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Masterarbeit

Evaluating Different Combinations of Haptic Feedback devices in Virtual Reality

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Abstract

VR-based systems have been using more and more haptic feedback devices for enhancing immersion and interaction, not only in the consumer market but also in industrial applications. However, different combinations of haptic feedback devices could result in different user experiences. To evaluate different types of multimodal haptic feedback, an exemplary use case was built in which combinations of STRIVE, STROE, and SenseGlove can be used. Since the use case was developed close to typical virtual buildability working patterns in the automotive industry, only VR experts from the respective departments were invited to participate in the subsequent user study, designed to evaluate the different combinations of haptic feedback devices. Participant feedback was recorded using a haptic questionnaire and an interview to obtain a broad spectrum of feedback that provides essential information for development in the future.

Feedback from participants shows that currently, a combination of collision simulation and weight force simulation by the STRIVE and STROE devices leaves the best impression. Other important findings show that haptic feedback is generally very well accepted, but that full haptic feedback is not always required, since not all haptic impressions are necessary for every work step. Thus, while haptic grasping is beneficial in some of the tasks, it cannot keep up with the simplicity of the controller due to imperfect precision, among other things. A promising prospect for the future is therefore the implementation of finger tracking in combination with collision feedback and weight simulation as a middle ground between haptic grasping and the use of a controller since the haptic feedback of STRIVEs and STROE could thus be applied directly to the user's hand.

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Acronyms

AR Augmented Reality. 23

BLE Bluetooth Low Energy. 25, 55

CI Confidence Interval. 42, 43

DOF Degrees of Freedom. 16

FPS Frames per Second. 30, 55

SDK Software Development Kit. 23

VR Virtual Reality. 3, 13, 14, 15, 17, 18, 19, 20, 22, 23, 33, 34, 35, 52, 57, 58

1 Introduction

The development of Virtual Reality (VR) has been very rapid in recent years. Thanks to new technical advances, and increasingly affordable hardware, it has become popular on the consumer market for several years. The constant improvements and decreasing costs have a similar effect on the industry. Here, too, there are now several use cases where VR is being applied, such as in medical applications or the automotive industry. They are not only used as visualization tools or for training or instruction for employees but also in product engineering. These range from product creation to product development and through the entire production process. By using VR, high costs can be saved that real prototypes would entail compared to virtual prototypes. Through numerous development iterations, no resources are expended in VR compared to real prototypes, but only the virtual models are updated before an actual prototype is created in the final step. Despite very detailed prototypes and the advantages of virtual simulations, there are also disadvantages that virtuality brings with it. In order for VR applications to present a smooth and precise simulation of reality, the requirements for the connected PC are very high. For private use, accuracy of virtual models can be compromised in favor of a fluid performance, but industrial use requires very high precision to keep the difference between the virtual twin and reality as small as possible. This has been achieved in multiple industries and working environments as Nomura and Sawada [NS01] show in their overview of different use cases for VR.

In order for virtuality and reality to match as closely as possible one important difference between VR and the real world, that must be bridged is haptics. Where haptics is defined in the most basic sense as feeling. In real world, this haptic sense is stimulated every time an object is touched, but in plain VR, this haptic sense is completely absent as the user usually interacts by using controllers. However, initial projects involving additional haptic feedback in VR already have been piloted [AM09; Sto00].

Robles-De-La-Torre [Rob06] provided a good foundation for this work to understand the importance of haptic feedback in VR by stating how important the haptic sense is for human perception, even comparing it with the sense of sight. These statements by Robles-De-La-Torre [Rob06] demonstrate how much haptic feedback can improve immersion and realism, as bare VR cannot address the haptic sense. Adding haptic feedback should therefore bridge the gap between VR and the real world, as the goal is to make interactions feel as natural as possible.

For this purpose, it is necessary to differentiate between haptic stimuli that exist in reality in interactions such as grasping or lifting an object. These different haptic impressions need to be translated into haptic feedback for the virtual world. The multimodal haptic feedback to be applied in the virtual environment must be induced by multiple devices since no device is known yet to provide full-scope haptic feedback. In general, the combination of multiple haptic feedback devices is still comparatively unexplored. Therefore, the challenge will be to evaluate which types of haptic feedback can reduce the difference between the real world and VR or whether multimodal haptic feedback might also be partially redundant.

For this work, the selection of which haptic senses should be stimulated was driven by the task of assembling parts in an automotive use case which mainly involves grasping and moving virtual objects. Here, the weight force that each real object brings with it plays an important role, as this force cannot be simulated in VR with controllers. Another important sense, the sense of physically holding an object, and touching it with individual fingers is much closer to a real interaction rather than just pressing a button. A further haptic sense, which is also involved when moving objects, is the feeling of collision resistance with other objects. With the use of multiple haptic feedback devices, the goal is to simulate these haptic senses.

In a next step, the devices that provide haptic feedback are then relevant. To deliver a convenient application for industry, the benefits generated by haptic feedback devices must be greater than the effort involved, which is not only cost but most important the time required to install and use them as well as reliability also plays a crucial role.

Therefore, in this thesis STRIVE [AAP+21], STROE [AASV22] and SenseGlove[1] were selected as haptic feedback devices and combined in an exemplary automotive use case, which could be encountered in the industry. By using STRIVE, haptic collision feedback can be applied. STROE is used to simulate weight force of virtual objects and SenseGlove provides the effect of haptic grasping. In a combination of haptic feedback devices, the haptic impressions that arise during natural interaction with objects are to be brought as closely as possible to VR. Through an expert study, different combinations of the devices will be tested with the intention to reveal which types of haptic feedback harmonize well together and are reasonable in use. Our contribution is therefore to achieve an initial assessment of what advantages and disadvantages different multimodal haptic feedback by combining multiple devices bring, and thereby provide a research basis for further development of multimodal haptic feedback.

[1] https://www.senseglove.com/

2 Background & Related Work

In order to get a first insight into the topic of haptic feedback, other work adjacent to this topic is considered in this chapter. To this end, various technologies and prototypes are first presented that provide different types of haptic feedback. After that, there are insights into the automotive industry, where haptic feedback in VR is already applied in research and different driving simulations. Since in this thesis combinations of haptic feedback devices are evaluated, resulting in different types of multimodal feedback, it is also interesting to see how far research in this area has progressed.

2.1 Haptic Technologies

Going back to the start of haptic feedback, Wang et al. [WGL+19] wrote about the evolution of haptics over the past 30 years. They discussed changes in technology, classified haptic devices as desktop, surface, and handheld haptic devices, and explained that handheld haptic devices play the most relevant role for VR interactions. They concluded that providing multimodal haptic stimuli accommodates best human perception. Regarding presence, Kreimeier et al. [KHF+19] showed in a different experiment, that both haptic and vibrotactile feedback perform better than visual feedback only. Also, other performance metrics like task execution time show significant improvements when using haptic feedback. Since the focus of this work is also on handheld haptic feedback devices, it is important to see what alternatives there are to the handheld devices used in this work.

2.1.1 SenseGlove Alternatives

As more and more haptic feedback gloves have come to market in recent years or existing ones have been further improved, there is now a wide range of different devices that can be used. For example, Shor et al. [SZA+18] have taken an older version of SenseGlove[1] used in this thesis and tried to improve it in terms of comfort, realism, and performance. They identified the sensation at the fingertips as well as in the palm of the hand as weaknesses and also redistributed the vibrotactile motors to improve vibration feedback all around. For this, they installed fixed caps on the fingertips to better distribute vibrations. The manufacturers of SenseGlove have also used stronger finger caps in their current model and replaced the older Velcro fasteners. When it comes to feeling on the palm of the hand, Shor et al. [SZA+18] have created a unique feature with multiple vibration motors connected with threads on the inside of the palm. These distinguish them from SenseGlove. On the outside of the hand, the same vibration motors have also been attached, but SenseGlove has also

[1] https://www.senseglove.com/

received a similar update in this regard and can also generate vibrotactile feedback here. Based on the conclusion of Shor et al. [SZA+18], it is visible that all these improvements create a significant improvement over the previous version of SenseGlove.

2.1.2 STROE Alternatives

When simulating gravity, different approaches lead to a similar result. STROE[AASV22] uses an electric motor to generate a real force, which is then transferred to the hand via a thread. In contrast, Grabity[CCM+17] simulates weight force by deforming the skin. This is done with a small device held in the hand that deforms the skin via adjacent finger pads thus generating virtual forces. A user study showed that objects of different weights could be differentiated in this way. However, the simulated weight amounts to less than 100g compared to STROE, which can simulate a weight force of 720g [AASV22]. Another approach, which is called Shifty is shown by Zenner and Krüger [ZK17]. Shifty implements dynamic passive haptic feedback to simulate weight force by using a rod with a stepper motor that can move a weight inside the rod. By shifting weight to different positions, different weights can be simulated. This, not only allows to simulate objects changing in shape and weight but also for a weight simulation initially on picking up virtual objects comparable to STROE. A disadvantage of Shifty compared to STROE is, that shifting weight inside the rod takes up to 2.8s of time and therefore creates a mismatch between the visual and haptic sense as opposed to STROE which can simulate shifting weights instantaneously. However, Zenner and Krüger [ZK17] used additional visual and auditory feedback to compensate for this inconsistency. Cheng et al. [CCC+18] took a different approach with a similar outcome to develop a dynamic haptic feedback device. Instead of moving weight, a plastic bag is filled with water or emptied to simulate different weights of virtual objects. Again, the same issues as with Shifty occur on object pickup, the water cannot be pumped instantaneously into the plastic bag and a similar delay is created.

2.1.3 STRIVE Alternatives

Also in the field of collision simulation, there are several approaches that produce a similar result as the STRIVE [AAP+21] used here. One of them is ElasticVR [TRC19]. ElasticVR is a haptic feedback device that can simulate resistance forces and impact forces. It is mounted on the forearm of the user and is attached to the palm of the hand via a cable pull with an elastic band and a strap. This allows the device to apply varying degrees of resistance to the user's wrist, up to a complete block, and to simulate a recoil force by pulling back on the elastic band. Compared to STRIVE, this provides a wider range of functionality, as STRIVE can only simulate total resistance and no partial restrictions, while ElasticVR is limited to haptic feedback, which is only directed at the wrist. As a result, a wider range of forces can be simulated, but ElasticVR is limited for usage only at the wrist. STRIVE has the advantage that the permanently mounted part of the device is not necessarily on the user's own forearm, but can be screwed firmly at a fixed point such as an assembly frame. Thus, the entire arm or other body parts can be stopped in their movement. Another effect is that movement in different directions can be stopped, depending on how many and in which directions STRIVEs have been set up.

A similar comparison can be made between STRIVE and Thor's Hammer [HCLW18]. The latter is also limited to hand use due to its hammer-like design. However, the hammer has the advantage over ElasticVR [TRC19] that haptic feedback can be simulated with 3-Degrees of Freedom (DOF), which is not limited to the wrist but affects the complete arm of the user. Thor's Hammer works by using six electric motors with propellers that can generate a resistance force through the blast of wind. However, this concept also has the disadvantage that the maximum force of 4N that can be generated by the propellers can be exceeded by the user and therefore cannot simulate a reliable complete stop as with STRIVE. Nevertheless, if we stay within the limits of the simulatable force, results of the user study show that the use of Thor's Hammer also increased realism and immersion.

The device that is most similar to STRIVE is Wireality [FZDH20]. The structure and operation of Wireality are almost identical to that of STRIVE. However, examples of use differ for it. As already described, several STRIVE modules are combined to simulate collisions from different directions. Wireality focuses more on making complex surface structures perceptible, which is why a comparison to SenseGlove is also possible. To use Wireality, several modules are placed in a row on the user's shoulder. The respective strings are mounted on the fingers via finger caps, as well as on the back of the hand and the wrist. If the virtual hand collides, this collision can be transferred very precisely to the real hand at the exact same spot. For example, when probing a surface, the individual fingers can be limited differently according to the surface geometry. The result is therefore also similar to the SenseGlove concept as the limitations on the fingers of the user can be induced in the same way. In a user study, Fang et al. [FZDH20] evaluated that this approach is very precise, comfortable, and immersive for users. A multi-sided setup of the Wireality devices, similar to that of the STRIVE could produce similar functionality to the STRIVE, since the single-sided direction of pull during setup at the shoulder they proposed can only simulate collisions in the frontal direction. This setup could then be much more precise than STRIVE due to the individual connection points on each finger, but would probably also be more susceptible to tangles between the strings, which would then destroy the immersion.

2.2 Haptics in Automotive Industry

In terms of the automotive industry, Lawson et al. [LSW16] have described benefits of using VR. They obtained these findings through interviews with eleven engineers in the automotive industry. Among other things, they also addressed haptic feedback. Thus, they formulated nine recommendations for using VR, one of which reads:

> "Provide haptic feedback for more robust ergonomics investigations."

More specifically, Lawson et al. [LSW16] characterize their statement by saying that vibration, torque, and force needed to hold objects should be simulated. In addition, haptic indicators should show the user's reach. This statement also aligns with the experiment conducted in the course of this work, as the haptic feedback devices that were used simulate these forces since SenseGlove in particular is designed to provide realistic gripping, which can then be supplemented by STROE's weight force simulation.

A similar use case as in this work was investigated by Kind et al. [KGK+20]. In their experiment, a teleoperated robot in VR is used to assemble the cockpit into a car. They stated that haptic feedback can be used to simplify this process and verify and validate human-controlled assembly. The exemplary use case of this thesis does not use a robot but assembles parts by hand since the automotive parts used in this work are smaller than a complete cockpit unit and can be carried with one hand. However, the effect to be created should remain the same. Again, we expect haptic feedback to facilitate the building process, as possible collisions transmitted from STRIVE to the user as well as a realistic weight force combined with realistic grasping provide additional information to validate whether buildability is also guaranteed in the real world. This is important because one of the most commonly encountered use cases of these haptic feedback devices in VR are buildability studies. In these buildability studies, a virtual prototype of the vehicle is created and tested for its buildability. This means that individual work steps are simulated, in which, for example, STRIVE can provide precise collision feedback when it comes to installing a component in a particularly narrow or convoluted area. In this way, potential problems during installation can be noticed and resolved before the vehicle is actually produced.

Further evidence for the effect of haptic feedback is provided by Wildenbeest et al. [WAH+13] who investigated different quality levels of haptic feedback in a teleoperated assembly task, which could be very close to a potential use case in the automotive industry. Even with low-frequency haptic feedback, results show significant improvements in task performance and minimized control effort. When using high-frequency haptic feedback, these results could be minimally improved. It can be concluded that existence of haptic feedback makes the biggest difference whereas quality is of secondary importance in this case. These results thereby further confirm the significance new haptic technology already occupies by now. Since Wildenbeest et al. [WAH+13] show that the quality of haptic feedback is secondary, it should not have too much impact in our case that some of the haptic feedback devices used are still in development stage. Accordingly, technical difficulties can be neglected and the actually important proof of concept can be performed to evaluate if and which haptic feedback makes sense in this use case.

As previous research focused on automotive development and production process, Stamer et al. [SMT20] investigated the advantages of haptic feedback for in-car interactions in VR. They used force feedback gloves to perform virtual in-car interactions, and participants in their study were able to perceive the interactions with haptic feedback significantly faster and more precisely than without haptic feedback. Nevertheless, no significant results in the area of realism could be generated. While the use case in this work does not involve in-car interactions, a potential positive outcome could still be transferred to it as well since SenseGlove and STRIVE alone can generate haptic feedback that covers many of the possible in-car interactions and thus could also be supportive to them.

A similar promising result was achieved by Azzi et al. [ARMK11]. They implemented a visual system in the center console, as well as a force feedback system on the accelerator pedal in a driving simulator to suggest the optimal acceleration level to the driver. This, along with other eco-friendly measures such as early upshifting, which can also be suggested by the system, can save emissions and fuel. Azzi et al. [ARMK11] found that the haptic system was perceived by users to be equivalent to the visual system, but when used simultaneously, the haptic system was relied upon more. This has the added benefit of allowing users to focus more on the road, as no additional visual cues are needed. Even this use case could be represented by a STRIVE mounted on the driver's foot or a modified version of STROE, which pulls the driver's feet away from the gas pedal to suggest a gearshift. Taking the approach of Azzi et al. [ARMK11] further, feedback could also be extended to the driver's hands using SenseGlove, which could then not only display gearshift suggestions through haptic feedback at the hand but also influence steering and, for example, indicate the optimal steering angle for the perfect corner radius. This combination of STRIVE and SenseGlove could also yield interesting results in terms of user experience since in our use case both devices transmit haptic feedback to the user's hand, but in this setup multimodal haptic feedback is induced at different parts of the body.

2.3 Multimodal Haptics

By combining several haptic feedback devices in this work, multimodal feedback is generated. In other experiments, multimodal feedback is commonly generated by stimulating multiple senses with a single haptic feedback device.

For example, Zenner et al. [ZUK21], who were also involved in the development of Shifty [ZK17], added haptic retargeting to Shifty to solve the colocation problem. Haptic retargeting is a software-based technique to bridge distances between real and virtual objects. By combining the software-based approach with haptic feedback, larger spatial distances between the proxy and virtual counterpart could be made imperceptible to the user. This approach differs from ours not only in that the developers of Shifty intended to use a single device to generate multimodal haptic feedback, which in this work is generated by combining multiple devices but also in that it uses a software-based solution to simulate haptic impressions.

A hardware-only approach is provided by Haptic Snakes from Al-Sada et al. [AJR+20], which are different snakelike robots that can provide multiple haptic feedback types on the front and back of the body. Using a snake-like arm, taps-, gestures-, airflow-, brushing- and gripper-based feedback can be generated [AJR+20]. The results of the experiment from Al-Sada et al. [AJR+20], in which users evaluated feedback types, show that there were different opinions about which haptic feedback is most useful, but there was a common conviction to use the robots. This work shows an approach to how multimodal haptic feedback can best be applied to the body. This approach could also be followed with STRIVEs or even with a modified version of STROE to generate multimodal haptic feedback on the body, which could consist of pulling forces in multiple directions or collisions on the upper body.

Multimodal haptic feedback is also used in medicine. Van der Meijden and Schijven [VS09] compared different studies regarding minimally invasive surgery simulations in VR, where they could not yet reach a unanimous positive result for using haptic feedback, but throughout results show a high level of acceptance among users and worse user experience if haptic feedback is missing. Users in this study even conclude that a negative learning effect may occur when performing tasks where pushing and pulling forces play a role without haptics. Another study showed that haptic feedback is the most important factor in learning surgical dexterous skills as it involves touching, feeling, and manipulating organs through instruments [CCMC02]. The work of Abiri et al. [APT+19] is also about minimally invasive surgery but this time with a focus on grasping forces. Abiri et al. [APT+19] use a pneumatic system to provide tactile, kinesthetic, and vibrotactile feedback with the goal of enabling natural grasping with well-dosed force for surgical robots, which is important to minimize tissue damage in surgery that could result from excessive grasping. Here, too, the robotic system can realize a grip strength much closer to that of a human thanks to multimodal haptic feedback. In medicine, a combination of SenseGlove and STRIVE could find an application, as these devices could induce precise multimodal haptic feedback to the surgeon's hand. For this to happen, however, the user study conducted during the course of this work would need to demonstrate perfect interaction between devices, as this application scenario is a high-risk scenario.

Nevertheless, one could assume that this combination would find an application in VR simulation of an operation in order to reduce the distance of the simulation to the real world and to ensure more realistic training for the surgeon.

Another approach is taken by Wolf et al. [WRHR19], who install all haptic actuators in the VR headset. By using a high number of vibration motors and thermal actuators, spatial information about the environment, such as cold winds or individual heat sources in the field of view, can be transmitted to the user. The users of this technique reported a higher level of presence and enjoyment by using this complex haptic feedback system. A combination with this approach would be another interesting research direction since so far STRIVE is the only haptic feedback device that can also be attached to the head. The principle of STROE could also be used here to test lightly dosed tugs on the head to see if, for example, cold winds could be represented even more realistically.

The deciding factor of this work will be how precisely the combinations of haptic feedback devices work, as it has already been shown individually that the devices are versatile. Depending on interaction, precision, and strength between different combinations, solutions could then be tested and further evaluated in the topics described above, which do not necessarily have to be in the automotive industry.

3 Utilized Haptic Feedback Devices

Haptic feedback technology is still in its early stages, and many challenges still remain to be solved. Some of the challenges include providing a wide range of haptic sensations. As MacLean [Mac00] noted in their article, haptic feedback is a multi-parameter design element because the human touch sense has many distinct components, which contain among others force, pressure, and texture. Since the study is conducted for the automotive industry and involves the assembly of automotive components, the surface texture of the individual components is negligible and the focus is therefore more on the different forces involved in the interaction with objects. The following section describes the haptic feedback devices used to represent these forces in interactions with virtual objects. In addition, some adjustments were made in advance, which are as well described in the following.

3.1 STRIVE

The first step in making virtual objects realistic is to make them no longer penetrable but to simulate a solid surface corresponding to their real counterpart. When touching surfaces, the human hand not only perceives the texture of the surface but also a certain resistance to pressure in the case of solid objects. For the virtual object, this means that at the moment of collision between the hand and the surface of an object, the hand must be stopped and further movement in that direction should not be possible.

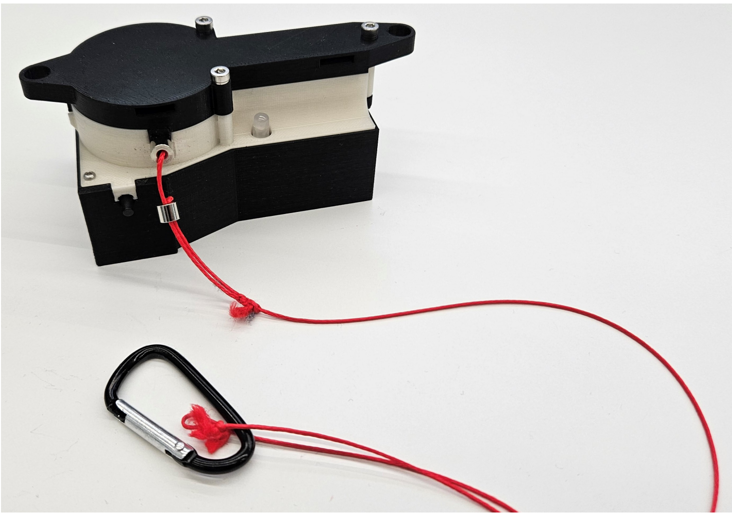


Figure 3.1: A STRIVE module that was used during the user study

This kind of haptic feedback can be achieved by STRIVE, which is visible in figure 3.1. STRIVE is a string-based haptic feedback device, consisting of a small box and a string that can be extracted through openings to each side. Inside the box, an Arduino Nano[1] with a Bluetooth module, that controls a solenoid, is located. By activating the solenoid, a ratchet pawl is pushed inside a ratchet gear, on which the spring coil with the rolled-up string is mounted, which blocks further movement of the gear and thus prevents the string from being pulled out any further. This results in the user being stopped and feeling resistance.

As soon as the collision with the surface of the virtual object is finished, this event is sent to the STRIVE, which deactivates the solenoid again. This allows the ratchet gear to move freely and the string is flexibly coiled or can be pulled out further, depending on the user's movement.

To obtain a collision simulation in all directions, a setup of several STRIVEs is used, which are attached to the controller from different directions. By selectively activating and deactivating the STRIVEs, all collision directions can be simulated. Due to the compact design and the low weight, the STRIVEs can not only be attached to the controller but also to any other body parts where collisions are to be simulated, such as the knee or elbow. [AAP+21]

3.2 STROE

Another parameter of force that can be simulated by haptic feedback is the weight force of virtual objects. Without haptic feedback, all tangible objects can be held in VR regardless of their weight, which can sometimes be unrealistic. Another aspect is, that plain VR does not cause any effects, such as muscle fatigue, which is important for our automotive use case, as heavy objects are regularly part of the assembly process.

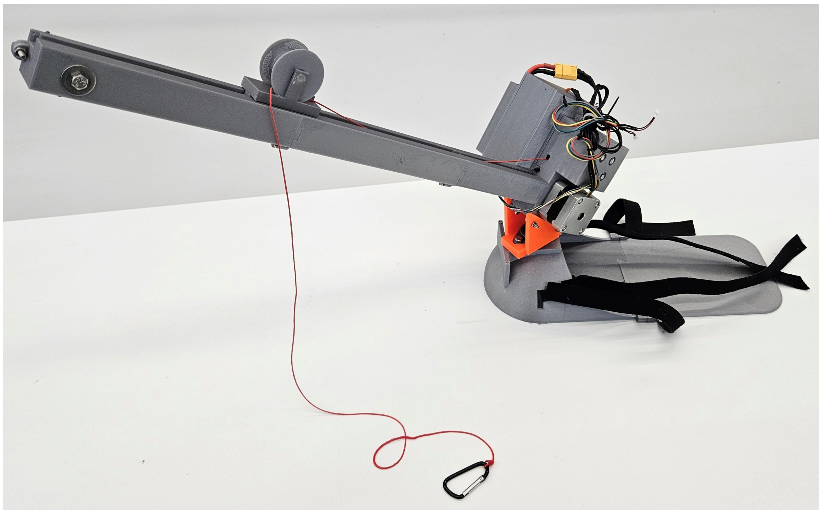


Figure 3.2: The haptic feedback device STROE

[1] https://store.arduino.cc/products/arduino-nano

STROE (figure 3.2) is a haptic feedback device that can generate real weight force through a motor via a rope connected to the user. It consists of a cover for the user's shoe, with a crane-like structure above it, in whose housing the electric motor is mounted along with the electronics and the rope coil. The rope is unwound via a diagonally upward arm with a pulley, from where it can be mounted on the user's hand, controller, or any other device on which the weight force is to be applied. When a virtual object is lifted, the motor is activated, which now rolls up the rope connected to the user and pulls on it with the appropriate weight force of up to 720g. The data necessary for communication with the computer is sent via a Bluetooth connection to a serial port. [AASV22]

3.3 SenseGlove

The SenseGlove is a haptic feedback glove developed for use in VR and Augmented Reality (AR) applications. In this study, the SenseGlove Nova[2] was used. It allows users to experience haptic feedback, providing a sense of touch and sensation as they interact with virtual objects. The glove includes a combination of sensors and actuators that simulate the shape, size, and texture of virtual objects. A tracker, like in this case the Vive trackers or other frequently used trackers or controllers can be mounted on the glove to keep them tracked in the scene. By measuring the finger movements through the attached strings in the finger caps in a calibration step, all real-world movements of the hand can be translated to the virtual hand in the scene.

If the user now grasps a virtual object, the strings can be stopped on contact by activating the motors and thus limiting the finger movements. This means that it is no longer possible to grasp through objects but rather resembles the feeling of grabbing a real object. The fingers can not only be stopped completely by the motors but also be given a resistance that can be partially pushed through. The application case for this is deformable objects that are made of rubber, for example. Thus, with a respective effort, the virtual object can also be pressed in. Objects are not only deformable but also breakable, in this case, the limitation of the finger movements is jerkily removed, in order to simulate a breaking of the virtual object. The SenseGlove can be used in a variety of ways, not only to represent the shape of virtual objects but also to simulate surface textures through vibrotactile feedback. For this purpose, vibration motors are used at the fingertips, which can simulate different surfaces through different vibration patterns and intensities.

In order to integrate these functionalities into the project on the software side, the SenseGlove Software Development Kit (SDK) provides out-of-the-box scripts that can be used to set all parameters that influence the behavior of the virtual objects.

3.4 Enhancements

Even before the pilot study, initial tests during development showed that the combination of these haptic feedback devices did not work out of the box and still had to be revised, both on the software side and on the hardware side. This is why the project and each of the haptic feedback devices were searched for vulnerabilities, that could be improved.

[2] https://www.senseglove.com/product/nova/

3.4.1 SenseGlove Enhancements

Starting with SenseGlove, which received the smallest modification of the haptic feedback devices used in this project, as SenseGlove is hardly modifiable as an external product. However, in order to use it in combination with the other haptic feedback devices, attachment options had to be created, since the strings of the STRIVEs and the STROE have to be attached to the user's hand as well. The strings could not be tied directly to SenseGlove because it had to be possible to switch systems quickly between conditions in the subsequent user study. Previously used Velcro straps could not be used in combination with the SenseGlove, as they tangled up with the cloth of the SenseGlove, which resulted in a bad user experience and also showed wear on the cloth really fast. For this purpose, instead of the Velcro straps, carabiners were attached to the string ends of the other haptic feedback devices, which then had to be hooked onto the SenseGlove. Originally, a thin thread was tied around the back of SenseGlove's hand to attach the carabiners. Finally, this design was revised and improved again after feedback from the pilot study. The final design consisted of a metal eyelet that was taped to the back of the SenseGlove's hand using an adhesive pad, and a small loop of thread was made on both the left and right sides of the SenseGlove for the strings on either side to be hooked into. The string of the STROE coming from below could be hooked on the palm of the hand to one of the fabric straps of the SenseGlove.

3.4.2 Bluetooth Connectivity Enhancements

One issue that had to be resolved before the pilot study could begin was Bluetooth connectivity. According to Lee et al. [LSS07], the limit of a Bluetooth network is eight devices, one of which acts as the master, which in this case is the PC running the project. This PC can connect to seven slave devices simultaneously. For this project, the following Bluetooth devices needed to be connected at the same time:

- HTC Vive Controller[3]
- HTC Vive Tracker[4]
- SenseGlove
- 3 STRIVEs
- STROE

Data rate and connection strength are additional factors, which can negatively impact this limitation of seven slave devices since the maximum data rate of the Bluetooth protocol is $0.72 MBit/s$ which may not be sufficient for communication with all of the devices that are combined for this study. As the Vive Tracker and Controller are not used at the same time, one could safely disconnect the unused one, regardless, the number of devices does not exceed the limit of seven and therefore the device can stay connected. Nevertheless, tests during development showed that in eight out of ten cases, a stable Bluetooth connection to all devices could not be established at the same time and individual connections often had timeouts. Since the exact data rates of the individual devices

[3] https://www.vive.com/de/accessory/controller/
[4] https://www.vive.com/de/accessory/tracker3/

are not known, it can only be assumed here that this was the reason for the connection problems. Evidence for this assumption is that all devices worked without problems as long as they were connected individually or only some of them were connected and others turned off. Only connecting all devices at the same time resulted in connection timeouts.

3.4.3 STRIVE Enhancements

To solve the problem described above, the Bluetooth Low Energy (BLE) protocol needed to be introduced replacing the standard Bluetooth protocol. Therefore the HC-05[5] Bluetooth module in the STRIVEs was replaced by an AT-09[6] BLE module. Regarding the connectivity to the PC only the C# script handling the connection needed to be changed, as the Asus USB-BT500[7] Bluetooth dongle, which was used here, supports both the standard Bluetooth protocol and BLE. To handle the BLE connection a prefabricated dll package by Adam Brunnmeier [Ada21] was imported into the project. Also, the connection handler script was oriented closely at this project. Switching to the BLE protocol also made the connection process more convenient. Previously, each STRIVE needed to be paired through Windows settings and was assigned a serial port number. Then, one could establish a connection and communicate by sending messages over this serial port. However, this was prone to errors, so the connection needed to be reset and the devices must be paired again. This resulted in them most likely receiving a different serial port number, which then needed to be changed throughout the project. Communication using the BLE protocol does not need the pairing step at all. BLE uses a unique Bluetooth Device Address, which never changes. Therefore as soon as the STRIVE, matching the hard-coded Bluetooth Device Address was found, the connection could be established by initializing the services and characteristics. This change was also noticeable in the startup speed of the program. Connecting to BLE STRIVEs took around 15 seconds, which is a large improvement compared to the standard Bluetooth connection, which could take up to one minute of time. Summarized, using the BLE protocol for the STRIVEs brings a stable connection to all devices because the data rate on the standard Bluetooth protocol is reduced, and multiple other benefits like more convenient usage and longer-lasting batteries for the STRIVEs because it is also more energy efficient than a standard Bluetooth connection.

3.4.4 STROE Enhancements

Regarding STROE, enhancements were only made to the software to further improve the weight simulation. As the Bluetooth connectivity was already improved by reducing data traffic through switching the STRIVEs to BLE, there was no need to also modify the STROE. However, this could be done in the future to obtain the same improvements, the BLE protocol provides to the STRIVE.

Until now, the weight simulation stopped, as soon as the held object touched the ground, as it now should stand on its own and no more force on the user's hand is necessary. There is, however, a particular case in which the weight simulation shouldn't stop completely. This special case concerns objects placed on the edge, which are only partially supported by the object beneath. In certain

[5] https://www.az-delivery.de/en/products/hc-05-6-pin?_pos=2&_sid=566923a3b&_ss=r
[6] https://www.roboter-bausatz.de/p/at-09-ble-bluetooth-4.0-modul-uart-kompatibel-mit-hm-10
[7] https://www.asus.com/networking-iot-servers/adapters/all-series/usb-bt500/

cases, a tipping force must still be applied, which can be simulated by STROE. For this purpose, it is important to be able to determine the center of gravity of the object. If the center of gravity is flattened on the surface, no weight force must act, because the object is fully supported, but if there is no supporting object beneath, a proportional weight force must be calculated. A special case, where the flattened center of gravity of the held object can also not be supported and still no weight force must prevail, is when the held object is supported by several objects on different sides.

Franklin [Fra06] developed a method to test if a point is inside or outside a polygon, and since a polygon is calculated from all contact points with every other object this algorithm is used here and automatically covers the problem described above. The center of gravity is flattened to the 2D surface, as for these calculations, the height is to be excluded. If the center of gravity is inside the previously calculated polygon, no weight force should be applied as the object is fully supported. If the center of mass is outside of the previously calculated polygon, the weight force is calculated with the following formula:

$$F = \frac{m * g * d_1}{d_2}$$

In this formula, d_1 describes the distance between the flattened center of gravity and the tipping edge of the object held by the user. d_2 is the distance between the tipping edge and the hand position of the user. The hand position of the user also needs to be considered because of the leverage force depending on it. An exception is if there is only one contact point, then an approximation over the horizontal distance to the center of gravity is used.

However, the algorithm of Franklin [Fra06] relies on the prerequisite that the points to calculate the polygons are ordered clockwise or counterclockwise. The pseudo-code proposed from Baeldung [Bae22] in algorithm 3.1 was implemented and shows the steps necessary, to create sorting metrics that can be used to sort all collision points clockwise.

Before starting with this algorithm, the center point between all contact points needs to be calculated and the contact points are translated to this center.

Then for each pair of points, the function described here can be called. In the first step, the respective angles between the points and the center are calculated. If the angle from the first point is smaller than the angle from the second point, or the angles are equal in the edge case and the distance to the center is smaller than the distance from the second point, the algorithm returns *true*. This means that the first point has a lower order than the second point and thus must be swapped in the list. In this way, the list is sorted until all points are in the correct order, after which all points can be translated back to their original position.

In order to use this collision simulation algorithm in real time, it must have low complexity. This depends mainly on the chosen algorithm of the sorting function, which in our case is the Quicksort algorithm. Thus, we obtain a complexity of $O(n * log(n))$ because we only have loops of complexity $O(n)$ for the pre- and post-processing algorithms described above.

Algorithm 3.1 Collision points sorting metrics

Input: pt_{center}, pt_1, pt_2

Output: return true if pt_1 order is less than pt_2

Require: A center point between all input points is found and the points are translated to this center.

$angle_1 \leftarrow getAngle(\{0,0\}, pt_1)$

$angle_2 \leftarrow getAngle(\{0,0\}, pt_2)$

if $angle_1 < angle_2$ **then**

  return true

end if

$d1 \leftarrow getDistance(\{0,0\}, pt_1)$

$d2 \leftarrow getDistance(\{0,0\}, pt_2)$

if $(angle_1 == angle_2)$ & $(d1 < d2)$ **then**

  return true

end if

return false

Require: All points are translated back from the center to their original position

4 Pilot Study

In the first step of the evaluation by others, four employees from the same department were asked to test the system in a pilot study and to check for errors. Both positive and negative feedback was received, with negative feedback subsequently being translated into improvements to ensure that the expert study ran smoothly.

4.1 General Feedback

The first general impression among participants was consistently positive. All participants in the pilot study attested that important feedback could be obtained from the experts with the planned changes described below that were worked out together throughout the pilot study. The different combinations of haptic feedback devices created a more useful impression than simply using controllers for the use case. However, it was consistently recognized by all conditions that SenseGlove still has significant problems grasping small objects. Thus, all conditions that contained the SenseGlove tended to be rated worse in the feedback conversation over the condition that consisted only of STROE and STRIVE and used the controller as a default fallback device for grasping objects. This preliminary observation will also be investigated later during the expert study. Additionally, participants stated that it took some time to get used to SenseGlove.

Another general impression that emerged in the pilot study concerns the condition in which all haptic feedback devices are combined together. Here, two of the four participants reported that the number of connected cables on the hand was very high. In some cases, some of the cables then got caught between the fingers, which was very immersion-breaking. In some cases, participants also had the thread of STRIVE connected from the left in their palm when grasping it, as the carabiner slipped between their thumb and index finger. Since the number of cables, in this case, cannot be reduced, this problem could not be solved as a general solution. In the further course of discussions, however, it became apparent that possibly a different attachment of the cords to the hand could remedy this situation. This possibility is discussed in section 4.3 since another issue was discussed with the participants regarding the attachment of threads.

4.2 Performance Feedback

A huge negative aspect that participants noticed was the performance of Unity[1], especially in the collision calculation. Because the imported models of the car parts had a complex mesh underlying them, there was a very high number of vertices that were a part of the collision calculation. If

[1] https://unity.com/

there was a collision between a held object and another complex car part, physics calculations in the background were too slow to calculate a precise collision and the held object could partially penetrate other components. This then caused the held object to tremble, as unrealistic forces acted due to the intrusion into another material. Intuitively, most test subjects tried to compensate for the trembling of the object by moving it with their hand, but this only intensified the negative effect. This was because participants could only see a delayed position of the object they held due to performance issues during the calculation. This resulted in them accidentally pushing the held object even deeper into other components. Since collisions were calculated by the penetration all around in all directions, wrong commands were also sent to the STRIVEs, which then limited the participants in all directions, thus almost completely restricting movement possibilities, and in a sense keeping them trapped in the component.

In addition to this unrealistic and immersion-breaking physical behavior, performance suffered significantly from these complex calculations, as mentioned earlier. The frame rate dropped to an average of 3 Frames per Second (FPS) during collisions between complex objects, which made the program partially unusable.

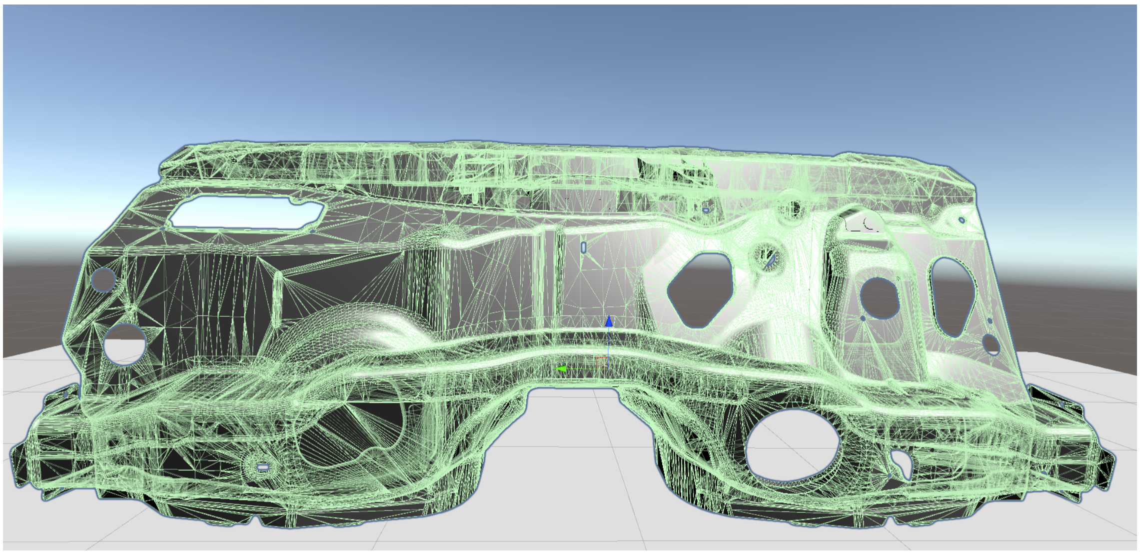


Figure 4.1: Collision mesh of an exemplary component

The example component in figure 4.1 shows what the original mesh looks like which has over 116 thousand vertices in total. Since collisions with complex objects like this inevitably occur during the course of the use case, the colliders had to be simplified. The component visible here was the only one to retain the original collider, as it was not possible to precisely remodel the notches and holes it contained so that the use case was not negatively affected. The problem could nevertheless be solved by re-modeling all tangible objects, as well as other parts of the chassis, using primitive shapes such as boxes, spheres, and cylinders. Although it was then not possible to guarantee a collision with millimeter precision, since the remodels simplified the objects, care was taken to ensure that all tangible objects as well as the directly adjacent components in the immediate surroundings were remodeled so precisely that the deviations were almost imperceptible to the user.

This solution completely eliminated the problems described above. Collision calculation was fast enough to send precise commands to the STRIVE modules so that objects could not be penetrated. In addition, the performance and frame rate of collisions improved to the point that there was no longer any noticeable difference from normal performance, and most importantly, objects no longer jerked behind on collision events.

4.3 Hardware Feedback

As mentioned above, participants of the pilot study also had some feedback regarding the hardware. The first noticeable point concerns the SenseGlove itself and thus all conditions in which it was used. All participants in the pilot study had trouble grasping smaller objects with SenseGlove. In the use case built for the study, there were two screws that needed to be placed during the course of the task. This caused major problems for the participants. In this context, it was noticeable that there is in some cases a discrepancy between the actual finger position and the virtual representation of the hand despite multiple careful calibrations.

The SenseGlove calculates the current finger position based on the length of the cords stretched from the fingertips over the top of the fingers to the back of the hand. From this length, an algorithm is used to calculate the virtual hand poses. Through closer inspection, we found that even with fingers limited to one cord length, different hand poses could be taken by the user. The algorithm recognized these different hand poses as the same pose. This allowed the discrepancies between the virtual fingers to occur, which were just noticeable when grip accuracy mattered for small objects. For large held objects, where the hand tends to be more open, this phenomenon was not noticeable.

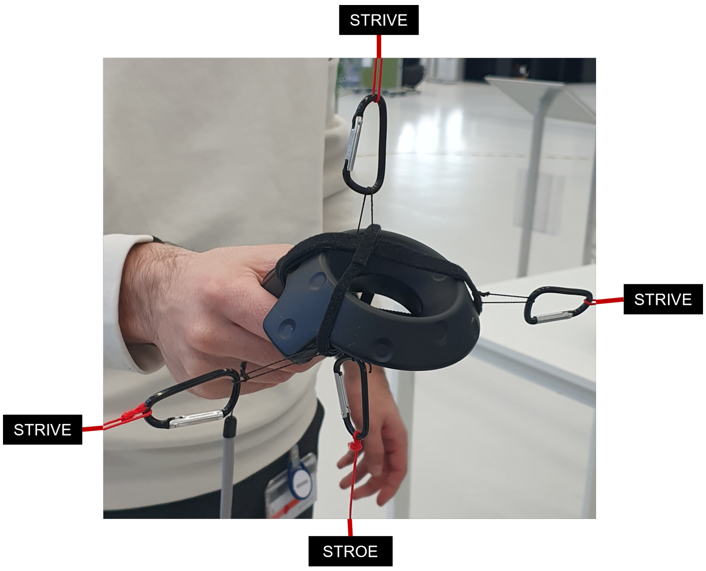


Figure 4.2: Attachment of strings on the controller

But since this problem is caused by SenseGlove and the included scripts of the manufacturers, there was no way to solve the problem. After a few tests, it was determined that the hand pose is best recognized when the real hand makes a tweezer-like movement with thumb and index finger, which is the best way to grab the virtual screw.

Another feedback point that was often mentioned in all conditions was the attachment of the strings of STRIVE and STROE to the SenseGlove or the controller. Prior to the pilot study, a thin thread was tied around both SenseGlove and controller as a connection option, into which all carabiners of the STRIVE modules and STROE could then be hooked. As described above, participants now had one of STRIVE's strings in their hand while grasping, or strings tangled around their fingers while turning their hand. However, participants in the pilot study noticed another negative effect here. Because the devices were all hooked into the same thread and were not completely anchored in their respective positions, they could be accidentally shifted in the course of the use case by turning the hand. By the end of the use case, some of the carabiners had slipped to the same position and haptic feedback could no longer be transferred to the user's hand accurately.

This feedback was implemented by creating individual attachment options from all directions. For the controller, this meant that a single loop was attached to each side, into which the carabiners could be hooked, which can be seen in figure 4.2. A similar solution was used for attachments to the SenseGlove, whereby an adhesive pad with a hook was used for the upper STRIVE since the thread around the entire back of the hand had too much space, as described above, in which the carabiner could slip undesirably. This solution is visible in figure 4.3.

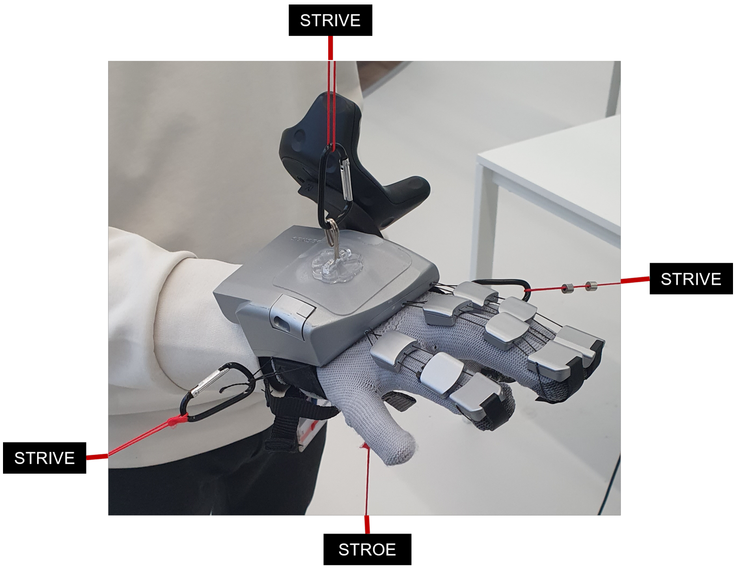


Figure 4.3: Attachment of strings on the SenseGlove

5 User Study

After the stated improvements of the pilot study were implemented, the user study with the goal to evaluate the effectiveness of different combinations of haptic feedback devices in VR started. Therefore experts from the automotive industry were invited to engage in a series of assembly tasks while using different combinations of the haptic feedback devices mentioned above. The advantage we hoped to gain by interviewing only experts was that individual exchanges about specific use cases from their everyday work would occur during the study. The experience that the experts bring with them from those work scenarios will then show the direction in which further development should head.

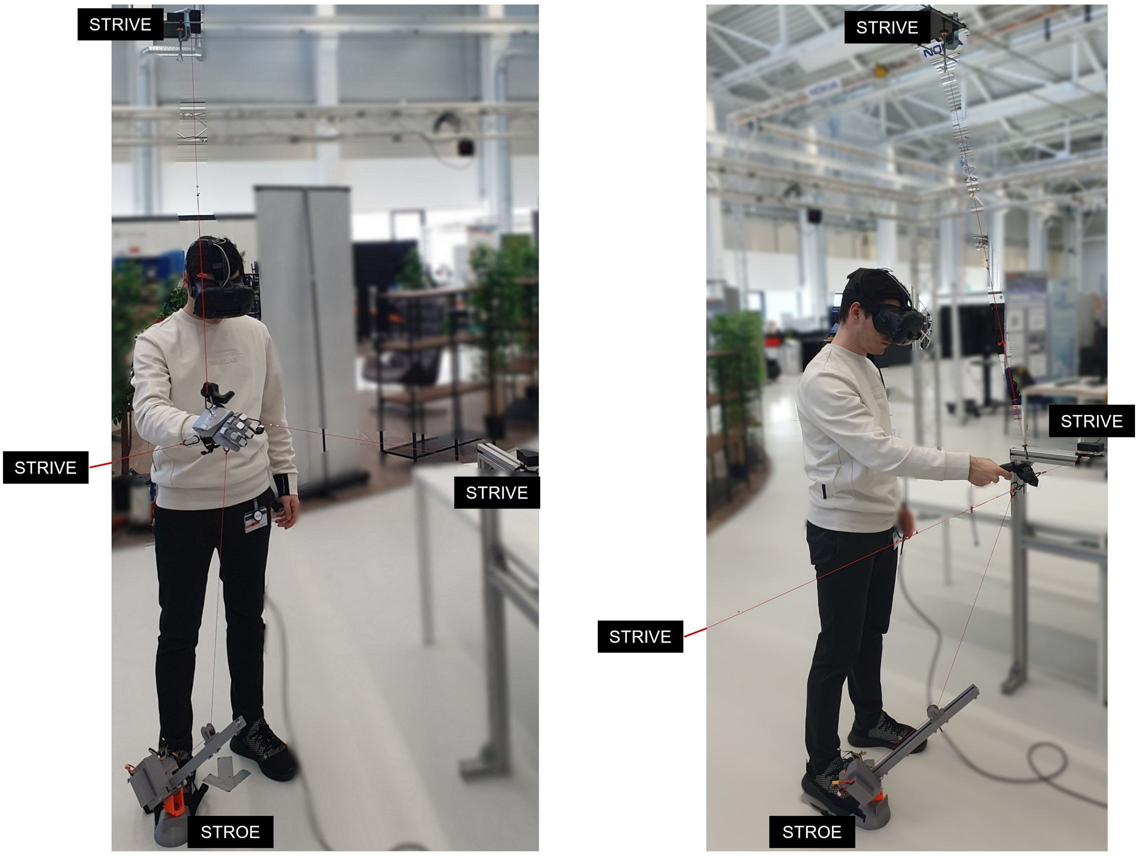
5.1 Apparatus

To perform the study, the setup was built on a Windows 10 PC, the same one on which it was developed. The development of the program took place in Unity [1] in version 2019.4.8f1. Steam VR [2] was integrated for the VR component. Hardware-wise, we used the HTC VIVE[3], plus first-generation VIVE trackers [4] for tracking, which were tracked by the corresponding base stations. Additionally, SenseGlove Nova, as well as STRIVEs and STROE were used to provide multimodal haptic feedback. The STRIVE modules were set up in a triangular shape, with one of them mounted above the user's head, and on both the left and right side STRIVEs were mounted on an aluminum profile so that they were positioned at a height of around 1.20m above the floor. This setup is partially visible in figure 5.1.

5.2 Study Design

The user study was conducted utilizing a within-subject design since it was necessary for each participant to test all four conditions to get a complete impression of the different combinations of haptic feedback devices. Thus, it is potentially possible for participants to find use cases related to their workspace where a particular combination of haptic feedback devices makes an advantage over VR without haptic feedback. Since all combinations of STRIVE, STROE, and SenseGlove were to be tested, this resulted in a total of four conditions. These were as follows: *STRIVE + STROE, STRIVE + SenseGlove, STROE + SenseGlove* and *STRIVE + STROE + SenseGlove*. In figure 5.1 a), the condition *STRIVE + STROE + SenseGlove* is visible. In comparison to figure 5.1 b), the

[1] https://unity.com/
[2] https://store.steampowered.com/app/250820/SteamVR/?
[3] https://www.vive.com/
[4] https://www.vive.com/us/accessory/tracker3/



(a) **(b)**

Figure 5.1: Combination of STRIVE and STROE with SenseGlove (a) and controller (b)

SenseGlove got replaced by a controller, which now builds the condition *STRIVE + STROE*. For both the other conditions either the STRIVEs or STROE were detached from the SenseGlove. In an effort to minimize learning effects, a latin square was used to shuffle the order of the conditions for each participant during the study.

The study was conducted with 12 participants (10 male, 2 female). The participants' age was clustered in multiple age groups, where the youngest participant was younger than 25 and the oldest participants were in the age group 51-60 years. Because participants were recruited from the same company from departments where VR is used, 11 of the 12 participants had over a year of experience with VR. A total of 7 participants indicated that their experience in VR was between 1-4 years. The remaining 3 participants had more than 10 years of experience with VR. The frequency with which VR was used during this time ranged from several times a day to no more than once a month, with 5 of the 12 participants reporting using VR several times a day. In addition, 11 of the 12 participants had experience with haptic feedback devices prior to the study. All of these 11 participants also reported having used STRIVE at least once in their work environment. Another haptic feedback device that was familiar to 4 participants was Manus VR[5]. One participant also had previous experience with STROE.

[5] https://www.manus-meta.com/products/quantum-metagloves

5.3 Measures

Since the user study focused primarily on haptic feedback, questions from the Kim and Schneider [KS20] questionnaire were used for the evaluation. This questionnaire was not queried in full, as some of the questions were redundant in this case. Participants had to answer the questions on a 7-point Likert scale, as well as describe their impressions in an interview, which was then written down as additional feedback. This qualitative feedback should play an important role, as the impressions of employees play an equally crucial role in the applicability for the company as the general classification by the haptic questionnaire. The following subscales were selected from the haptic questionnaire by Kim and Schneider [KS20]:

- Intensity: The overall perceived strength of feedback
- Timbre: The overall tone, texture, color, or quality of the feedback
- Utility: The ability of haptics to benefit user experience
- Causality: How easily can a user relate haptic feedback to the source of interaction?
- Consistency: The system's ability to provide reliable haptic feedback
- Saliency: The noticeability of the haptic feedback as it relates to its purpose
- Harmony: How tightly do the haptic impressions fit together?
- Immersion: Does the user feel immersed as a result of experiencing haptic feedback?
- Realism: Whether the haptic feedback convincingly portrays what someone would expect to feel in reality

Before the start of the study, demographic information was collected, such as the age of participants or their experience with VR and haptic feedback devices. At the end of the study, participants were then asked to summarize what they perceived as positive and what they perceived as negative, as well as to make optional suggestions for improvement. In addition, they were asked which haptic feedback was individually most important for completing the tasks, as well as which combination of devices seemed to make the most practical use. These questions were related to the current state of the devices as well as asked abstractly with the addition: „If none of the devices would cause technical difficulties". The goal was to find out whether combinations of different haptic feedback types themselves are promising and possibly only limited by the current state of the devices used.

The hypotheses for the study are then also formed from the subscales of the haptic questionnaire, whereby the null hypothesis h_0 states in each case that there is no significant difference between the groups and the alternative hypothesis h_1 that there is a significant difference. The same applies analogously to the concluding questions at the end of the study. Here, the overall impression of which of the conditions is perceived as best by the participants is particularly interesting.

5.4 Procedure & Tasks

This section is divided into the overall study process and the individual tasks in the virtual scene. The study flow is explained first to create a broad picture and then the individual tasks that users had to perform during a run are described.

5.4.1 Study Procedure

The study procedure began with the mandatory consent form, which informed the participants about what data will be collected. In the first step thereafter, participants were then educated about the different haptic feedback devices and the topic of the study. Demographic information was also collected during this process. Since participants of the pilot study had the impression that it takes a brief period of time to get used to SenseGlove, the experts were then shown a test scene in which objects with different tangible materials were presented on a table. This was to prevent a learning effect during the actual study, as the participants could now learn to handle the SenseGlove in the test scene. After users felt comfortable handling the SenseGlove, they were shown the exemplary use case and a first test run without haptic feedback devices was started. This served not only to prevent the learning effect but also to get a comparable impression of the advantages of haptic feedback in the subsequent runs.

After the test session was successfully completed and all open-ended questions were answered, the first condition with haptic feedback devices began. This was then followed by an interview in which participants were asked the questions described in section 5.3. Feedback received during this interview was noted, and in addition, participants scored each question on the questionnaire on a 7-point Likert scale. This process was conducted for all four conditions.

As described before, after all conditions of the study were completed, additional questions were asked with the aim to get a final verdict on which combination of haptic feedback devices makes the biggest impact, as well as shed light on advantages and disadvantages during usage.

5.4.2 Tasks

The tasks performed by the participants during the study were divided into two use cases. In the first use case, the exemplary scenario is a defective hose underneath the cooling water reservoir. This hose is to be replaced by a new one, for which the parts above have to be dismantled and reassembled afterward.

In figure 5.2 the virtual scene in which the participant is placed can be seen. The standing position is marked in the center of the engine compartment. The viewing direction points in the direction of the working area, which is also marked in red. To ensure that this was the case for all participants, an arrow was stuck on the floor of the test area to indicate the correct position and direction. This arrow is visible in figure 5.1 a). All the required materials, as well as the power drill that will also be needed in the following, are located on the table within reach so that the participant does not have to move away from the given standing position. For convenience there was a function included, that respawned all objects on the table if they fell beneath the virtual car model and dropped on the floor.

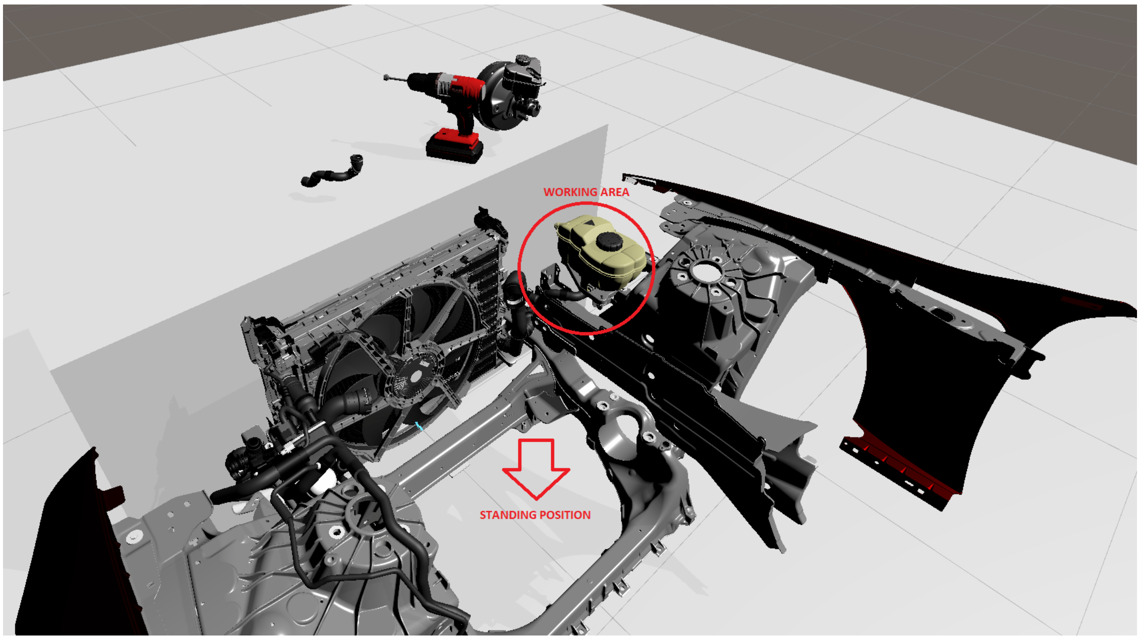


Figure 5.2: Overview of the virtual scene

The first task of the use case was to remove the water reservoir visible in figure 5.2. This reservoir was clipped into the holder below (figure 5.3) and could only be pulled off in the direction of the table before it could then be moved freely. Users could then place the water reservoir on the table, as it was not needed again until the end of the use case for reassembly.

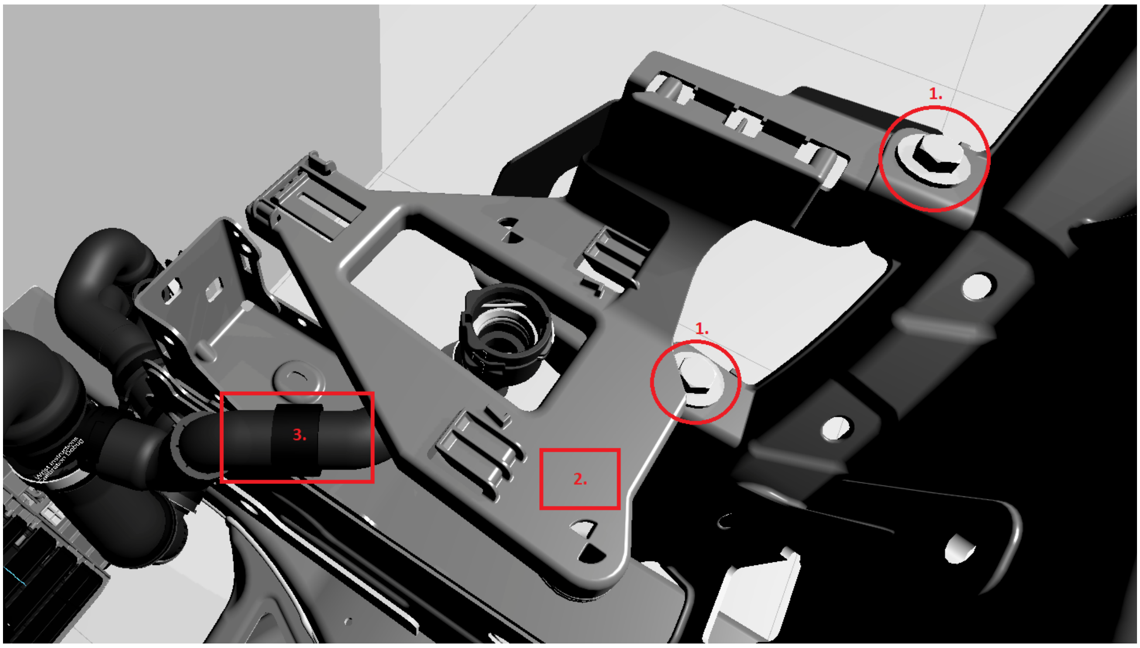


Figure 5.3: Instructions for the first use case

In figure 5.3 the detailed view is now visible after the container has been removed with the next working steps marked. Now, the participants had to take the power drill visible in figure 5.2 from the table and use it to unscrew the screws marked in red. With the controller, the screwing worked automatically as soon as the tip of the power drill touched the screw head. With SenseGlove, this interaction could be modeled more accurately and the screwdriver only worked when the trigger of the power drill was pressed with the index finger, which was communicated to the user through vibration feedback. Marked as working step two, the user now can grab and remove the metal bracket to free up space for the hose below. This hose, which is marked as the third step, now needs to be grabbed and removed. It will be substituted with the replacement hose on the table in figure 5.2. As soon as the replacement hose is mounted, the metal bracket can be put back on top of the hose. To simplify the process and to maintain the ability to solve this use case one-handed, the virtual objects snap in place as soon as the user puts them into the correct position. This also applies to the screws, which must then be placed over the respective holes before they are screwed tight again with the power drill. The last step of the first use case is to clip the cooling water reservoir back into the metal bracket.

After solving the first use case, there was a five-second break, before the scene was rotated by 180°. This is due to the second use case being on the other side of the engine compartment and happens to simplify the process as it would be a huge overhead to turn around with multiple haptic feedback devices mounted to the user's hand. Additionally, the engine compartment wall was added to the scene. The new setup is visible in figure 5.4.

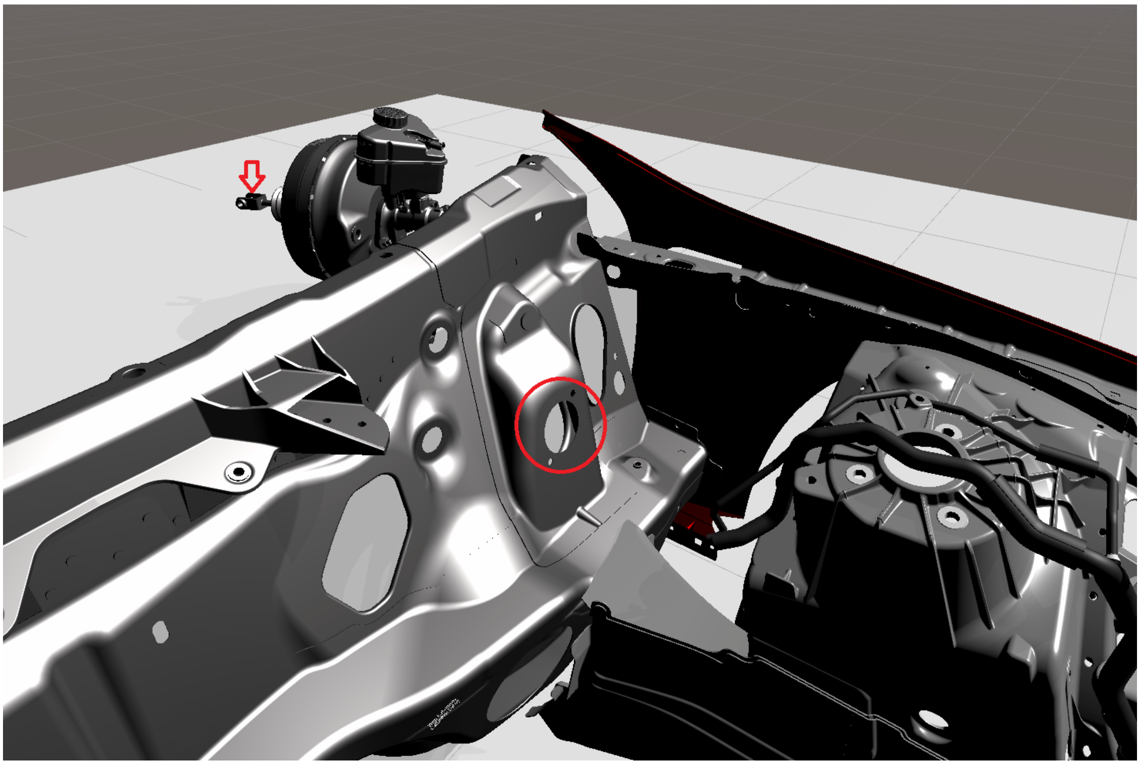


Figure 5.4: Instructions for the second use case

This second use case consisted only of a single task, namely placing the brake vacuum servo into the engine compartment. The fork of the brake vacuum servo, which is marked with the red arrow needed to be guided through the hole, which is marked with the red circle. As soon as the user guided the object to the perfect position, it snapped in place and the task was finished. The difficulty in this task was the very limited space and paying careful attention to potential collisions, during the assembly process.

All tasks had to be solved with the right hand, as there was only one STROE available. Also, attaching multiple haptic feedback devices to both hands would have resulted in cluttered strings of the STRIVEs and STROE, which then would break immersion and worsen the user experience.

5.5 Results

The results of the user study are divided into the results of the haptic questionnaire and qualitative feedback. As described above, participants not only had to answer selected questions of the haptic questionnaire by Kim and Schneider [KS20] during the study but also had to provide additional feedback and answer customized questions during the interview. The scoring on the questionnaire and the qualitative feedback are first analyzed separately before combined conclusions are drawn in a further step.

5.5.1 Haptic Questionnaire

The data of the haptic questionnaire are evaluated individually for each subscale in order to be able to analyze separately which of the conditions performs better or worse on which subscale. In the first step, the data must be tested for normal distribution using the Shapiro-Wilk test [HTZ16]. For the non-normally distributed data, the Kruskal-Wallis test [MN10] is then performed to see if there are differences between the groups, and for the normally distributed data, a one-way ANOVA [HNHN09] is used. It should be noted that in order to perform a one-way ANOVA, the normal distribution of the data must be given over all conditions of the respective subcategory of the questionnaire. Between which groups potential differences exist can be assessed with the respective post-hoc tests. For all subsequent statistical tests, the standard significance level of 5% was chosen.

Shapiro-Wilk Test

For the Shapiro-Wilk test [HTZ16], the null hypothesis h_0 states that the data is normally distributed. According to the Shapiro-Wilk test, if the p-value is < 0.05, then we reject the null hypothesis i.e. there is sufficient evidence to say that the sample does not come from a normal distribution. The test has been conducted for each condition and subcategory of the haptic questionnaire individually and the results are shown in table 5.1. All fields for which the null hypothesis is rejected and therefore the data is not normally distributed are marked yellow.

Shapiro-Wilk Test								
	STRIVE + STROE		STRIVE + SenseGlove		STROE + SenseGlove		STRIVE + STROE + SenseGlove	
	statistic	p-value	statistic	p-value	statistic	p-value	statistic	p-value
Intensity	0.9187	0.2759	0.8698	0.0650	0.7697	0.0043	0.9361	0.4493
Timbre	0.8544	0.0416	0.8779	0.0650	0.9136	0.2372	0.9328	0.4117
Utility	0.8740	0.0736	0.9347	0.4332	0.9359	0.4475	0.8787	0.0845
Causality	0.8670	0.0600	0.9374	0.4659	0.8542	0.0414	0.7580	0.0032
Consistency	0.8273	0.0194	0.9347	0.4332	0.8938	0.1320	0.9374	0.4659
Saliency	0.9347	0.4333	0.8965	0.1432	0.8590	0.0476	0.9030	0.1738
Harmony	0.8454	0.0322	0.9472	0.5968	0.8698	0.0650	0.9048	0.1833
Immersion	0.8844	0.1000	0.9135	0.2369	0.9197	0.2834	0.9112	0.2211
Realism	0.8625	0.0526	0.9283	0.3630	0.8477	0.0344	0.8956	0.1392

Table 5.1: Results of the Shapiro-Wilk Test

The result needs to be looked at more closely as there are different reasons why the data is not normally distributed. One of these reasons that could be responsible is that there are outliers in the data. The Shapiro-Wilk test deals very strictly with outliers and the data may therefore be incorrectly labeled as not being normally distributed. Individual outliers from the data can be revealed with a boxplot.

Indeed, the boxplot in figure 5.5 for the *STRIVE + STROE* condition shows anomalies in the *Timbre* and *Consistency* subcategories. The points visible below the whiskers can be categorized as mild outliers from the data. Therefore, the outlier data points are removed and the data set is retested for normal distribution again.

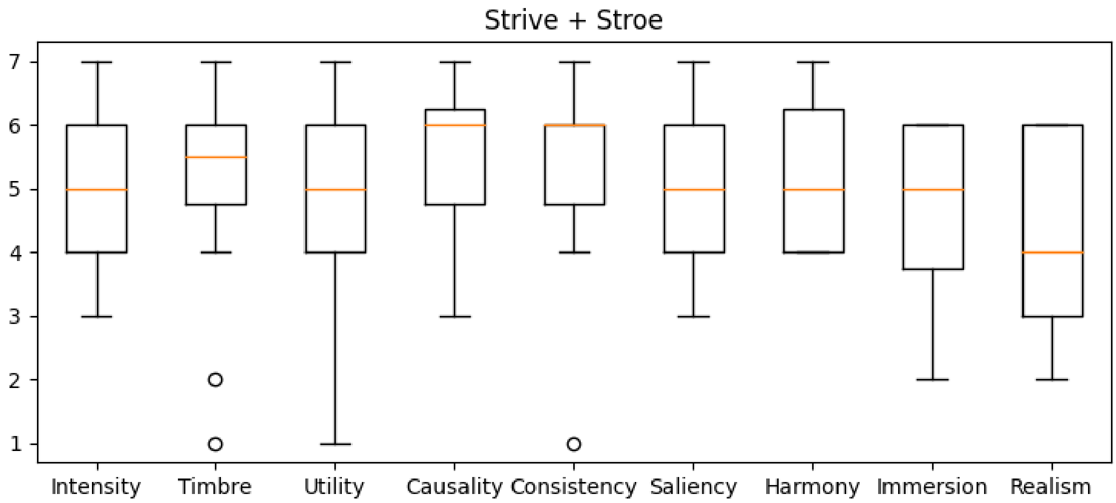


Figure 5.5: Haptic questionnaire results for the condition *STRIVE + STROE*

A newly conducted Shapiro-Wilk test with the remaining data yields the result $statistic = 0.8913$, $p-value = 0.1755$ for the subcategory *Timbre* and $statistic = 0.8785$, $p-value = 0.0998$ for the subcategory *Consistency*. Thus, in both cases, the data is now normally distributed, if the outliers are left out. To be completely sure, both the Kruskal-Wallis test and a one-way ANOVA are performed for these two categories in the following analysis, which can then be compared with each other to determine whether a common conclusion can be drawn.

For the conditions *STROE + SenseGlove* and *STRIVE + STROE + SenseGlove*, which also show data, that is not normally distributed in some of the subcategories, no outliers were found with a boxplot visualization. In these cases, the Kruskal-Wallis test will be used for further analysis.

Kruskal-Wallis Test

As described above, to perform a one-way ANOVA, the data needs to be normally distributed for each of the conditions regarding the respective subscale. This is not the case for the subscales *Intensity, Causality, Saliency, Harmony* and *Realism* as table 5.1 shows that for each of the mentioned subscales, at least one condition is not normally distributed. As the results are ambiguous for the subscales *Timbre* and *Consistency* depending on the inclusion or exclusion of outliers, the Kruskal-Wallis test [MN10] will be performed for these as well.

The null hypothesis h_0 for the Kruskal-Wallis test states that there are no differences between the individual groups regarding the respective subscale. Table 5.2 shows the results for the Kruskal-Wallis test. It can be observed, that none of the p-values is < 0.05, which means that none of the null hypotheses can be rejected. Therefore one needs to assume that there is no significant difference between the groups in none of the subscales.

Kruskal-Wallis Test		
	statistic	p-value
Intensity	6.8353	0.0773
Timbre	6.3806	0.0944
Causality	5.0233	0.1700
Consistency	5.566	0.1347
Saliency	0.8849	0.8290
Harmony	3.1876	0.3635
Realism	0.8738	0.8317

Table 5.2: Results of the Kruskal-Wallis Test

Levene Test

Before a one-way ANOVA can be performed, not only the normal distribution of the data must be given, but also the homogeneity of the variances. To check this homogeneity, the Levene test [Sch85] is applied. For the Levene test, the null hypothesis h_0 states that the homogeneity of variances is granted. As for the other statistical tests before, if the p-value is < 0.05, then we reject the null hypothesis i.e. there is sufficient evidence to say that the variances are not homogeneous. However, as visible in table 5.3, all p-values are > 0.05, which means the null hypothesis is accepted for all subscales and it can be assumed that the homogeneity of variances is given for all subscales. Important to note is, that the outliers for the subscales *Timbre* and *Consistency* already have been removed, as they will not be part of the ANOVA.

Levene Test		
	statistic	p-value
Timbre	0.4308	0.7319
Utility	0.7506	0.5278
Consistency	1.6312	0.1961
Immersion	0.8253	0.4869

Table 5.3: Results of the Levene Test

One-way ANOVA

After it has been shown by the previous tests that all requirements for a one-way ANOVA [HNHN09] are fulfilled, in the following this ANOVA can be carried out for the subcategories *Timbre, Utility, Consistency* and *Immerison*. As described in advance, the outliers were removed from the categories *Timbre* and *Consistency*, since a normal distribution must be given. For the one-way ANOVA, the null hypothesis h_0 states that there are no significant differences between groups. As before, if the p-value is < 0.05, then we reject the null hypothesis i.e. there is sufficient evidence to say that there are differences between groups.

One-way ANOVA		
	statistic	p-value
Timbre	3.2429	0.0313
Utility	0.4898	0.6910
Consistency	2.999	0.0408
Immersion	0.2283	0.8761

Table 5.4: Results of the One-way ANOVA

As marked in yellow in table 5.4, there are p-values for the subscales *Timbre* and *Consistency* that are < 0.05. This means for these subscales the null hypothesis h_0 can be rejected and thus the alternative hypothesis h_1 can be accepted. This is because there is sufficient evidence that there is a difference between the groups. To find out between which groups this difference exists, Tukey's HSD post-hoc test [AW10] is performed.

Tukey's HSD

To find out between which groups the differences revealed by the ANOVA exist, Tukey's HSD post-hoc test [AW10] is applied in the following. This test is now only applied to the subscales *Timbre* and *Consistency* since the other subscales did not show significant results in the ANOVA. Here, the null hypothesis h_0 states that there is no significant difference between the pairwise tested groups. If the p-value is < 0.05, the null hypothesis can be rejected and there is sufficient evidence that there is a significant difference between the pairwise tested groups. However, there is a second method to analyze this post-hoc test, namely the Confidence Interval (CI). If the CI for the mean difference given by the values lower CI and upper CI is exclusively positive or negative and does not contain the null value, a significant difference can also be found.

Tukey's HSD: *Timbre*				
Comparison	statistic	p-value	lower CI	upper CI
STRIVE + STROE / STRIVE + SenseGlove	1.717	0.050	0.002	3.432
STRIVE + STROE / STROE + SenseGlove	1.550	0.089	-0.165	3.265
STRIVE + STROE / STRIVE + STROE + SenseGlove	1.717	0.050	0.002	3.432
STRIVE + SenseGlove / STROE + SenseGlove	-0.167	0.993	-1.802	1.469
STRIVE + SenseGlove / STRIVE + STROE + SenseGlove	0.000	1.000	-1.635	1.635
STROE + SenseGlove / STRIVE + STROE + SenseGlove	0.167	0.993	-1.469	1.802

Table 5.5: Results of Tukey's HSD for the subscale *Timbre*

Table 5.5 shows the results of Tukey's HSD test for the subscale *Timbre*. Noticeably, the p-value is exactly 0.05 in two cases and thus actually, albeit narrowly, shows no significance, as it should be < 0.05. However, the CI in the columns next to it show exclusively positive values in both cases, which would attest to a significant difference. Again, it is visible that in both cases the lower CI is only very slightly above 0 with a value of 0.002. According to Tukey's HSD test, both variants should be consistent. Since the p-value is rounded to three decimal places in the Python analysis used to perform these statistical tests, it can be assumed that this was just under < 0.05, but the result was rounded up. Thus, greater confidence can be placed in the CI statement here, which indicates significant differences. A significant difference exists between the *STRIVE + STROE* and *STRIVE + SenseGlove* groups, and between the *STRIVE + STROE* and *STRIVE + STROE + SenseGlove* groups. Since the statistical value is 1.717 in each case and thus positive, it can be stated that the group *STRIVE + STROE* received a higher Likert scale score for the subscale *Timbre* in both cases and thus performed significantly better than the groups *STRIVE + SenseGlove* and *STRIVE + STROE + SenseGlove*.

Tukey's HSD: *Consistency*				
Comparison	statistic	p-value	lower CI	upper CI
STRIVE + STROE / STRIVE + SenseGlove	1.386	0.203	-0.463	3.235
STRIVE + STROE / STROE + SenseGlove	1.803	0.058	-0.046	3.652
STRIVE + STROE / STRIVE + STROE + SenseGlove	1.803	0.058	-0.046	3.652
STRIVE + SenseGlove / STROE + SenseGlove	0.417	0.926	-1.392	2.225
STRIVE + SenseGlove / STRIVE + STROE + SenseGlove	0.417	0.926	-1.392	2.225
STROE + SenseGlove / STRIVE + STROE + SenseGlove	0.000	1.000	-1.808	1.808

Table 5.6: Results of Tukey's HSD for the subscale *Consistency*

The results regarding the subscale *Consistency* are shown in table 5.6. Here, none of the p-values indicate significance. The CI confirm this result and also show no significant differences in pairwise comparisons of groups. This is not necessarily in contrast to the ANOVA performed prior, as the tests have different statistical power. With two pairwise comparisons showing p-values of only just > 0.05, one can carefully assume that the significant differences indicated by the ANOVA exist between the respective groups. However, this cannot be fully proven because this is a borderline case.

In both tables, it is noticeable that there is one comparison that has a p-value of 1.000. Here, the means between groups are identical, which may be due to the small number of participants, which was 12.

Mean Comparisons

Despite the few significant differences between the groups, this section compares the means in order to nevertheless identify any abnormalities or a trend that could not be detected by the previous analysis.

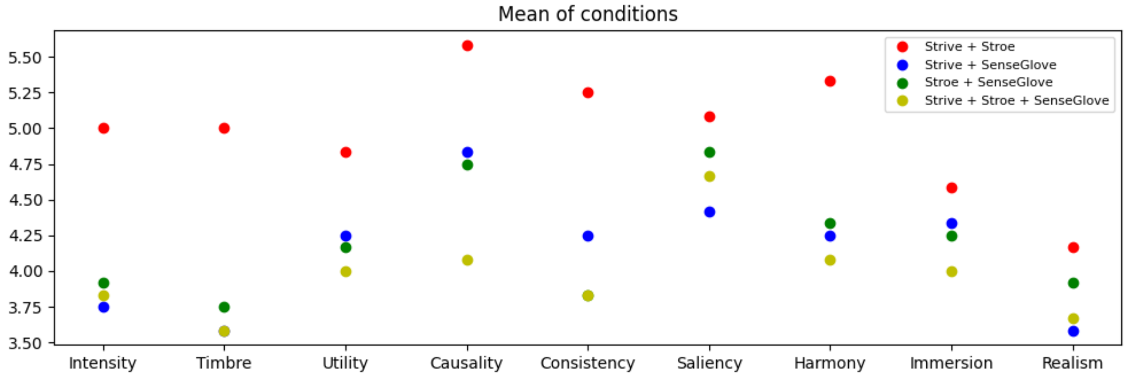


Figure 5.6: Means of conditions for the haptic questionnaire

The mean values for all subscales are visualized in figure 5.6. Most striking here is that the *STRIVE + STROE* group consistently has a higher mean than the other groups across all subscales. Despite the significances being only measurable regarding the subscales *Timbre* and *Consistency*, noticeable differences are evident in the *Intensity, Timbre, Utility, Causality, Consistency* and *Harmony* subscales. The remaining groups behave similarly and show no discernible trend. Only in the subscale *Causality*, it can be seen that the group *STRIVE + STROE + SenseGlove* received a significantly lower score than the other groups. In almost all other subscales, the groups *STRIVE + SenseGlove, STROE + SenseGlove* and *STRIVE + STROE + SenseGlove* behave very similarly and have mean values that are very close to each other. In the subscales *Timbre* and *Consistency* even identical mean values could be determined by the above analysis. In figure 5.6 this is recognizable by the fact that the points overlap and are therefore partially not visible.

This finding can still provide meaningful arguments in the following sections when combined with and reinforcing the participants' statements from the interviews.

5.5.2 Qualitative Feedback

The different oral feedback recorded during the interview in the study is analyzed in this section. During each rating of the subscales of the haptic questionnaire, the participants depicted their experiences and opinion regarding to this subscale. This way further individual questions could be asked to understand their point of view. Also because of that, and in order to maintain the previous procedure, the feedback will be analyzed on the basis of the individual subscales of the haptic questionnaire, before the additional feedback collected on the general questions at the end of the study will be described.

Intensity

The first subscale on the haptic questionnaire is *Intensity*. This was rated very differently in relation to the different experimental groups. In the condition *STRIVE + STROE*, six of the 12 participants reported that the overall intensity was very good, with one person adding that the realistic gripping of the SenseGlove was not missed. Another point that stood out is that three people had a similar opinion, which can be summarized as the weight simulation by STROE being too inaccurate in this combination.

In the conditions *STRIVE + SenseGlove*, as well as *STROE + SenseGlove*, five participants each reported that the overall impression was too weak, and especially that the gripping intensity was too low. Particularly in the condition *STRIVE + SenseGlove*, the participants differentiated and reported that the collision feedback actually had a perfect intensity, but the haptic feedback during grasping was too little noticeable.

In the condition *STRIVE + STROE + SenseGlove*, four people reported that the overall intensity was very good, but four other people reported the exact opposite, stating that in a combination of three types of haptic feedback, too many overall impressions were felt at once.

Timbre

For the subsection *Timbre* again the condition *STRIVE + STROE* received the best feedback with nine of the 12 participants stating that the multimodal haptic feedback felt good and that it felt like high-quality feedback. One participant stated that the other conditions including the SenseGlove felt more like a gimmick, whereas with the controller a high work rate is given. This statement matches that of another participant who described realistic grasping in the condition *STRIVE + SenseGlove* as redundant. In this condition, five participants reported that the haptic feedback is not precise enough, with three of them specifying this is due to SenseGlove. Another two persons stated that the weight simulation of STROE is missing to attest a good character.

For the condition *STROE + SenseGlove* three persons stated that this combination of haptic feedback feels unrealistic. One of them mentioned this is because collisions play an important role in natural interaction and the collision feedback was missing in this condition.

Combining all haptic feedback devices in the condition *STRIVE + STROE + SenseGlove* a similar result to the subscale *Intensity* showed. Again four people stated that the amount of overlaying impressions was too much. Again also four people didn't mind the high amount of haptic feedback and stated that this combination felt good.

Utility

For the condition *STRIVE + STROE* five participants stated that this form of multimodal haptic feedback felt useful, with another participant stating that the collision feedback from STRIVE was more useful than the weight simulation. Two participants found this combination not useful, one of them stating that there was no form-giving inspiration without using SenseGlove.

In the other conditions, where SenseGlove was used, there were very divergent opinions. Six participants stated that the condition *STRIVE + SenseGlove* was useful but needs to be much more precise. Three participants stated that this combination was not useful with the explanation that there was a high effort needed compared to simply pressing a button on a controller.

The condition *STROE + SenseGlove* had similar ambiguous results. Here, opinions split into two, with half of the participants finding this combination useful and the other half not. As justification for why they didn't classify this condition as useful, they stated that it was too unrealistic and therefore rather disturbing.

For the combination of all haptic feedback devices in the condition *STRIVE + STROE + SenseGlove*, this opinion changed, as seven participants found this condition useful and another two found it was good but not worth the effort. Only three participants shared the opinion with the *STROE + SenseGlove* condition and found this condition equally disturbing.

Causality

The subscale *Causality* revealed interesting findings. In general, over all conditions, the same result arose. Around half of the participants stated in each condition that they could identify very easily which source of interaction resulted in which type of haptic feedback. Also, some participants stated that they could not identify the source consistently, especially in the condition *STRIVE + SenseGlove* when one of them added that this happened while doing rotary movements with the arm.

The most striking feedback collected here was that in both the condition *STRIVE + STROE* and the condition *STRIVE + STROE + SenseGlove* one person each reported that they could not clearly assign the different haptic impressions to the source of interaction, but perceived this impression as positive. Both participants explained this impression with the argument that the impressions merged well with each other, which created a very realistic impression because, in an interaction in the real world, the haptic impressions also blend.

Consistency

For the subscale *Consistency*, there were large differences between the individual conditions. The condition *STRIVE + STROE* received by far the most positive feedback, as here nine of the 12 participants attested that this combination of haptic feedback devices worked smoothly. Of the remaining three participants, two noted that it did not work consistently, as the weight simulation through STROE had brief dropouts. The last participant was able to identify the non-performing collision calculation in Unity described in the sections before. This was also confirmed by two participants in the condition *STRIVE + STROE + SenseGlove*.

In the condition *STRIVE + STROE + SenseGlove*, as well as the conditions *STRIVE + SenseGlove* and *STROE + SenseGlove*, the feedback was significantly more negative, as in each condition between five and seven participants stated that the SenseGlove does not work consistently and therefore significantly worsened the overall impression. Particularly when grasping small objects, the participants had difficulties. Two participants also noticed that the tracking of the fingers sometimes had a high latency, which also left a negative impression.

Saliency

In terms of the *Saliency* subscale, the impressions in the conditions were very close to each other. In each of the evaluated conditions six persons, the exact half of the participants, expressed positive feedback. Only in the case of negative impressions, the conditions differed. For example, in relation to the condition *STRIVE + STROE*, two participants made the statement that the force of STROE was too weakly felt. Another participant added that STRIVE was too strong in comparison. Further, one participant expressed feedback that the force of STROE behaved poorly with light objects and was generally not sensitive enough.

In the condition *STRIVE + SenseGlove*, a participant also said that small objects were not sensitive enough even with this combination of haptic feedback devices. He expanded on this statement by saying that in his opinion, the sensation was not as important for large objects, since one had a better perception of larger objects anyway.

For the conditions *STROE + SenseGlove* and *STRIVE + STROE + SenseGlove* the opinions largely coincided and the just described statements that the combinations were still too unprecise were also repeated. Another person additionally reported for the condition *STRIVE + STROE + SenseGlove* that the overall impression was too strong.

Harmony

With regard to the subscale *Harmony*, the condition *STRIVE + STROE* again stood out positively. Here, six participants confirmed that the different haptic feedback types fit together well, the other half of the participants did not provide bad feedback but found harmony in an average range. One participant said that the impressions blurred well into each other, making it feel like a cohesive system. Another participant first noticed in this condition that SenseGlove interfered subconsciously in other conditions.

A conflicting statement was made by participants in the *STRIVE + STROE* condition and in the *STRIVE + SenseGlove*. One participant said that in the *STRIVE + STROE* condition it was striking that the continuous force generated by STROE matches the on/off behavior of the STRIVE very well. An exactly opposite statement was made by another participant in the *STRIVE + SenseGlove* condition. This participant found the on/off character of the STRIVE combined with the continuous feedback of the SenseGlove disturbing and therefore attested to a poor harmony between the devices.

Another negative aspect mentioned in the condition *STRIVE + SenseGlove* was, that this combination was difficult to use because both devices use restrictions and make similar noises, therefore it was hard to distinguish which device activated and resulted in a feeling of insecurity.

The condition *STROE + SenseGlove* received mixed feedback regarding the subscale *Harmony*. Exactly half of the participants found that these devices harmonized well and the other half of the participants found them not harmonious. An additional point that was raised is that this combination of haptic feedback devices provided all the necessary sensations that play a role in natural grasping and therefore harmonize very well together.

For the condition *STRIVE + STROE + SenseGlove* the distribution of opinions was identical, but here one participant added that the poor harmony could be due to the technical limitations of the SenseGlove. Ideally, the devices could even harmonize very well, but this cannot be judged due to poor gripping behavior.

Immersion

Regarding the subscale *Immersion*, the participants had rather consistent opinions throughout all conditions. In condition *STRIVE + STROE* eight participants confirmed an immersive experience through the haptic feedback, in all other conditions it was six participants each. The feedback that stood out in the condition *STRIVE + STROE* was that the simplicity of gripping with the controller did not distract from the otherwise complex gripping and therefore it was more immersive although realistic gripping should be more immersive in theory. In addition, one participant testified that it was bad for immersion that STROE's weight simulation was attached to the controller rather than directly to the hand.

In the other conditions, one person each criticized the fact that the cables of STRIVE collided with the fingers of SenseGlove or get partially caught and that this behavior was immersion-breaking. For the condition *STROE + SenseGlove*, there was additional feedback that this combination was not immersive because the collision feedback was missing which played an important role, especially in the second use case. The missing collision feedback made it impossible to understand why the task could not be accomplished.

Realism

On the subscale *Realism* all conditions were rated rather negatively. One participant said that the weight force in the condition *STRIVE + STROE* was initially very realistic but lost realism during movements. According to the participant, this effect was amplified when collisions occur during movement.

In the condition *STRIVE + SenseGlove*, two participants mentioned that this combination made an unrealistic impression because the weight force was missing in the overall impression. Two participants also stated in relation to this condition that the collision feedback of STRIVE made a positive impression on realism.

However, a majority of participants across all conditions agreed that the details cannot be simulated precisely enough and therefore it was far from a realistic experience. One addition that stood out to one participant in the condition *STRIVE + STROE + SenseGlove* was that grabbing with the SenseGlove had a similar positive impact as STRIVE. However, this statement contradicts the consensus of the vast majority that SenseGlove was mainly responsible for inaccuracies and therefore rather bad for realism.

Additional Questions

The general questions at the end of the study also provided important results apart from the haptic questionnaire. For example, the question about the most important type of haptic feedback was unanimously answered by all 12 participants with the collision feedback of the STRIVE. Neglecting the technical limitations, the collision feedback still came out on top with six votes. However, the realistic grip of SenseGlove was seen as the most important feedback type by five people, if one could assume that it would work perfectly. Only one person would find the weight simulation by STROE important in this constellation. This impression is also reflected in the answer to the question of whether participants would use haptic feedback devices in their daily work. Here, nine participants were in favor of wanting to use STRIVE in their daily work. Three participants said that haptic feedback in general does not add any value to their work and would therefore not use any of the haptic feedback devices. Strikingly, four people were positively surprised by STROE and attested that it would be well conceivable in their work environment. For SenseGlove, the answer to this question was rather negative. Three participants said that there is no need for the SenseGlove because precise gripping is not important for work and simple gripping with a controller is completely sufficient. Three participants also added that SenseGlove is too inaccurate in its current state to provide any added value. However, even if the gripping would work perfectly, all three persons agreed with the opinion that SenseGlove could become more important but still does not provide any added value in many use cases. The statements of the other participants then coincided with each other.

When asked which of the combinations of haptic feedback devices was best, there was also a clear result. Nine participants found the condition *STRIVE + STROE* best. Only two participants found the condition *STRIVE + STROE + SenseGlove* best and one participant would use the combination of *STRIVE + SenseGlove* or *STROE + SenseGlove* depending on the use case. Abstracted to perfectly functioning devices, this opinion changed drastically. In this situation, only two participants would still choose the condition *STRIVE + STROE*. Now ten participants were convinced that without technical limitations as much haptic feedback as possible was best and therefore choose the condition *STRIVE + STROE + SenseGlove* as the best possible combination of haptic feedback devices.

In an overall summary of the experiences participants had during the study, the majority of participants reported a generally good feeling in the scene. This positive experience was further confirmed by the quick setup of the haptic feedback devices. The quick setup and removal were also mentioned as important points by the participants to be applied in the company in the daily work routine. In this conclusion, the collision feedback provided by STRIVE was again mentioned positively, and STROE also made a positive impression on the participants due to the simple methodology of simulating weight force with a pulley. On the negative side, the lack of precision of SenseGlove was repeatedly mentioned. Furthermore, the opinion of one participant was that individual faulty impressions like this, which are insignificant in themselves, add up and thus worsen the overall impression.

Suggestions for improvement mentioned by the participants included making the haptic feedback by the STRIVE quieter since the clacking sounds of the solenoid have a negative impact on the immersion. Another suggestion mentioned by two participants regarding STRIVE would be to implement a surface simulation to be able to glide along virtual objects. For STROE, there were few suggestions for improvement, but three participants noted that the crane sometimes hit the leg, which should be prevented in the future. Other suggestions were mainly based on the principle that the system has to work consistently and therefore an alternative to the SenseGlove should be considered that allows finger tracking in combination with STRIVE.

6 Discussion

In order to draw clear conclusions, the results of the user study explained in the previous section will be analyzed and summarized in the following.

As an overall result of the haptic questionnaire, there was a clear impression according to the Likert scale results. The condition *STRIVE + STROE* consistently achieved a considerably higher score than the other conditions. Also, the subjective feedback in the interview showed that the participants had the best overall experience with this condition because the feedback was among other things clear and precise. As soon as haptic grasping was added by SenseGlove, this impression became blurred. This was partly due to the fact that the combination of SenseGlove with either STRIVE or STROE was often perceived as not intense enough but the combination of all three haptic feedbacks as too intense. From this, one could infer that the SenseGlove itself has a rather low intensity, which is then not noticeable in a combination with STRIVE and STROE together since these themselves provide a high intensity. One participant provided meaningful reasoning for this thesis in the interview. The participant said that gripping did not completely lock the fingers and there was still room for movement in the fingers. This made all feedback with grasping feel rather weak and not as precise as collision feedback.

This impression is also reflected in the subscale *Timbre*. Here, too, four persons confirmed that in the condition *STRIVE + STROE + SenseGlove* the character suffered from the fact that the impressions overlapped. As a result, the impression of weak haptic grasping was then submerged. However, since users were aware that they were wearing haptic feedback gloves and expected balanced feedback here, this led to a poorer overall impression when the haptic feedback from STRIVE and STROE overlapped that of SenseGlove. One participant suggested a solution to this problem. The participant suggested that SenseGlove could be replaced by controllers with finger tracking since the real advantage that SenseGlove offered was not the haptic feedback on the hands but the precise tracking of the fingers. One such controller with which this would be possible is Valve's Index[1] controller, for example. Even with a controller like this, the haptic feedback on the hand would not be completely lost, since it can also convey haptic impressions through vibrations. Using finger tracking in combination with STRIVE and STROE would also potentially increase usefulness. Here, one participant testified that an important form-giving impression that SenseGlove can provide is missing in the condition *STRIVE + STROE*. However, a new study would be needed to evaluate whether a controller with finger tracking could also provide this shape-giving impression or whether it was solely due to the haptic constraint of the fingers.

A solution like this could, among other things, also eliminate the problems mentioned by the participants in the *Consistency* subscale. This category provided very hardware-related results, which are related to the haptic feedback devices. However, the reliability and reproducibility of haptic feedback played an important role for the majority of participants. Participants felt that

[1] https://www.valvesoftware.com/de/index/controllers

reliable haptic feedback validated their actions, and when those actions were reproducible, it gave participants a sense of confidence in using haptic feedback. However, once haptic feedback from one of the devices used was not consistently reproducible, participants tried other methods to reproduce the haptic feedback they had previously received and thereby confirm themselves in their actions. Thus, they were distracted from the actual work step. This phenomenon occurred mainly in the conditions with SenseGlove. Eight participants confirmed in the interview that this was particularly due to the haptic feedback when grasping small objects. For larger objects, it only occurred for two of the eight participants mentioned above, and for a large majority, grasping large objects made an intuitive impression. One participant made the following statement: „Especially the power drill felt realistic to use with the combination of SenseGlove and STROE as one could feel the drill working through vibration feedback and also had a realistic feeling of weight.“

This statement was surprising, as weight force was often mentioned in this and several other participant statements, but was by far the least important haptic feedback in the final questions at the end of the interview. Here, all participants in the current state of the devices agreed that collision feedback was the most important. Therefore, it can be assumed that the simulation of the weight force left more of a subconscious impression on the participants. Thus, another participant also said the following: „The more STROE is absent, the more you realize how important weight simulation was.“ However, weight simulation did not remain only in the background, because four people confirmed that a fatigue effect occurs in the conditions where STROE is included. This was realistic and important for the work in the company, as it could create a better approximation to reality in the virtual buildability studies and reveal crucial factors in the evaluation of the assessed process. According to one participant, in previous buildability studies, it was difficult to implement fatigue by simulating the weight force and thus it could have happened that the load capacity of the employees was overstressed. This could be prevented by introducing weight force. Nevertheless, much more present than the simulation of the weight force was not only the collision feedback but also the haptic gripping, because six persons confirmed that the haptic gripping would have left the most important impression if one leaves the technical limitations aside.

These statements also became clear in relation to the realism scale, because one participant stated in relation to the *STRIVE + STROE* condition that by using the controller the important information of grasping is lost. In other conditions, the participant had to partially regrasp objects when initially holding them incorrectly, so the task was not solvable with this hand position. Also as feedback on the realism scale in the condition *STRIVE + STROE* the statement was made that by introducing collision and weight simulation with this combination of haptic feedback devices important elements of realism in VR are added. Nevertheless, it is questionable whether haptic feedback even needs to be as realistic as possible to serve its purpose. Similar feedback was also found when using the SenseGlove, as a majority of participants considered grasping itself to be a positive factor for realism, but small inaccuracies then quickly turned into a strong negative effect. This is reminiscent of a form of an uncanny valley that could be transferred to haptic feedback. The existence of this effect is proven by Berger et al. [BGOH18] with their article. Thus, based on the feedback from the user study, one can argue that the condition *STRIVE + STROE* is at a high point of the uncanny valley. However, by adding SenseGlove to the other conditions, the overall experience then slips into negative territory, as it cannot ensure a perfectly realistic simulation of a real hand due to inaccuracies.

This also explains why the condition *STRIVE + STROE* was rated as the best by nine participants but was replaced by the condition *STRIVE + STROE + SenseGlove*, since this would be preferred by ten participants if there were no technical limitations. Without technical limitations, the uncanny valley could be jumped over and the entire haptic feedback could be applied. Therefore, in theory, the condition *STRIVE + STROE + SenseGlove* would be the most promising for the future, but in practice, it could be difficult to implement the necessary improvements, which is why the condition *STRIVE + STROE* should take precedence in practical use.

Another aspect that was received differently by the participants was the different character of the haptic feedback. For example, the collision feedback provided by the STRIVE has an on/off character, whereas the feedback provided by the SenseGlove and STROE provides continuous haptic impressions that can also vary in strength. In the condition *STRIVE + STROE*, one participant confirmed that these devices fit well together and despite the different characters, a harmonious impression was created and the impressions even merged into each other. In the condition *STRIVE + SenseGlove*, however, the participant could not confirm this statement. Although here, too, hard on/off feedback meets continuous haptic feedback. Other participants also had split opinions regarding the combination of the different characters, which is why no clear statement can be made in this regard. The participants even had fundamentally different opinions when it came to how strongly the haptic impressions should merge into each other. One participant preferred an overall haptic impression that was as close to reality as possible and another participant thought it would be better to be able to identify the individual haptic impressions so that it was easier to distinguish the information conveyed by the haptic feedback. Therefore, the question also arose whether feedback that is as close to reality as possible is useful or whether abstract individual haptic impressions are more helpful for the users. In this respect, it can be assumed that the respective extremes are preferred by the participants depending on their individual preferences, but that only a halfway harmonious combination of different haptic impressions will be perceived negatively, similar to the uncanny valley effect described in the previous section.

7 Limitations

This section describes the limitations encountered during this work that may have had an impact on the results obtained. One limitation that could be eliminated during the work prior to the user study was the Bluetooth restrictions by switching to a BLE connection. As mentioned in section 3.4.2, the number of Bluetooth devices used in this study was higher than the possible number of Bluetooth devices that could be connected to a computer. In the following, however, we will not only deal with technical limitations but also with other factors that could influence the results.

Since STROE is a single prototype and no second model is available, only one hand with weight force could be simulated. Thus, two-handed interactions were not possible, which could possibly create a completely different impression for the users. However, this could turn out to be both positive and negative, since in the user study five participants reported that by connecting too many devices with strings to the hand or controller, respectively, the freedom of movement is restricted. Thus, the number of strings that can be connected to the hand without restricting freedom of movement can be seen as another limitation. The number of strings is also a limitation for the above-mentioned ambidextrous interactions, as they would most likely get tangled in an ambidextrous setup. However, it was also stated that one could choose a combination of only STROE and SenseGlove for an ambidextrous setup.

Another major limitation, already mentioned in section 4.2, was, that Unity did not provide the necessary performance to calculate collisions with highly detailed objects. As already described, the frame rate drops to about 3 Frames per Second (FPS) due to the enormous computational overhead of complex collisions.

It was already mentioned, that this limitation was partially circumvented by remodeling objects with simple colliders. However, the remodeled objects cannot provide the perfect precision that is needed for these tasks in everyday work in this field. This tolerance of a few centimeters could only be used for the exemplary use case in the conducted study to demonstrate the concept of different haptic feedback combinations. In real work, however, a few centimeters of discrepancy can have fatal consequences and determine whether, for example, a buildability study can be carried out successfully or reveals potential problems.

In addition, the time required to remodel the objects is high, which is not acceptable in a working environment. One possible solution would be to use an external tool for collision detection, such as IC.IDO[1], which was designed specifically for working with detailed three-dimensional objects. Here, however, the question arises whether it would not be more sensible in the future to integrate all haptic feedback devices directly into an external tool and run the entire simulation from there instead of using Unity.

[1] https://www.esi-group.com/products/virtual-reality

All of these technical limitations could have a non-negligible impact on the user experience. As described in the previous section, without technical limitations the majority of users would prefer multimodal haptic feedback consisting of all available devices. This opinion shows how large the influence of haptic limitations is on the outcome. Thus, it could well turn out that the preference would change to the fact that the complete multimodal haptic feedback from STRIVE, STROE, and SenseGlove could be best regardless of the use case.

This leads directly to the next limitation, which has already been mentioned. Depending on the use case used for evaluation, the results could also change. During development, it was emphasized to ensure an evenly distributed use of all haptic feedback devices, showing both the advantages and disadvantages of each device. However, whether this was successful cannot be completely guaranteed, as personal opinion plays a very strong role here.

A final limitation that must be considered when interpreting the results is the sample size. Because only 12 participants tested the different systems during the user study, the significance of the results is not as great as it could be obtained in a large field test. In order to obtain more meaningful results, the haptic feedback systems would have to be installed in the respective departments of the workspaces and used by the participants over a longer period of time. In this way, it would be possible to confirm or contradict the results obtained so far.

8 Conclusion & Future Work

After the preceding analysis of the data, this section draws a final conclusion from the findings obtained during this work. Thanks to the versatile feedback given by the participants of the study in the interviews, various perspectives for the future can also be pointed out, as well as individual suggestions for improvement can be implemented.

8.1 Conclusion

In this work, different combinations of haptic feedback devices were evaluated in VR. For this purpose, an exemplary use case was modeled, which was intended to introduce the characteristics of the different multimodal haptic feedback through a user study. The participants of the user study evaluated the different combinations using a haptic questionnaire and reported their impressions in an interview.

The results of the study show that the combination of STRIVE and STROE provides the most promising haptic feedback at present. On the *Timbre* subscale of the haptic questionnaire, a conducted one-way ANOVA indicates that the combination *STRIVE + STROE* is significantly better than the groups *STRIVE + SenseGlove* and *STRIVE + STROE + SenseGlove*. For the subscale *Consistency*, the ANOVA also indicates significant differences, but Tukey's HSD post-hoc test does not lead to a significant result between which of the groups this difference exists. However, one can assume that again the condition *STRIVE + STROE* is significantly better because in all subscales of the haptic questionnaire the condition *STRIVE + STROE* achieves on average the best results. This result is further confirmed by the subjective feedback of the interview. Here, nine of the 12 participants stated that they found the condition *STRIVE + STROE* the best, thus preferring the haptic feedback consisting of collision simulation and weight simulation. However, disregarding the technical limitations, it can be seen that the haptic gripping of SenseGlove also left a positive impression. When considering haptic feedback alone without respect to technical limitations, ten of the 12 participants would prefer a combination of *STRIVE + STROE + SenseGlove* and thus use as much haptic feedback as possible.

However, since the feedback was very broadly distributed, positive conclusions can also be drawn from the other combinations of haptic feedback. A frequently mentioned statement of the participants was that the advantage of haptic feedback depends very much on the use case. To substantiate their statements, participants also mentioned use cases in which, for example, a combination of weight simulation with haptic grasping is useful. Another aspect shown by the results is that the haptic feedback does not necessarily have to be realistic, as a kind of uncanny valley emerges, whereby even abstractly held haptic feedback can provide a better user experience than partially realistic feedback which does not perfectly match reality. Finally, a throughout positive conclusion can be drawn for this work, as the haptic collision feedback is already used in everyday work and the prospect of combining the collision feedback with a weight force simulation shows promising approaches that can be further refined in future work.

8.2 Future Work

Having presented promising concepts of different multimodal haptic feedback in this work, a look into the future can provide ideas on how to further improve these approaches.

The first approach that could be evaluated for the future is based on the feedback that the participants of the study brought towards SenseGlove. Since haptic gripping was still too imprecise, but conveyed a more direct feeling to users, implementing pure finger tracking would be an option for the future. By tracking the hands and fingers of the users in combination with the collision simulation of the STRIVE, the haptic feedback could be transferred even more precisely to the user's hand instead of to a controller that is held. However, it would then have to be evaluated in a further step whether the renunciation of haptic grasping also entails disadvantages, since pure finger tracking cannot provide haptic impressions. Weight simulation could also continue to play a role in this approach since the combination of STRIVE and STROE was found to be very positive.

Another idea that was frequently mentioned is a haptic system that can be used ambidextrously. Since there are often larger components in the automotive industry, some use cases would be conceivable where users need both hands for interactions or to hold an object and therefore haptic feedback would also have to be implemented on both hands. However, this approach has the problem that the STRIVE will encounter a technical limitation because, in such a system, many strings of the STRIVEs would have to be connected to both hands of the users, which would then inevitably interfere with each other. Still, such an approach could be useful for a combination of weight force simulation and haptic grasp, as these devices would not conflict with each other. Since participants also said that they would choose between the different haptic feedback individually tailored to their use case and not necessarily always choose the full multimodal haptic feedback, this ambidextrous system could be implemented in use cases where weight force in combination with realistic grasping plays an important role, for example, because a large or heavy virtual object has to be held.

Other ideas, mainly related to collision feedback, would be an implementation of pushable resistors, which would make it possible to move objects in the scene with resistance or to deform solid objects and get haptic feedback. Among other things, this could make it possible to evaluate corruptible models. This means that a possible collision with other objects could cause damage to a component. This would provide additional information to the user, which could be particularly important for fragile components. The haptic feedback could therefore not only provide information about a collision but also about the robustness of the materials and give an impression of how strong of a force causes damage.

Concluding, with all the positive aspects that arise from multimodal haptic feedback, the statement of one participant in the study should not be overlooked. The participant stated that, in some cases, it is difficult to convince people who are not familiar with the topic of VR of the benefits of haptic feedback in everyday work. According to the experiences made, the more complex the design of the haptic devices, the stronger this effect will be. In the future development of multimodal haptic feedback, the devices should therefore be constantly evaluated by potential users and care should be taken that the haptic feedback is individually tailored to the required use case, as well as the user group. A flexibly combinable system would make practical sense that allows only simple haptic feedback for new users but can be quickly modified to provide fully comprehensive multimodal haptic feedback for experienced users.

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Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

Stuttgart, 21.03.2023 P. Gebhardt

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