptic feedback and what they assumed was the trigger, they mentioned breaking the targets or making an error instead of the actual trigger.

Second of all, the delay between the user’s actions and the corresponding feedback was likely too long. Unity had to interpret the intent of the motion of the user, which it failed to do if the participant moved too quickly. Then it had to send a signal to the Arduino, which had to
send a new signal to the haptic actuators on the Palm Strap prototype. Including intent interpretation, sending and listening for data, data conversions and the slower response time of servomotors, the delay between motion and corresponding feedback became significantly long.

Finally, the prototype did not fit perfectly on the hands of every participant. This could not have influenced the LRA and Brushing modules of the prototype, since both of these modules were applied directly to the palm area. It could, however, have had an influence on the servomotors on both sides of each hand. These servomotors were used to provide the feedback for the Pushing scenario, and the ‘end of rotation’ feedback for the other scenarios if the participant hit the rotational limit of the virtual steering wheel.

Various other factors could have played a role in the erroneous interpretation of the haptic feedback as well, although they were not noticed during the experiments by the participants nor the examiner. Examples include hypothetical very temporary short-circuits or faulty soldered connections of the prototype’s protoboard.

Across participants, the data showing no statistically different values is in part because of the large variations in the dependent variables from each individual participant, and in part because the scenarios did not have consistent lengths across participants.

Each scenario ended after a participant destroyed 15 targets. This led to varying lengths of scenarios. With the location of each hand being logged every 20ms, the longest scenarios consisted of significantly more data points than the shortest scenarios. When concatenating scenarios to look at the data across participants, the longest scenarios pull the data towards their own mean and median values.
Recommendations

While none of the proposed types of haptic feedback are a significant improvement over the base SenseGlove, there is a lot of room for improvement in terms of perceived realism. This suggests that a type of additional haptic feedback on top of the base SenseGlove functionality is desired, but the proposed implementations do not feel sufficiently realistic to the user. On the other hand, all of the participants did hold the virtual steering mechanism with a prismatic power grasp of their own accord, as one would hold a physical steering wheel. This is an improvement over the more common precision grasp that the wearers of a SenseGlove tend to use when grasping objects.

Therefore it is recommended to implement one of the proposed types of haptic feedback in a way that enhances perceived realism by preventing confounding factors.

Choice of feedback

The choice of haptic feedback should not be based on the outcome of the lab study. The amount of participants is too small for statistical significance, and the data is too variable among participants. The exact amount of participants required to reach a statistically significant result is currently unknown, but can be calculated with a Power Analysis should SenseGlove B.V. wish to execute an improved version of this Lab Study.

Instead of the outcome of this research, the choice for the haptic feedback type should be based on other factors, such as the cost of the components and the ease of implementation for SenseGlove B.V. This haptic feedback choice is made in the next chapter: Feedback Choice.

Preventing confounding factors

The variability of the data is due to the confounding factors described in the Discussion above. The interference due to the confounding factors can be reduced with higher quality electronics and a design that addresses various design challenges that surfaced during the experiment. These design challenges are used in the Ideation chapter as the basis for a redesign that incorporates one of the proposed types of haptic feedback.

Many of the confounding factors can be removed by using a printed circuit board instead of a soldered protoboard, and by improving the algorithm that Unity uses to detect the intended motion of the user’s hands. The other confounding factors are due to the implementation of the haptic feedback.

Before use the product should be calibrated to its user. This way the user can familiarise themselves with the feedback and what it means, and the functionality of the product can be evaluated before use. If the feedback is not coming through to the user, the issue can be identified and fixed before use.

The duration between visual and haptic feedback, or the onset-to-offset-duration, should be reduced as much as possible. This can be done by switching to anticipatory feedback.
instead of relying on reactive feedback. This means that rather than guiding the user’s motions from one hand to the other, the non-dominant hand is cued into motion when the dominant hand should start moving, instead.

Finally, contact between the haptic actuators and the user’s skin should be ensured for optimal feedback.

The recommendations are summarised below:
1. Provide haptic feedback to the palm with one of the proposed feedback types
2. Base the choice of feedback type on other factors than the research itself
3. Prevent confounding factors by
   a. Calibrating the product to the wearer before use
   b. Explaining what the feedback means to the user in advance
   c. Ensuring skin contact for optimal feedback
   d. Switching to anticipatory feedback instead of reactive feedback
Feedback Choice

Introduction
As explained in the Recommendations of the Lab Study, the choice of feedback for the new Palm Straps should not be based on the outcome of the research itself. Instead, it should be based on criteria that are relevant to SenseGlove. A choice is made using these criteria within a Harris Profile.

Criteria
The three feedback types that are being compared are the Vibrotactile Feedback, the Brushing Feedback and the Pushing Feedback. The criteria for the feedback choice are as follows:

Ergonomics
During the lab study it was not always clear for the participant what the haptic feedback meant. Most of the participants did mention that they found the brushing feedback ‘very funny/ interesting, but not like a steering wheel at all’.

SenseGlove’s preference
SenseGlove has a preference for vibrotactile feedback over servomotor feedback because as a company they have experience on the subject of vibrotactile feedback

Low Cost
SenseGlove B.V. uses off-the-shelf vibrotactile actuators in their current iteration of the SenseGlove. According to various webshops, these actuators cost a fraction of the cost of the servomotors used in the prototype. Smaller and cheaper servomotors than the Batan B2122 do exist, but they are still more expensive than vibration motors by a factor 5-10. (Industries, n.d.) (“Motors - AC, DC | Motors, Solenoids, Driver Boards/Modules | DigiKey”, n.d.)

Technical specifications
The technical specifications criterion encompasses maintenance and onset-offset-duration. The brushing feedback wears the fastest because of the component it rubs over the participant’s skin, requiring more or earlier maintenance than the other two options. The onset-offset duration, or the delay between the user’s actions and the corresponding haptic feedback, is much shorter for vibrotactile actuators compared to servomotors.

Ease of Implementation
It is much easier for SenseGlove B.V. to integrate vibrotactile feedback into the SenseGlove and its development kit than either of the feedback types that rely on servomotors. The company already uses internal haptic libraries to actuate their vibrotactile motors, meaning no new libraries would have to be created if this type of feedback is chosen.
The company also has a lot of experience in assembling and designing for products with vibrotactile actuators in them.

Choice

A Harris Profile is used to make the final choice between the types of haptic feedback. A Harris Profile is normally a tool used by designers to compare concept designs, but can be used for choices like these based on multiple criteria as well.

A Harris Profile is a visual tool, where the criteria are listed from highest to lowest from top to bottom on the side of the profile. Each of the feedback options are placed on the horizontal axis and scored on a four point scale for each of the criteria. The four point scale has the options -2, -1, 1 and 2, from left to right. The tool is used to make a decision by judging which of the resulting pillars would tip over to the right side the most if it were made out of actual blocks.

For the proposed feedback types with the above criteria, the resulting Harris Profile looks as follows:

Figure 48: Harris Profile for the feedback types

As can be seen from the Harris Profile above, vibrotactile haptic feedback is the best choice for the new haptic palm straps based on these criteria.
The Design of a Haptic Palm Strap

This chapter describes the design process of a pair of matching Palm Straps for the SenseGlove. The design is based on Palm Straps designed by Linda Plaude, and provides vibrotactile feedback to the palm of the user’s hands.

The chapter starts with a Program of Requirements that the design should adhere to. In the Ideation phase, ideas are generated using various creative techniques in order to solve the Design Challenges that came to light during the Lab Study on Synchronised Haptics in the previous part of this document. These ideas are then combined using a Morphological Chart into three product Concepts.

The Concepts are each described in greater detail and compared using a Harris Profile. The most promising Concept is picked for further development.
Program of Requirements

This program of requirements consists of two sections: Requirements that the design must adhere to, and Wishes that it should adhere to as much as possible. The Wishes are used to evaluate designs against each other with a Harris Profile at the end of the Conceptualisation Phase.

Functionality:

- The product must provide vibrotactile haptic feedback to the palm area adjacent to the first phalanges of the fingers, with the goal of providing a directional sensation across the skin of its user
- The product must provide this haptic feedback regardless of the orientation of the user’s fingers
- The product must provide this haptic feedback based on the actions of the user in Virtual Reality
- The product must anticipate the actions of the user, providing anticipatory feedback instead of reactive feedback
- The haptic actuators of the product must be in contact with the user’s skin at all times during use
- The additional functionality of this product must be integrated into the Linda Palm Strap and/or the SenseGlove itself, making the product a redesign of either or a combination of both
- The product’s functionality must work seamlessly with the functionality of the SenseGlove and Linda Palm Strap
- The product must allow for aligning its haptic actuators with the proper locations on the user’s palm area
- The product must allow for (virtual) calibration

Ease of Use

- The product must be able to be donned and doffed by the user without help
- The product must be able to be donned and doffed within 3 minutes

Safety

- The product must not harm or impede the user in any way
  - The product must not exert forces on the user that cause discomfort to the user
  - The product must not hamper blood circulation in the user’s hand and arm
  - No sharp edges or corners must be exposed
  - No risk of electrocution, burning or exposure to harmful chemicals must occur
- The product must not impede the motions of the user more than the SenseGlove currently does, including folding of the palm and fingers
Ergonomics
- The posture of the user’s hand must not change during use compared to using the current SenseGlove

Aesthetics, design and materials
- The product must fit the form language of the SenseGlove

Production
- The product must be produced using production processes that the company is already familiar with

Transport, Storage and Packaging
- The product must fit in the current SenseGlove packaging with minimal changes to the packaging

Installation and Initial use
- The product can be installed by the user with the use of a manual
- The product can be calibrated by the user with the use of a manual
- The actuators can be aligned by the user with the use of a manual

Maintenance and Repair
- The product can be calibrated before each use

End of Life
- The electronics (actuators and wiring) must be able to be separated from the rest of the product at the end of its life

Electronics
- The wiring within the product must not be exposed to the skin of the user
- The wiring within the product must be hidden from view

Wishes
- Contact Maintenance
- Signal Consistency
- Lack of SenseGlove Modifications
- Ease of Aligning the Actuators
- Ease of Donning and Doffing the design
- Remaining Degrees of Freedom
- Ease of Integration
- Virtual Simplicity
- Mechanical Simplicity
- Robustness
Ideation

Introduction
During the Ideation Phase product ideas are generated using various creative techniques. These product ideas start from Design Challenges, which were identified based on the outcome of and confounding factors in the Lab Study of this project. These ideas are combined through a design tool, called a Morphological Chart, to create three product concepts.

Design Challenges
The most important Design Challenges that came to light due to the Lab Study are the following:

1. Aligning the Actuators with the proper locations on the palm
2. Keeping the Actuators on the skin at all times during use
3. Integration on a Physical Level with the
   a. Linda Palm Strap (housing)
   b. SenseGlove (housing/ connection)
4. Integration on an Electronic Level with the
   a. Linda Palm Strap (actuator and wiring)
   b. SenseGlove (wiring)
5. Preventing Resonance between vibrotactile actuators
6. Allowing for folding the hand

Solving these challenges will prevent the confounding factors from the Lab Study from interfering with the intended haptic feedback.
Idea Generation

Based on the design challenges identified above, ideas for solutions that address those challenges were generated using various creative techniques. These techniques include but are not limited to How-To’s, Reframing, Brainstorming, Brainwriting, Flower Diagrams and Brainsketching.

*Figure 49: Flower Diagrams*

The flower diagrams in Figure 49 above illustrate the most important design challenges and their potential solutions. These solutions were used as a basis for brainsketching potential modifications, replacements and additions to Linda’s version of the Palm Straps for the SenseGlove. An overview of these sketches can be found below in Figure 50 below.
Figure 50: Sketch Overview
Collage

Inspiration was drawn from competitive VR gloves and research papers on haptic feedback on the palm area, as well as gloves and gauntlets used for other sports, concept gloves, robot arms and various other sources. The following collage shows the major inspirations for the design and concept phases.

Figure 51: Collage
Morphological Chart

The ideas generated during the Ideation phase were combined into a Morphological Chart to aid in the creation of three concept designs for a new palm strap for the SenseGlove with added functionality of adding sequential vibro-tactile feedback to the palm of the hand. The Morphological Chart can be seen in Figure 52 on the next page.

By combining the most promising or most interesting solutions to each design challenge, concepts can easily be created for the new palms traps. The colored circles on top of the Morphological Chart illustrate these combinations of design challenge-solutions.
Figure 52: Morphological Chart

- Adhesive
- Robot arm
- Suction
- Gravity
- Springs b
- Springs a
- Glove
- Tight fit
- Voice with
- Vela
- Semi-rigid
- Layer
- Projective
- Spring integration
- Keeping skin contact
- Preventing resonance
- Physical integration
- Allowing for folds
- Allowing the actuators

- Finger
- Hand
- Wrist
- SC Front
- SC Side
- Casting
- Strap
- Bracket
- Clicking
- Slider
- One size fits all
- Velo
- Trench
- Crank
Conceptualisation

Introduction
From the ideas generated in the previous chapter, three concepts were created using an inspirational collage and a combination of Brain Sketching and a Morphological Chart. These three concepts show three designs that solve the Design Challenges identified at the start of the Ideation phase, and are further developed using design sketching. At the end of this chapter, one concept is chosen through the aid of a Harris Profile for further development. The three concepts are described in more detail below.

For clarity, each of the concepts has been given the same blue-green color in the design sketches below. This allows them to easily be distinguished from the components of the SenseGlove and Linda Palm Strap. Similarly, the vibration motors have been colored bright orange in every concept to make them stand out in the design sketches; they will not have this color in the final design.
Concept 1: The Flap

This concept is inspired by damping materials, and using them as housing for vibration motors. The flexible nature of damping materials allows for a single sized strap that can be used by multiple hand sizes, and easy alignment of the vibration motors. The concept builds on the flexible basis of the Linda Palm Strap, and is a natural extension of its design, as can be seen in Figure 53, above.
The ‘flap’ is a piece of flexible damping plastic that is attached on one side to the casing of the Linda Palm Strap. The ‘flap’ can be bent, curved and folded to make it easier to align with the correct position on the palm of the user. The other side of the casing of the Linda Palm Strap features a small velcro patch, matching a velcro patch at the end of the ‘flap’. By folding the ‘flap’ over the palm of the hand, the velcro patches can be connected, which automatically aligns the actuators embedded in circular cuts in the damping material. Allowing both the flap to stretch slightly and the casing of the Linda Palm Strap to deform slightly, makes the design accessible to a variety of hand-widths. The folding nature of the ‘flap’ and the velcro connections are illustrated in Figure 54, below.

![Figure 54: Left side unfolded and front](image)

While the actuators protrude 1mm from the damping material of the ‘flap’, the wiring is embedded deeper into the flap itself. It travel through the flap in-between the casing and lining of the Linda Palm Strap and into the housing of the PHB of the SenseGlove itself.

The assumption is made that the flexibility and stretchy nature of the damping plastic in combination with the deformable properties of the casing of the Linda Palm Strap, will allow the vibration motors to stay on the user’s skin while the palm of the hand is being folded.
Concept 2: The Dancer Glove

This concept is inspired by competitive haptic gloves that use fabric gloves instead of the exoskeleton approach that SenseGlove B.V. uses for their flagship product. Using a whole glove however would conflict with the velcro straps on the finger digits that the SenseGlove relies on, as well as the plastic lining of the Linda Palm Straps. For this reason, a partial glove based on dancer’s gloves was combined with the Linda Palm Strap, as can be seen in Figure 55, above.
The ‘dancer glove’ is a piece of stretchable cloth that is attached to either side of the geometry of the Linda Palm Straps. It can be attached with a velcro strap to the first digit of the middle finger of the wearer. The vibrotactile actuators and their wiring are sewn into the cloth. The wiring travels via the cloth, in-between the flexible Linda Strap shell and its plastic lining, into the housing of the SenseGlove itself.

The flexible nature of the cloth aligns the actuators on the user’s hands automatically, while the actuators stay on the user’s skin, albeit with a thin layer of fabric in between, because of the tight fit of the fabric. The lower side of the glove is kept in place by one of the two main straps, ensuring that the actuators stay on the skin even when the hand is folded into a power grip.

![Figure 56: Front view of the Dancer Glove](image)

To wear the ‘dancer glove’, the user must move their hand underneath both of the straps and under the glove. Then, the wrist strap should be tightened and the glove should be attached to the middle finger by wrapping the attached velcro strap around the proximal phalange. Finally, the middle strap should be fastened. One size fits all.
Concept 3: The Finger Folds

![Image of Finger Folds]

**Figure 57: The Finger Folds**

During Ideation, the discovery was made that aligning the actuators to their proper location on the hand of the user can easily be done by attaching them to the proximal phalanges of each finger. Even folding the hand inwards to form a fist does not un-align them. This product concept is based on that principle, and can be seen in Figure 57, above.

Instead of being attached to the Linda Strap casing like the other two concepts, these ‘finger folds’ are attached directly to the housing of the SenseGlove’s PCB itself. The new housing features additional circular extrusions at the base plate, that act as one half of a double hinge. The other half of the double hinge is a mechanical arm that connects to a small plate that can be attached to the proximal phalange of the wearer with a velcro strap. It is a very similar system to the one used by the mechanical arms of the SenseGlove itself.
In fact, the plate that attached the user’s finger to the mechanical arm is identical to the one that the user wears on their distal phalange, but oriented backwards.

On the other side of the velcro strap is a new component, which is a small plastic housing that holds a vibration motor and two small springs. One spring is used to suspend the vibration engine, while the other is used to fold the housing away from the velcro strap onto the skin of the user. An illustration of this housing can be seen in Figure 59, below.

![Figure 58: Finger Fold Component](image)

The wiring of the vibration motor is woven into the velcro strap or in-between two layers of cloth. The wire then travels through the mechanical arm and the double hinge to the PCB inside the SenseGlove housing, in a similar way to the flex pcb inside each of the SenseGlove’s mechanical fingers.

![Figure 59: Front View](image)
Concept Choice
The choice between concepts was made using a Harris Profile, in the same way the haptic feedback choice was made in Chapter 4: A Lab Study on Synchronised Haptics, on page 72. The criteria used for this Harris Profile come from the Wishes in the Program of Requirements earlier in this chapter, on page 75.

Criteria

Contact Maintenance
The confounding factors from the Lab Study have shown that in order to get the hypothetical best result in perceived realism, the actuators need to maintain skin contact with the user at all times. This criterion involves continuous contact maintenance both during regular use and extreme orientations and configurations of the hand and its fingers. It is also the most important criterion because the product performance and many of the other criteria depend on it.

Signal Consistency
Signal Consistency is the second most important criterion, and deals with travel of the physical actuators across the skin of the user. If the actuators travel across the skin too much or too little, the signal as the user perceives it, might lose its consistency.

Lack of SenseGlove Modifications
SenseGlove B.V. have expressed their wish for as few modifications to their flagship product, the SenseGlove, as possible. Making modifications to the Linda Palm strap is allowed, but the fewer modifications to the SenseGlove are required for a concept, the better the concept scores.

Ease of Aligning the Actuators
Aside from contact maintenance and signal consistency, the ease of aligning the actuators to the correct location on the skin before use, and keeping them aligned during use, is another important criterion for the concept choice.

Ease of Donning and Doffing
This criterion includes the number of steps required to don and doff the glove, and the estimated amount of effort and time required to do so. Fewer steps and the ability to don and doff the product individually and without aid, result in a higher score.

Remaining Degrees of Freedom
The Remaining Degrees of Freedom is another important criterion, and encompasses how much the combined glove hampers the motions of the user through its geometry. These motions are specifically about folding the palm of the hand and moving the fingers.
Ease of Integration
The Ease of Integration with the Linda Strap and SenseGlove criterion is about the physical integration of the combined glove. It is about the physical connections between parts and the wiring between the actuators and PCB(s).

Mechanical Complexity
The Mechanical Complexity criterion is about the number of components of the new palm strap, and the number of changes that need to be made to the existing SenseGlove and Linda Palm Strap design to accommodate the new design.

Hygiene
The Hygiene criterion includes expected sweating and cleaning the combined glove.

Harris Profile

![Diagram of Harris Profile](image)

**Figure 60: Harris Profile for Concept Choice**

The Harris Profile above shows that the Finger Folds concept scores best in terms of Contact Maintenance and Signal Consistency. It is also the concept solution with the most consistency in terms of keeping the actuators aligned during use.

Judging from the overall shape of the towers in the above Harris Profile, the Finger Folds is the concept that shows the most potential as a product to compliment the SenseGlove. Therefore, the Finger Folds concept will be further developed in the Embodiment phase, detailed in the next part of this chapter.
You can see Virtual Reality, you can touch Virtual Reality, and now you can feel Virtual Reality move in the palm of your hand with four haptic rings that provide vibrotactile feedback independently from one another in any configuration of the user’s fingers, with maximum signal clarity and contact maintenance.
The Finger Folds form a modular expansion to the SenseGlove which enables the user to feel motion across the palm of the hand when they touch something which moves in Virtual Reality. This motion is made tangible through localised vibrations at ideal locations on the human palm.

The Finger Folds design consists of four modules and a central hub. Each finger fold module can easily be connected to the hub, which is located between the body of the SenseGlove and Linda’s Palm Strap.

Each Finger Fold module provides localised vibrational haptic feedback independently from one another. Each of the modules is connected to one of the user’s fingers, which aligns it automatically and keeps the module aligned even when the finger is at extreme angles or when the hand is folded.

Two Injection moulded pieces of ABS form a housing for a PCB that converts incoming signals from Virtual Reality into four separate vibrational patterns, one for each connected Finger Fold module.

A computer sends one data package to the SenseGlove and the Hub, and it arrives at both through a split micro-USB cable. The SenseGlove and the Hub both only read the information that is important for them, and discard the rest. No changes were made to the SenseGlove itself, nor the data it needs to send.
The Finger Fold modules can be connected to the Hub using 2-pin 0.78mm connectors. These connectors transfer the ideal amount of data for haptic actuators, and feature a snug fit. They are commonly used in the designs of earbuds specifically for athletes. Because of the length of the cable, no stress is exerted on the connection during intended use. Easy to connect and disconnect, with minimal risk of detaching during use, no matter the configuration of the user’s fingers.

Each module contains a D40 Linear Resonant Actuator which is separated from its housing by a thin damping layer of cast skin safe silicone. This damping layer prevents resonance and travel of the signal through the geometry of each module, directing the haptic feedback into the skin. The actuator itself is separated from the skin through a protective layer of Nylon, which has no noticeable impact on the haptic feedback. This layer facilitates physical travel of the actuator over the skin slightly, allowing for a smoother user experience when transitioning the fingers from extreme orientations.

The hinge is the most pivotal part of the design. This mechanism is what keeps the Linear Resonant Actuator that provides the vibrational haptic feedback on the skin at all times. A little torsion spring keep the part of the finger fold that contains the actuator positioned at a downward angle. The hinge itself also contains a mechanical lock, preventing it from going further than 15 degrees downward, into the palm of the user. This, together with the unique geometry of the housing, prevents the component from digging into the skin during use. The limit for upward rotation is 90 degrees.
The wiring of each actuator travels through the hinge and into the top housing of each Finger Fold module. From there it travels down through a Nylon tube sewn onto the velcro strap, into the bottom housing. From the bottom housing it is a straight line through a shielded cable towards the 2-pin 0.78mm connector.

The Finger Fold modules can be connected to the Hub using 2-pin 0.78mm connectors. These connectors transfer the ideal amount of data for haptic actuators, and feature a snug fit. They are commonly used in the designs of earbuds specifically for athletes. Because of the length of the cable, no stress is exerted on the connection during intended use. Easy to connect and disconnect, with minimal risk of detaching during use, no matter the configuration of the user’s fingers.

A Nylon layer is present between the ABS housing and the skin of the finger of the wearer. This is partly to increase comfort, and partly to shield the wire from the user’s skin.
Linda Plaude's design for the Palm Strap ties the Hub and SenseGlove together through velcro straps and velcro patches. The geometry of the SenseGlove, Hub and Linda's Strap are flush, keeping them locked in place relative to each other during use.

The velcro straps allow for control over the tightness of the fit around the finger. It is a slimmer version of the velcro strap used for the thimbles of the SenseGlove itself.

The ABS housing follows the form language of the SenseGlove and can be produced using the same production processes.

Linda Plaude’s design for the Palm Strap ties the Hub and SenseGlove together through velcro straps and velcro patches. The geometry of the SenseGlove, Hub and Linda's Strap are flush, keeping them locked in place relative to each other during use.
Embodyment

Usage Scenario

The image below, Figure 61: Scenario, shows the steps required for donning the combined SenseGlove, Linda Palm Strap and Finger Fold product. After these seven steps, the

1. Use the velcro straps of Linda’s Palm Strap to tie the Hub and SenseGlove together
2. Move your hand underneath the velcro straps of Linda’s palm strap and tighten the straps
3. Pre-form the velcro strap of the Finger Fold modules so they are easier to put on
4. Slide the Finger Fold modules over the finger to the proximal phalanx and tighten the velcro strap
5. Plug in each 2pin connector to the closest socket on the Hub
6. Put on the thimbles of the SenseGlove, one on each finger
7. Insert one end of the split micro-USB cable into the SenseGlove and one end into the Hub

Figure 61: Scenario
The actuator

Each Finger Fold Module is equipped with a D40 Linear Resonant Actuator. These actuators are used in the newest iteration of the SenseGlove for each of the fingertips, and have been recommended by the Chief Technical Officer of SenseGlove B.V.

Using the same actuators that the SenseGlove already uses, means the interaction experience is consistent for the user between products. It also allows SenseGlove to order their actuators in bulk, use the same haptic drivers, and rely on their existing haptic library.

An image of a D40 LRA can be seen below in Figure 63, while Figure 62 shows an exploded view of a standard LRA design similar, if not identical, to the design of the D40.

Figure 62: A ‘standard’ LRA design
("Linear Resonant Actuators - LRAs - Precision Microdrives", 2019)

Figure 63: A D40 Actuator
Information Communication

Figure 64 shows the information communication between the different products and modules. Unity, running on a PC, determines what haptic feedback needs to be provided based on positional data it receives from the SenseGlove through a micro-USB cable. In return, it sends information on the haptic feedback that should be provided by the SenseGlove and each Finger Fold Module back through the same micro-USB cable. The cable is split with a conventional micro USB splitter. The signal is received by both the SenseGlove and the Hub.

The SenseGlove ignores the data meant for the Hub, and the Hub ignores data meant for the SenseGlove. The Hub then uses an I2C Multiplexer to select the correct driver so the signal for the haptic feedback arrives at the actuator in the correct Finger Fold Module. The Hub features four drivers, one for each connection that a Finger Fold Module can be plugged into. According to Chun Lam of SenseGlove B.V. the hardware components on the Printed Circuit Board of the Hub will take up roughly 24x20m2 for the drivers and the micro-usb connection, and 19x14m2 for the I2C Multiplexer.

![Diagram](image)

*Figure 64: Communication between the different products and modules*

In the above figure, the grey part of the communication scheme is the current communication scheme of the SenseGlove. The addition of the Hub and the Finger Fold modules is shown in light blue. The exact internal working of the SenseGlove’s hardware and firmware in confidential information and has been left out of this report.
Wiring

One of the key factors of this design is the wiring of the D40 actuator to the PCB inside the Hub. The wire travels from the actuator through the hinge and into the housing as illustrated in Figure 65, below. Then, it travels from the left housing through the nylon tube into the right housing. From there, it travels through the plastic cable to the 2 pin connector that can be plugged into the PCB of the Hub.

*Figure 65: The path the wire has to travel from actuator to 2-pin connector*

When the human finger is moved around its axis through its connection to the metacarpal bones, as shown below in Figure 66, the length of the cable required to cover the required distance to the Hub can increase with up to 15mm.

*Figure 66: The required length increases as the finger is folded*

This issue can be resolved by increasing the length of the cable to a size where the extra distance is no longer a problem. This is the easiest and cheapest solution, and the extra cable length facilitates the use of the Finger Folds as a potential prototyping tool for the company. The cable curves slightly as a result.
Connector to Hub

The SenseGlove received information from a PC through a Micro-USB connector. Micro USB connectors are too large for the connection between each Finger Fold Module and the Hub. They are also capable of sending much more data than required. Audio Jack connectors have present similar issues.

Instead, a 2 pin 0.78mm connector was recommended by Chun Lam from SenseGlove B.V. These connectors are commonly used to connect the earbuds of athletes. They are easy to plug in and detach, but fit snugly enough into the hub so that there is no risk of them disconnecting during regular intended use.

The wiring is not taut enough either to put force on the connector during regular use nor while the fingers are held in extreme angles.

Figure 67:
Top: The connector with its corresponding plug in the Hub
Bottom: An example 2 pin 0.78mm connector
("Earphone Accessories from Consumer Electronics on Aliexpress.com | Alibaba Group", 2019)
Material

The housing for the Hub is made of the same material as the housing of the SenseGlove itself: Acrylonitrile Butadiene Styrene, or ABS for short. This polymer is well known for its relatively high impact resistance and toughness. Making the Hub from the same material as the SenseGlove makes it a natural fit with the company’s corporate identity and a clear add-on for the SenseGlove itself. The housings on each Finger Fold Module are made of the same color ABS as the Hub and the SenseGlove.

![LEGO bricks](image)

*Figure 68: LEGO bricks are made from Acrylonitrile Butadiene Styrene (ABS) ("The Lego Movie: The 10 greatest individual Lego bricks ever made | Metro News", 2019)*

Linda’s Palm Strap consists of two layers of plastic: a Nylon outer layer, and a Sorbothane X-Tra Flex Vibration Damping Sheet as the inner layer. The specific Nylon fabric used for the Palm Strap is supplied by the brand Fatboy and is water and dust resistant. This material would lend itself well for the fabric tube for the wiring in the Finger Fold Modules.

![Fabric samples](image)

*Figure 69:*

Left: The Fatboy Nylon Fabric
Right: The Sorbothane Vibration Damping Sheet
The velcro strap itself is very similar to the velcro straps used in the latest iteration of the SenseGlove. The only difference is the width of the strap, and the addition of the Nylon tube. The velcro strap without the Nylon tube looks as shown below in Figure 70.

![Velcro Strap Close Up](image1)

*Figure 70: Velcro strap close up*

The thin layer of fabric covering the D40 actuators, so they do not touch the skin directly, should be fashioned from the Fatboy-supplied Nylon as well. A brief test between direct skin contact and a thin layer of Nylon resulted in no perceivable difference in the signal consistency or signal propagation. The Nylon layer did result in the actuators physically traveling over the skin more easily, which prevents the geometry of the Finger Fold Modules from digging into the user’s skin when making a fist. Figure 71 below shows a prototype with and without a protective nylon layer on the LRA.

![Prototype with and without Nylon Layer](image2)

*Figure 71: Nylon vs no-layer: no perceivable haptic difference*
The silicon rubber damping layer between the D40 actuator and its housing in each module should be made from Cured Ecoflex GEL. Ecoflex Gel is a low viscosity silicone rubber that is soft, stretchy and most importantly, skin safe. It can absorb the vibrations from the actuator without irritating the skin of the user. It is commonly used for haptic devices. ("Mold Making & Casting Materials | Rubbers, Plastics, Foams & More!", 2019)

![Example skin safe Ecoflex GEL](image-url)  
*Figure 72: Example skin safe Ecoflex GEL*

The Finger Folds and the Hub also feature 4 standard stainless steel torsion springs, a Printed Circuit Board, electrical wires and 12 standard m2.5 stainless steel hex bolts.
Production

Injection Moulding is the production process of choice for the ABS pieces of both the Finger Fold Module and the Hub. Injection Moulding is currently used for the housing of the SenseGlove itself. The company is familiar with the production process and can rely on their current partners for the production of these parts. Each of the housing parts of the Finger Fold modules, and the housing of the Hub, have been design with injection moulding in mind.

The ecoflex silicone rubber damping layer will have to be cast by mixing the base components and using a special mould. SenseGlove B.V. could do this in-house with a 3D printed (and sanded) mould.

The velcro strap and the nylon tubing for the wiring have to be sewn together. The materials required for the components can be provided by the current suppliers of velcro straps for SenseGlove B.V. as well.

The Printed Circuit Board for the Hub can be supplied by the same supplier that SenseGlove B.V. currently employs for the PCBs of the SenseGlove and the Linkbox.

The remaining components (the spring, actuator, m2.5 hex bolts), are all off-the-shelf components that can be bought in bulk.
Assembly

The product consists of seven sub-assemblies that need to be assembled in order to work together. Four of those assemblies are the Finger Fold modules. The other three sub-assemblies are the Hub, Linda’s Palm Strap and the SenseGlove (which itself consists of at least six sub-assemblies).

The assembly of the Hub is relatively simple. The first step is to align the PCB in-between the two parts of the housing. The second step is to close the housing by placing the top part on the bottom part. The final step is to insert the off-the-shelf m2.5 hexbolts and lock the housing.

The assembly of a Finger Fold module contains more steps. The main challenge for the assembly is the path the wiring has to follow from the actuator to 2-pin connector. The Hinge is the most complicated part of the Finger Folds, and consists of three pieces of housing that can be slid onto each other and finally screwed shut.

The Nylon tube on the velcro strap must be sewn on.

The assembly process can be seen on the next page in Figure 73: Assembly Process.
Figure 73: Assembly Process (continues on the next page)

Figure 74: Exploded View of combined product (left) and Finger Fold Module (right) (continues on the next page)
Cost

The SenseGlove is not sold on a large scale yet, and since the Finger Folds only work with a SenseGlove, the batch size of the Finger Fold Hub and its Modules should be small. This increases the individual costs per component. Many of the components used by the Finger Fold modules are already bought in bulk by SenseGlove B.V. at this time, including the screws and velcro straps.

The table below shows estimates for the costs for each component, assuming 100 Finger Fold products, consisting of one Hub and four Modules. The costs for the ABS housing parts include tooling costs for the moulds and were estimated using custompartnet.com. The exact estimates provided by the website can be found in Appendix E: Custompartnet Estimates.

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost in Euros per part</th>
</tr>
</thead>
<tbody>
<tr>
<td>D40 Actuator</td>
<td>4.00</td>
</tr>
<tr>
<td>Velcro Strap</td>
<td>1.00</td>
</tr>
<tr>
<td>Nylon Tube and strips</td>
<td>1.00</td>
</tr>
<tr>
<td>ABS Housing, Hub</td>
<td>43.63 (174.50 divided by 4 modules)</td>
</tr>
<tr>
<td>ABS Housing, Module (combined)</td>
<td>29.80</td>
</tr>
<tr>
<td>Printed Circuit Board</td>
<td>2.00 (8.00 divided by 4 modules)</td>
</tr>
<tr>
<td>2 pin connector</td>
<td>4.20</td>
</tr>
<tr>
<td>35mm of shielded electric cable</td>
<td>~ 0.002</td>
</tr>
<tr>
<td>Stainless Steel Spring</td>
<td>~ 0.002</td>
</tr>
<tr>
<td>m2.5 Hexbolts (per 2)</td>
<td>~ 0.0005</td>
</tr>
</tbody>
</table>

The total estimated material and component cost per combined Finger Folds expansion to the SenseGlove amount to:

342.566€

The Hexbolts cost less than 0.50€ per 1000 pieces at various webshops, and SenseGlove B.V. already owns a sizeable amount of these Hexbolts. Similarly, the stainless steel torsion springs cost 0.20 per 100 pieces. The shielded electric cable can be found on the same webshop at the price of 0.44$ per meter if a coil of 500-2000m is purchased. (“Alibaba.com”, 2019)

The 2 pin 0.78mm connectors are listed on aliexpress.com for 4.60$ per two, which converts to roughly 4.20€ at the time of this writing. If a store can be found that sells them in bulk, the cost per part should drop down significantly.
The cost for worker hours on assembly has not been taken into account in the above calculation. This part of the cost estimation largely depends on whether the company wants to outsource the assembly and how large the batch sizes are.

The Ecoflex material costs are hard to estimate because of the difference in volume between the base materials and the required amount of finished material for the damping layer. Ecoflex is made by combining base components and casting the resulting mix into a mould, which can be 3D printed by SenseGlove B.V. at their own workshop. The volume for the damping layer is approximately 0.45 cm^3, or 0.00045 L.

It is currently unknown how large the volume of base components is that are required to produce the required amount of Ecoflex GEL. The base components for the material cost 32.21$ for 2lbs. To calculate the volume provided for that price, the density of the base components is required. Unfortunately, the Ecoflex website does not list this value.
Prototyping

This design was made possible through the aid of a small prototype. This prototype was the first step in Iterative Design for this phase of the project. Unfortunately, no time was allocated for consecutive iterations of prototypes, but the first prototype did improve the design.

The prototype can be seen in Figure 75 below. It shows a 3D printed model using the same actuators as in the Lab Study earlier in this project. The prototype made it apparent that the axis of rotation of the hinge needed to be lowered and the angle of rotation mechanically locked. It also allowed for testing of the haptic feedback consistency, especially in regards to protective layers on the actuator.

![Prototype finger folds](image)

*Figure 75: Prototype finger folds*

Other issues that came to light thanks to the prototype were the actuator housing digging into the skin, and the housing on the velcro straps limiting the degrees of freedom of the user’s fingers. These issues have since been addressed in the current iteration of the design.
Recommendations

Design

The raison d’être for this design is to allow the user to feel a sufficiently realistic motion across the palm of their hand. This largely depends on the waveform the vibration motors put out, and a sufficiently realistic experience has yet to be defined. The first recommendations for SenseGlove therefore is to identify this waveform through testing.

The form language of the Finger Fold modules is close to the SenseGlove, but did not hit the mark. The form language of the SenseGlove is rounder with more curved edges. A next iteration should match the form language better.

For future iterations of the design, the hinge should be looked into more carefully. Its geometry and mechanism can both be simplified to allow for easier production and better performance. The mechanical lock that the geometry provides could also be improved. The fillet on the geometry in the renders of the model increase the angle before the lock kicks in slightly, which should be prevented in future iterations.

Its spring is currently a torsion spring, but different kinds of springs might suit the mechanism better. Leaf springs will permanently deform and are therefore unsuitable, but a coil compression spring, like the ones used by common ballpoint pens, might have potential if it runs perpendicular to the length of the finger. With a Hexbolt at the far end of the top housing, a compression spring could improve the design by making the force of the spring configurable by adjusting the Hexbolt.

In order to allow for maximum flexibility, the size of the housing on the finger should be reduced, together with the width of the velcro strap. The length of the housing and the width of the velcro should be based on the size of the visible part of the proximal phalange of the little finger of the P5 part of the population database. Unfortunately, this measurement has not been documented in DINED.

Figure 76: The shorter version of the Finger Fold module
An ABS casing for the actuator as a replacement for the Nylon coating between the actuator and the skin has not been tested, but could be a good alternative to the Nylon patch. The Nylon patches currently do not have a good way to be fastened to the housing. This could be done with double sided tape, but this should not be used as a permanent solution. In a future iteration, a Nylon patch could be locked in place by two edges of the injection moulded ABS housing. The next iteration should also place the wiring inside the housing, instead of next to the skin and separated by only a thin layer of Nylon. The Nylon layer is recommended for mental and physical comfort.

All housings in the design can be injection moulded at this point, but some of the moulds would have to consist of four parts, which means the housing parts are too complicated. Each of the housing parts should be brought to moulds that consist of three parts at most. The wall thickness of the housings is also not consistent through the design, which leads to potential issues with injection moulding. The next iteration should have consistent wall thickness.

The cable between the 2 pin connector and the bottom housing of the Finger Fold module needs to be looked at as well. It is currently not fastened in the housing, although the mousing does leave enough room for this to be implemented in the next iteration of the design.

Aside from feeling motion across the skin, the design lends itself well for prototyping through its modular design, or “Haptic Sketching”. Any individual Finger Fold module can be worn in numerous ways to prototype interactions, and with the correct waveforms, vibrations can be used to create the illusion of impact just as easily as the illusion of motion.

*Figure 77: Various ways to wear a Finger Fold Module to prototype different interactions*
The Hub lends itself well to prototyping as well through its four 2-pin connectors. Any future modular expansion to the SenseGlove that features a Linear Resonant Actuator can be hooked up to it and used in conjunction with the SenseGlove.

The micro-USB connection between the PC and the Hub, as well as the PC and the SenseGlove, should be replaced with USB-C ports in the future. These ports allow for more data to be sent faster than the current micro-USB solution.

**Interaction**

As mentioned after the Lab Study, the user should be taught what the feedback means in advance as long as a suitable waveform for motion across the skin has not been found. This way the user can familiarise themselves with the feedback and what it means, and the functionality of the product can be evaluated before use. If one of the Finger Fold modules is not working as intended, this can be recognised in advance and a faulty module can be switched out for a working one easily because of the modularity of the design.
Evaluation

The Product

Without a prototype of the final iteration of the design, it is difficult to accurately assess the design on all requirements. However, the first iteration prototype of the Finger Folds and the subsequent theoretical changes made to the design, do allow for a fairly accurate estimate.

The prototype proves that the product provides haptic feedback to the intended area regardless of the orientation of the fingers, thanks to continuous contact maintenance of the actuator with the skin. There is no significant travel of the signal through the product itself, nor any noticeable resonance of parts. The newest iteration of the Finger Fold modules no longer prevents one degree of freedom for each finger.

All these aspects of the design combined lead to clear signal consistency and clarity, and a robust design that follows the form language of the product it is intended to enhance: the SenseGlove. The design succeeds in its intended purpose without modifying the existing design of the company’s flagship product.

Program of Requirements

Aside from two requirements, all of the design criteria were met. The design currently can not be manually calibrated, but a suggestion has been added to the Recommendations on how to implement physical calibration for hand sizes that the current model fails to account for.

The second criterion that has not been met, is that the wiring must not be exposed to the skin of the user. To save material and keep injection moulds relatively simple, the ABS housing of the Finger Folds has a shape that does not allow the wiring to be hidden from view completely. In fact, the skin and wiring are currently separated by a small layer of Nylon fabric, which is a poor protective layer for the electronics of the Finger Folds. However, this criterion can be met in a future iteration of the design without issue.

Research

The Lab Study did not show significant results because of the many confounding factors in the setup, but its results did suggest the need for a more realistic handling experience of a virtual steering mechanism, and an application most suited to SenseGlove B.V. to implement it.
Project

This project originally started as a proof of principle from SenseGlove B.V. for the Dutch Ministry of Defense. During the project, the focus shifted and became smaller and smaller, until just the palm area of the user’s hand was left.

In hindsight, there are many things that could have gone better or that I would do differently knowing what I know now, ranging from increasing clarity in the first phases of the project to starting with iterative prototyping earlier. Research by doing, not by reading.

I picked up many new skills during this project, which I intend to keep relying on in future projects. These skills include, but are not limited to: working with Unity, MatLab, Arduino, soldering electronics, setting up and executing an advanced Lab Study, and making and sticking to realistic plannings.
Appendices

The appendices consist of multiple datasets and large, inter-connected files of code that rely on one another to analyse those datasets, 3D models and technical drawings. Due to the large size of these files, the appendices have been uploaded separately and can be accessed through a persistent link.

A .zip file containing the appendices can be found at the following DOI:

10.4121/uuid:94b0d382-0a93-4a34-93b6-853d0bd110ce

The Appendix list is:

Appendix A: Keywords
Appendix B: Arduino Code
Appendix C: Data per Participant
Appendix D: Matlab Code
Appendix E: Custompartner Estimates
Appendix F: Questionnaire
Appendix G: Questionnaire Data
Appendix H: Material Data Sheets
Appendix I: Technical Drawings
Appendix J: Exploded View of Lab Study Prototype
References


MIHELJ, M. (2016). Virtual reality technology and applications. [Place of publication not identified]: SPRINGER.


