Moving Haptics Research into Practice: Four Case Studies from Automotive Engineering

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Summary

Virtual Reality (VR) has gained popularity and found applications in various fields, including the automotive industry. Over the years, VR has been used in assembly, ergonomic studies, and other automotive use cases to aid development. Engineers already benefit from using VR at different stages of development, but the current setups provide only visual, auditory, and limited vibrotactile feedback on controllers. These feedback types cannot accurately simulate forces for realistic collisions or weight simulation of virtual car components. Despite ongoing research in haptic technology, there are still limitations in creating a perfect haptic feedback system that can accurately simulate all tactile and kinesthetic stimuli without hindering movement or comfort. The automotive industry needs suitable haptic feedback devices, but most research focuses on developing new devices rather than integrating them practically.

We conducted four case studies to address this challenge to bridge the gap between haptic research and practical applications in automotive VR tasks. During these studies, we collaborated closely with automotive VR engineers to understand their needs and obtain feedback on using haptic devices. Our approach involved developing new haptic feedback devices based on technique- and problem-driven approaches. We created the PropellerHand, an ungrounded hand-mounted haptic device that allows forces on the hand without hindering hand use. STRIVE and STROE were developed based on problem-driven approaches, providing string-based haptic feedback devices to simulate collisions and weight. Finally, we created a multimodal haptic feedback system by combining STRIVE, STROE, and the haptic feedback glove SenseGlove, enabling users to simultaneously experience grabbing, weight, and collision feedback. Over three years, we extensively researched and implemented haptic feedback devices in practical settings. We interviewed more than 25 VR experts from the automotive industry, observed over 45 VR use cases, and collected feedback from over 200 individuals who tested our feedback devices. Based on this information, we formulated recommendations for moving haptic

research into practice.

The results of the case studies indicated that STRIVE showed the most promising outcomes for practical implementation due to its simplicity and versatility. It has already been integrated into five locations in a major automotive industry, with more than 15 users utilizing it for their automotive VR tasks.

Zusammenfassung

Virtual Reality (VR) hat an Popularität gewonnen und findet Anwendungen in verschiedenen Bereichen, einschließlich der Automobilindustrie. Im Laufe der Jahre wurde VR in der Montage, ergonomischen Studien und anderen automobilbezogenen Anwendungsfällen zur Unterstützung der Entwicklung eingesetzt. Ingenieure profitieren bereits von der Nutzung von VR in verschiedenen Entwicklungsphasen, aber VR bietet momentan nur visuelles, auditives und höchstens vibrotaktiles Feedback auf den Controllern. Diese Arten von Feedback können Kräfte für realistische Kollisionen oder die Simulation des Gewichts virtueller Autoteile nicht genau genug wiedergeben.

Trotz laufender Forschungen im Bereich der Haptik gibt es immer noch Einschränkungen bei der Entwicklung eines perfekten haptischen Feedback-Systems, das alle taktile und kinästhetische Reize genau simulieren kann, ohne Bewegungsfreiheit oder Komfort zu beeinträchtigen. Die Automobilindustrie benötigt geeignete haptische Feedbackgeräte, aber die meisten Forschungen konzentrieren sich darauf, neue Geräte zu entwickeln, anstatt sie praktisch zu integrieren.

Um diese Herausforderung anzugehen und die Lücke zwischen Haptik-Forschung und praktischen Anwendungen in automobilen VR-Aufgaben zu schließen, haben wir vier Fallstudien durchgeführt. Während dieser Studien haben wir eng mit Ingenieuren, die VR in ihren automobilen Arbeit benutzen, zusammengearbeitet, um ihre Bedürfnisse zu verstehen und Feedback zur Verwendung von haptischen Geräten zu erhalten.

Unser Ansatz umfasste die Entwicklung neuer haptischer Feedbackgeräte, basierend auf technik- und problemorientierten Ansätzen. Wir haben die PropellerHand entwickelt, die ein handmontiertes haptisches Gerät ist, das Kräfte auf die Hand übertragen kann, ohne die Handbewegungen zu beeinträchtigen. Wir haben die Feedbackgeräte STRIVE und STROE entwickelt, die auf der Grundlage von problemorientierten Ansätzen entwickelt wurden. Sie sind seilbasierte haptische Feedbackgeräte, die Kollisionen und Gewicht simulieren können. Abschließend haben wir ein

multimodales haptisches Feedback-System entwickelt, indem wir STRIVE, STROE und den haptischen Feedbackhandschuh SenseGlove kombiniert haben, wodurch Benutzer gleichzeitig Greifen, Gewicht und Kollisionsrückmeldungen erleben können.

Über einen Zeitraum von drei Jahren haben wir intensiv die Implementierung von haptischen Feedbackgeräten in der praktischen Umgebungen von automobilen VR Aufgaben erforscht und umgesetzt. Wir haben über 25 VR-Experten aus der Automobilindustrie interviewed, über 45 VR-Anwendungsfälle beobachtet und Feedback von über 200 Personen gesammelt, die unsere Feedbackgeräte getestet haben. Auf der Grundlage dieser Informationen haben wir Empfehlungen für die Umsetzung von haptischer Forschung in die Praxis formuliert.

Die Ergebnisse der Fallstudien zeigen, dass STRIVE die vielversprechendsten Ergebnisse für die praktische Umsetzung aufweist, aufgrund seiner Einfachheit und Vielseitigkeit. Es wurde bereits an fünf Standorten in der Automobilindustrie integriert und wird von mehr als 15 Benutzern für ihre automobilen VR-Aufgaben genutzt.

Chapter 1

Introduction

The primary focus of this thesis is to apply haptics research practically in the field of automotive virtual reality tasks. We extensively researched and developed haptic feedback devices for three years for practical automotive settings. Specifically, we interviewed over 25 VR experts from the automotive industry, observed more than 45 automotive VR use cases, and collected feedback from over 200 individuals who tested our haptic feedback devices. As a result of this research, one of our haptic feedback devices has been successfully integrated into five locations within a large automotive company. More than 15 users currently utilize this device for their daily automotive VR tasks. Throughout this thesis, the term "*we*" refers to the authors of the publications included in this work. In this chapter, we provide an introduction to the thesis topic and summarize our work's primary contributions and research goals.

1.1 Haptics in Virtual Reality

Virtual Reality (VR) has become increasingly popular and is being applied in a variety of fields such as gaming [5], education [77], medicine [121], arts [159], immersive analytics [46], and industry [146, 35]. VR provides new possibilities for interacting with virtual objects and experiencing virtual environments in a more immersive and realistic way. Currently, most VR setups only utilize visual and audio feedback. However, adding multisensory cues such as haptic, olfactory, and taste can positively impact the VR experience.

Melo et al. [99] reviewed 105 studies utilizing multisensory feedback in VR and found that approximately 85% of them positively impacted the user experience. Of these studies, about 87% used haptic feedback as an additional sensory cue.

Haptic feedback can be found in various areas such as medicine [41], teleoperation [91], education [112, 86], arts [19, 145], and gaming [76]. Haptic feedback is not limited to virtual reality applications; it can also be found in products such as mobile phones, teleoperation systems [69], and even the steering wheel of cars, providing helpful feedback to the user. However, in this thesis, we are focusing on haptic feedback in VR.

There are different kinds of haptic stimuli. Tactile feedback provides feedback on the skin, such as texture, softness, or temperature. In contrast, kinesthetic feedback provides feedback to the muscles and tendons, such as the resistance when opening a door or weight simulation.

Currently, VR headsets and commonly used controllers or gloves provide good visual and audio feedback, and some controllers include vibration feedback. However, vibration feedback has limitations in its ability to provide realistic physical sensations, such as the feeling of a realistic collision with a virtual object.

Despite the availability of simple haptic feedback, such as vibration, providing suitable kinesthetic haptic feedback remains an open challenge, as it requires complex and scarce hardware [37].

As haptics is a comprehensive research field, this thesis focuses on kinesthetic haptic feedback in VR. In the next section, we will describe our problem domain, where suitable haptic feedback devices are still in their infancy, and discuss what we intend to explore and change.

1.2 Problem Domain: Haptics for Virtual Reality in the Automotive Industry

VR has been utilized in the automotive industry for several years now [21]. Although research has been conducted on using haptics for in-car interaction [61, 66, 43], this thesis does not focus on that research area. Instead, the thesis concentrates on the car development process, where VR is already a tool used to support engineers in different development stages [169]. The main goal of VR in this context is to identify errors in data or design early on before creating physical prototypes. The earlier an error is found, the less expensive it will be to fix. Furthermore, VR is used to reduce the need for expensive hardware prototypes. Within the automotive industry, there are various VR tasks:

- **Design Choices:** Design tasks allow designers to view new car designs inside and outside the vehicle.
- **Buildability Studies:** They conduct buildability studies to determine whether specific car components can be assembled without interfering with other components or if they have enough space.
- **Ergonomic Studies:** They conduct ergonomic studies to ensure that mechanics can assemble the car without risking injury.
- **Comfort/UI Testing:** Investigations whether users can reach specific components comfortably, such as the UI display.

Design choices mainly require visual feedback, as users do not need to interact with the virtual model. In most other tasks, however, mechanics interact with the model by moving objects or colliding with virtual components. Currently, virtual and audio feedback is the only available option for these tasks, or at most, vibration feedback. However, there are limitations to this type of feedback, such as the difficulty in determining how far mechanics can move without colliding with car components, difficulty in recognizing collisions due to occlusion, and inability to detect collisions with the head or other body parts. To improve the accuracy and reliability of the automotive VR task results, the industry aims to increase the realism and immersion of their tasks. They have several requirements for a haptic feedback device that would be useful for them. However, as of now, no devices meet all of these requirements. Some research demonstrates that integrating force feedback devices can help engineers complete their tasks more efficiently [127, 30]. However, these studies do not consider the real industry environment or VR experts of the automotive industry, which is essential in integrating haptic feedback devices into their daily VR tasks. Therefore, suitable haptic devices for the described VR tasks are scarce [21] due to their complex requirements.

In this thesis, we address the open haptic research challenge related to our described problem domain, which we will describe in more detail in the next section.

1.3 Haptics Research Challenges for VR Applications

Haptic technology is widely used in various research fields such as medicine [136], arts [19, 145], education [112, 86], gaming [76] and industry [21]. Each field has specific requirements for haptic feedback, including the type of feedback (tactile or kinesthetic), the body parts on which feedback is needed, the level of accuracy required, and the type of task being performed (stationary or mobile). Despite ongoing research in haptic technology, we are still far from creating a perfect haptic feedback system that can accurately simulate all types of tactile and kinesthetic stimuli without any limitations on movement or comfort. This gap is still one of the significant challenges in the field of haptics [40]. Currently, commercial VR input devices mostly provide vibrational feedback, limiting the spectrum of haptic stimuli they can provide. Based on our experience, we observed that kinesthetic haptic feedback holds more potential for our described problem domain. Therefore, we focus on this type of haptic stimuli.

We conducted a literature review, identified 105 kinesthetic feedback devices, and analyzed the methodological approach used in their development. We found two primary approaches, namely, technique-driven and problem-driven. Sedlmair et al. [133] define technique-driven work as an approach that involves developing a new or improving an existing technique without focusing on a specific problem domain. Typically, these papers introduce a new technique, evaluate its effectiveness, and present possible applications. Examples of such techniques include Thor's Hammer [67], Wireality [49], and Drag:on [168]. On the other hand, the problem-driven approach is defined by Sedlmair et al. [133] as an approach that focuses on a specific problem, identifies and understands it, and then seeks a new solution with creativity, flexibility, and adaptability.

Only seven of the 105 devices we investigated were developed with a problem-driven approach. This fact indicates that the current haptic research in kinesthetic feedback devices is more focused on inventing new techniques than developing devices to solve real-world problems. According to McGrath [97], the research methodology significantly impacts the evidence gathered. He summarizes three aspects that need to be maximized to increase the total evidence: generalization to a wider population, precision that describes the external factors that can negatively affect the results, and realism that specifies the difference between the situation where evidence is gathered and where it is applied. However, maximizing one aspect reduces one or two of the other aspects. Therefore, focusing on generalization and precision usually reduces the realism to a controlled laboratory study, which creates a gap between the evidence where it is gathered and where it should be applied. Most haptic research prototypes are evaluated in laboratories, reducing the realism aspect. In contrast, studies focusing on realism, such as field case and design studies [133], are still scarce in haptics, specifically when used in VR.

Our problem domain has unique needs and requirements that current research prototypes do not meet [21]. Building devices that meet various industries' requirements and use cases is complex. Engineers need feedback on different body parts and tools and have specific requirements for the haptic feedback devices. Hence, most haptic feedback devices are only used in research because they mostly do not meet the requirements of industry engineers. Therefore, we see another open haptics research challenge: the need to move haptic research into practice, especially concerning VR use cases in the automotive industry.

1.4 Move Haptics Research into Practice

As previously mentioned, we face the open research challenge of moving haptic research into practice, particularly regarding VR tasks in the automotive industry. As researchers from the Visualization Institute at the University of Stuttgart, we have a strong background in visualization and have published papers in the context of the automotive industry [11]. Therefore, our research environment inspired us to move research into practice in the field of haptics. The visualization community addressed and studied this issue, and successful methods were developed over the past 15 years to expand the impact of visualization research, as noted by Thomas and Cook [141]. Following the terrorist attack on September 11, 2001, there was a strong motivation to introduce visual analytics into homeland security in the United States to protect the US from further terrorist attacks. The growing amount of data made it increasingly difficult to analyze, necessitating new methods and techniques developed through the collaboration of visualization researchers and homeland security experts, as noted by Thomas and Cook [141].

As a result, the number of problem-driven research approaches for new visualization techniques increased. Sedlmair et al. [133] focused on design studies as a problem-driven research approach that contributes to solving real-world problems involving real users. They explain the contribution of a design study is divided into three parts: problem characterization and abstraction, validated visualization design, and reflection on the design study.

Inspired by the promising results of problem-driven approaches in moving research into practice in the visualization community, we seek to transfer these ideas to haptics research, particularly in our problem domain of VR tasks in the automotive industry. In the following, we will define our research goal.

Research Goal: M< thesis aims to move haptics research into practice within the context of VR tasks in the automotive industry. To achieve this, we conduct case studies inspired by Sedlmair et al.'s work [133].

Their approach involves three key elements: first, a clear definition of the problem; second, the creation of a validated design - in our case, a new haptic feedback prototype; and third, a reflection on the study design used. Despite the specificity of our problem domain, we believe that our research findings can support haptics researchers in other domains where suitable haptic feedback devices are still scarce.

1.5 Contributions

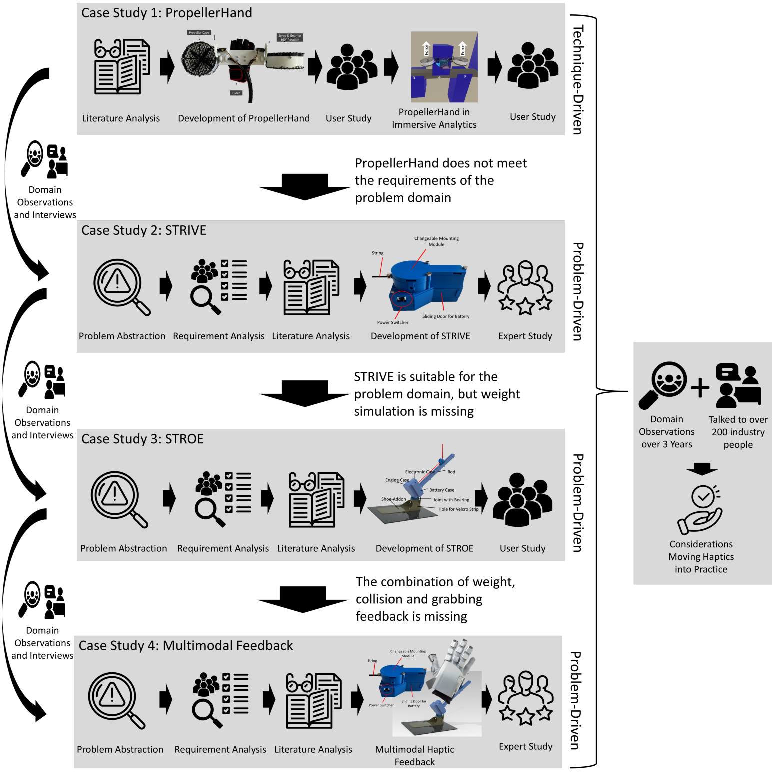


Figure 1.1 — An overview of the thesis contribution. The four case studies PropellerHand, STRIVE, STROE, and our multimodal haptic feedback system with its own steps and the followed considerations how to move haptics research into practice.

We have conducted four case studies to facilitate the practical applications of haptic research in the automotive industry. These studies involve characterizing the problem, designing and testing new haptic feedback devices, and reflecting on the study approach.

The first case study followed a technique-driven approach commonly used in literature to develop and evaluate a new haptic device. Based on the findings of this study, we shifted to a problem-driven approach in our next three case studies. Here, we first analyzed and characterized the specific problem before developing and evaluating new haptic feedback devices. Finally, we reflected on the study design approach in all three case studies.

1.5.1 Case Study: PropellerHand

Most of the research on haptic feedback devices has followed a technique-driven approach, where a new or improved technique is developed without addressing a specific problem. This approach has the advantage of inspiring people to use their resulting technique and apply it to existing needs or problems or adapt it as necessary. Sometimes, a technique is invented before there is an actual need for it.

The invention of the car is a prime example of this. Before the car was invented, people used horses and horse-drawn carriages for transportation. However, in 1886, Carl Benz developed a new technique to transport people without the need for muscle strength. His approach was driven by the desire to improve transportation technology rather than to solve a specific problem. At first, the car had more disadvantages than horses, but improvements over time have made the car a product that is now used by billions of people.

Examples of devices that have been created using a technique-driven approach include Thor's Hammer [67], which used the thrust of propeller propulsion for the first time to produce force feedback in a handheld device, Cheng et al.'s [32] use of a compressor and a liquid to simulate weight in a controller's container, and Lopes et al.'s [92] use of electric muscle stimulation to simulate forces in virtual reality.

Our approach to moving research into practice initially followed the typical technique-driven approach. We were inspired by propeller-based devices such as Thor's Hammer [67] and Aeroplane [75], due to their mobility. However, we identified limitations in these devices that we wanted to improve. Firstly, we did not want a predefined handle; we wanted our device to be compatible with common VR controllers or gloves. Secondly, we wanted our device to generate forces and torques. Based on these new requirements, we developed PropellerHand [12].

PropellerHand is an ungrounded hand-mounted haptic device with two rotatable propellers that allow for the exertion of forces on the hand without obstructing hand use. It can simulate feedback such as weight and torque by generating thrust up to 11 N in 2-DoF (Degrees of Freedom) and a torque of 1.87 Nm in 2-DoF. We evaluated our final version through a qualitative user study in various VR scenarios that required participants to manipulate virtual objects differently while changing between torques and directional forces. Results showed that PropellerHand improves users' immersion in virtual reality.

We saw potential in PropellerHand for data visualization tasks due to its ability to provide torque and forces on a user's hand without restricting movement. We conducted a second user study in the field of immersive visualization to investigate the potential benefits of PropellerHand in this area [13]. Additionally, we see potential benefits of PropellerHand in other domains, such as simulating weight in a loud environment.

However, we identified limitations in using PropellerHand in the automotive industry. In many automotive VR use cases, there is more than one person in a room, and the loud noise of PropellerHand would be too disturbing. It cannot simulate impact sufficiently due to the weak force and high latency.

We attributed these limitations to the characteristics of the technique-driven approach commonly used in haptics, which have drawbacks when building suitable haptic feedback devices for the automotive industry. However, these drawbacks may not have a large impact in other domains. As our next step, we began to define and understand the problems and requirements of automotive VR engineers and conducted a case study using a problem-driven approach.

1.5.2 Case Study: STRIVE

As mentioned previously, we were inspired by the approach used in the visualization community to implement research findings in real-world settings. Therefore, we decided to adopt a problem-driven approach for our second case study. However, analyzing problems outside one's research area can be challenging. To effectively analyze a problem, it is important to have close contact with the people experiencing it and understand their surroundings, tasks, and motivations. Unfortunately, some researchers may find it difficult to obtain this information because they are solely focused on their research environment. As a result, problem-driven approaches are not commonly used in haptics, and researchers tend to rely on technique-driven approaches.

To implement the problem-driven approach, we first identified the problems that VR engineers in the industry faced that could be solved using haptics. Then, we conducted a participatory design study spanning over 10 months with 13 engineers to create our new device, named STRIVE [10]. We drew inspiration from existing feedback devices, such as Wireality and INCA 6D, to design STRIVE, a string-based haptic feedback device. This process also led to a set of requirements for incorporating haptic devices into industrial settings, including the need for flexibility in terms of forces, comfort, and mobility. We evaluated STRIVE with 16 engineers across five different VR use cases in the automotive industry. The results showed increased trust, perceived safety, and new steps toward transitioning haptics research into practice. Most of the engineers considered STRIVE suitable for the industry.

However, based on our study results, we also noticed that some participants expressed a desire for weight simulation, which STRIVE cannot provide. Therefore, we employed a second case study with a problem-driven approach to focus on simulating weight. We chose this approach because it yielded better results than our first case study.

1.5.3 Case Study: STROE

We approached the issue of simulating weight in virtual reality by conducting a third case study with a problem-driven approach. Firstly, we conducted a requirement analysis with VR engineers to better understand the problem and specific requirements. However, we discovered that existing haptic feedback devices had limitations that did not meet our needs. Therefore, we turned to existing feedback devices for inspiration and developed the new haptic feedback device STROE [9].

STROE is an add-on worn on the shoe and connected to the user's hand via a controllable string. A motor applies force to the string to simulate the weight of various objects. The design of STROE allows for greater freedom of movement than other state-of-the-art weight simulation devices, and it is also quieter and more cost-effective. Through our user study, we found that STROE effectively simulates weight and increases users' perceived realism and immersion in VR scenes.

Overall, the problem-driven approach was more beneficial as it allowed us to observe the problem and requirements closely. A user study showed that participants could realistically feel the weight of virtual objects during standing and movement. Additional feedback from the user study revealed a need for the combination of collision, weight, and grabbing feedback, which we investigated in the next case study.

1.5.4 Case Study: Multimodal Haptic Feedback

After conducting our previous case studies and more detailed observation of automotive VR use cases, we discovered that certain scenarios require multiple haptic feedback types simultaneously rather than switching between different haptic feedback devices. To address this need, we again adopted a problem-driven approach. Based on the needs for automotive VR tasks, we focused on simultaneously simulating the haptic feedback types collision, weight, and grabbing. Currently, haptic feedback approaches mostly remain unimodal, limiting the ability to simulate multiple senses simultaneously. This is crucial for simulating complex tasks like maintenance, where engineers experience sensations like grabbing, collision, and weight. To tackle this issue, we tested a multimodal feedback approach by combining affordable haptic devices capable of delivering these three feedback types. Two user studies were conducted: a pilot study involving four participants to gather formative feedback and an expert study with twelve automotive VR experts. The results demonstrated that combining weight and collision feedback yielded the best performance. However, the study also highlighted technical limitations in the current grabbing devices. Our findings provide valuable insights into haptic device combinations' effectiveness and practical boundaries for automotive VR tasks.

1.6 Publications

Below is a list of all the author's publications, both within and outside of this thesis.

1.6.1 Thesis Publications

- Achberger Alexander, Frank Heyen, Kresimir Vidakovic, and Michael Sedlmair. "PropellerHand: A Hand-Mounted, Propeller-Based Force Feedback Device." ACM Conference on Visual Information Communication and Interaction (VINCI), 2021.
  doi: 10.1145/3481549.3481563 [12]
- Achberger Alexander, Frank Heyen, Kresimir Vidackovic, and Michael Sedlmair. "Touching data with PropellerHand." Journal of Visualization, 2022.
  doi: 10.1007/s12650-022-00859-2 [13]
- Achberger Alexander, Fabian Aust, Daniel Pohlandt, Kresimir Vidackovic, and Michael Sedlmair. "STRIVE: String-Based Force Feedback for Automotive Engineering." ACM Symposium on User Interface Software and Technology (UIST), 2021.
  doi: 10.1145/3472749.3474790 [10]
- Achberger Alexander, Pirathipan Arulrajah, Michael Sedlmair, and Kresimir Vidackovic. "STROE: An Ungrounded String-Based Weight Simulation Device." IEEE Conference on Virtual Reality (VR), 2022.
  doi: 10.1109/VR51125.2022.00029 [9]
- **In Preparation:** Alexander Achberger, Patrick Gebhardt, and Michael Sedlmair. "Exploratory Expert-Study in the Field of Multimodal Haptic Feedback with Automotive VR Tasks." IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2024

1.6.2 Other Publications

- Gebhardt, Patrick, Maximilian Weiß, Pascal Huszár, Xingyao Yu, Alexander Achberger, Xiaobing Zhang, and Michael Sedlmair. "Auxiliary Means to Improve Motion Guidance Memorability in Extended Reality." In IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2023.

- N. Hube, A. Achberger, P. Liepert, J. Vogelsang, K. Vidačković and M. Sedlmair, "Study on the Influence of Upper Limb Representations and Haptic Feedback in Virtual Reality," IEEE Conference on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), 2022.
- Achberger, Alexander, René Cutura, Oguzhan Türksoy, and Michael Sedlmair. "Caarvida: Visual Analytics for Test Drive Videos." ACM Conference on Advanced Visual Interfaces (AVI), 2020.
- Knierim, Pascal, Thomas Kosch, Alexander Achberger, and Markus Funk. "Flyables: Exploring 3D interaction spaces for levitating tangibles." ACM Conference on Tangible, Embedded, and Embodied Interaction (TEI), 2018.
- Achberger, Alexander, Rückspiegel für ein Fahrzeug DE Patent DE102020001572A1, 2020

1.7 Thesis Structure

This thesis aims to bridge the gap between haptics research and its practical application in the automotive industry's VR tasks. The next Chapter 2 presents related work and background, including existing haptic feedback devices, current haptic practices, and the transfer of research into practice in other fields. Chapter 3 shows our first case study, which resulted in a propeller-based haptic feedback device called PropellerHand. Afterward, Chapter 4 introduces our second case study, which revealed the string-based haptic feedback device STRIVE. Chapter 5 presents the case study that resulted in STROE, a string-based weight simulation device. The last case study is about multimodal haptic feedback in automotive VR tasks and can be found in Chapter 6. In Chapter 7, we give an overview of our results, which resulted in considerations for transferring haptic research for automotive VR use cases to practice. In the end, Chapter 8 consists of a summary of the thesis and future work.

Chapter 2

Background and Related Work

In this chapter, we discuss this dissertation's background and related work. We start with an overview of various haptic feedback research devices for virtual reality and talk about their limitations. Then, we describe the current practical applications and haptic feedback devices. Lastly, we present how other research areas tackle the challenge of moving research into practice and how their approaches differ from ours.

2.1 Haptic Feedback Devices for Virtual Reality

There are already many haptic feedback devices available, but most of them are still in the research prototype stage. To provide a comprehensive overview of current haptic feedback devices and to investigate their limitations, we categorize them based on their technical approach. In this work, we only focus on kinesthetic devices used in virtual reality and do not consider tactile devices. A comprehensive list can be found on Haptipedia [134].

In the field of haptic feedback, devices are mainly divided into two categories: grounded and ungrounded. Grounded devices are stationary and connected to the physical environment, while ungrounded devices are either attached to the user's body or can move on their own, such as drones. In the first section, we highlight the most widely known grounded devices. The remaining sections cover ungrounded devices and are categorized based on their technical approach. In the end, we show a definition of multimodal feedback and show example devices.

2.1.1 Grounded

In this subsection, most of the following devices are intended for use outside of VR. However, we have included them in our related work because they can still be utilized in VR. One of the earliest haptic feedback devices, SPIDAR [68], comprises a small rig with motors on its edges that control a string tension connected to a controller that users can move. This approach enables SPIDAR to generate forces via string tension control.

Another device, Inca 6D [122], uses a technique similar to SPIDAR but is bulkier, costlier, and has a much larger working space, allowing users to move around in a larger area.

Mechanical arms, such as Phantom [96] and Virtuose 6D [54], are other examples of haptic feedback devices that produce forces to the user via motorized joints. These arms enable users to move their end and perceive haptic feedback. However, the main limitations of grounded haptic feedback devices are their limited mobility or bulky design, which make them unsuitable for use cases that require mobility.

2.1.2 Body-Grounded

Wearable haptic feedback devices can be attached to the user and offer unlimited workspace. Backpack devices like SPIDAR-W [110] and HapticGear [70] provide force feedback, with SPIDAR-W capable of 6-DOF forces on both hands and HapticGear offering 3-DOF on one hand. Wire-Man [24] is another backpack device, while Melchiorri et al. [98] developed a one-wire version to explore the potential of single-wire force feedback. This device was able to detect obstacles, but it could not generate forces to the ground.

HapticSerpent [15] is a snake-like robotic arm that attaches to the user's waist, can hold objects, and perform actions but cannot provide haptic feedback without obstructing hand usage. The Actice VI-Bot [56] is an exoskeleton that simulates forces. Still, its use is limited by its long setup time, weight, discomfort, and the fact that it can only simulate forces in relation to the body.

In conclusion, the drawbacks of these types of devices include discomfort, long setup time, and the limitation of only simulating forces in relation to the body.

2.1.3 Shifting Weight

There exist devices that can simulate a shift in weight for objects with varying centers of mass. One such device is Transcalibur [137], which is a handheld device that can change its shape to imitate a weight shift. Another device, Shifty [167], is similar but uses a movable weight along a pole. While these devices can simulate weight shifts, they have a constant overall weight and may not be suitable for VR applications where users need to hold objects of varying weights.

2.1.4 Propeller-Based

Several devices use propeller propulsion to generate forces. Examples include Thor's Hammer [67], Aero-Plane [75], Wind Blaster [76], and Leviopole [131].

Thor's Hammer [67] is a handheld device that resembles a hammer with a large cubic head. It has six propellers, one on each face, which provide three degrees of freedom with a force of up to 4 N.

Aero-Plane [75] is a handheld device with two propellers and can simulate a virtual object's moving center of mass. It can imitate the center of mass of different tools when grasped.

Wind Blaster [76] is a wrist-mounted device that attaches two propellers, allowing for free-hand interactions.

Leviopole [131] is a device that consists of two quadcopters mounted on a pole. It generates linear force in one degree and torque in two degrees of freedom using the thrust of its eight propellers.

However, a major drawback of these handheld devices is that they occupy the user's hand, limiting their ability to interact with virtual or physical objects or controllers. Most VR applications require either controller interaction or direct hand interaction. Holding a feedback device like Thor's Hammer limits the interaction possibilities with data or virtual objects.

Drones have also been explored to provide users with haptic feedback. Abtahi et al. [8] attached different materials to the sides of a drone, enabling the user to touch an object in VR. Yamaguchi et al. [162] used a piece of paper fixed to a drone and stabilized by its airflow as an interaction surface. BitDrones [59] used drones equipped with an RGB LED, an acrylic mesh and frame, or a small touch screen, allowing for augmented reality scenarios without head-mounted displays.

HapticDrone [7] used a quadcopter to create up- or downwards force feedback of about 1.5 and 3 N. TactileDrones [82] provided tactile feedback through small drones, conveying the impact of arrows or the sting of a bumblebee by hitting the user with differently shaped tips.

VRHapticDrones [71] used drones fitted with mesh surfaces or objects, providing either a surface the user can touch or an actuator that touches the user. The user can also grab the drone to move the virtual object.

However, drone-based approaches have limitations as haptic feedback devices. They cannot provide much force and cannot be used for torque feedback. They are also loud, making them unsuitable for VR use cases that require concentration or communication. Additionally, their propeller-based design leads to high latency due to the acceleration of the rotors.

2.1.5 Air-Based

This section explores air-based methods for creating force feedback that do not rely on propellers.

The AirGlove device [64] uses six nozzles that emit compressed air to generate thrust in any direction. This approach provides realistic weight and force sensations of up to 7 N but requires a compressor that restricts user mobility due to its weight and power connection.

The AirWand [128] is a pen-shaped device with nozzles on both ends capable of producing a force of approximately 3 N. However, it only provides force feedback in one dimension.

Suzuki and Kobayashi [138] proposed an AR system that includes a projection-based stereo display and air pressure-based force feedback. Air nozzles in a table blow air upward, which users can receive by holding a cup-shaped object. However, the system has limitations as the compressor and nozzles are fixed to the table, preventing users from moving in a larger area or receiving feedback from other directions besides upward.

Drag:on [168] utilizes two flamenco fans to create drag on a handheld device instead of generating airflow directly. By adjusting the surface area of each fan separately, the device can produce different levels of drag and torque. However, the effect depends on the device's orientation and can only be felt perpendicular to the surfaces of the fans.

2.1.6 Other Approaches

Various methods exist for providing force feedback to users in virtual reality, each with strengths and limitations. Lopes et al. [92] introduced a system that utilizes electro muscle stimulation (EMS) to activate a user's muscles. This approach creates force feedback effect by triggering the opposing muscle to the one being used. For example, when the user holds an object, the system triggers their triceps to activate their biceps. However, this method has some drawbacks, including the lengthy setup time and the restrictions imposed by multiple cables connecting the user to the system. Moreover, placing the electrodes on the body can be challenging.

Wireality [49], on the other hand, employs strings to limit a user's hand and finger movement inside virtual objects. When the user touches an object's surface, the spools of strings fixed to their shoulder lock, preventing further movement. Although this device can generate feedback for the user, it is complex in design.

Yano et al.'s [163] handheld device and the iTorqU [155] both use a rotatable flywheel to create torques through the gyroscopic effect. However, these systems do not generate force feedback and are unsuitable for many VR use cases.

GravityCup [32] and Niiyama et al.'s approach [111] employ a liquid-filled tank to simulate weight. However, this system requires a compressor, limiting the user's ability to move freely. Additionally, carrying or placing the liquid in a stationary position causes high latency, which can be problematic in VR scenarios.

2.1.7 Pseudo-Haptics

Some approaches create an illusion of forces through tactile feedback instead of haptic feedback devices that provide real forces to the user. Although these devices are not kinesthetic, they are included in the list because they aim to imitate kinesthetic feedback.

Gravity Grabber [104] and Grabity [34] use asymmetrical skin deformation on the fingers to create the illusion of weight. Kuniyasu et al. [88]

employed a similar technique to simulate the sensation of someone holding their hand. Samad et al. [129] provide visual feedback to the user to create the illusion of weight, which is achieved by manipulating the control-display ratio of the grabbed object. Kuniyasu et al. [88] also simulated the illusion of weight through tangential deformation of the forearm skin.

However, these approaches that only provide weight illusion do not generate real forces, leading to a lack of fatigue, and may not be suitable for certain VR scenarios, such as automotive buildability studies.

2.1.8 Mid-Air Haptics

As we conducted a user study with PropellerHand in the field of data visualization, we provide a brief overview of related work that covers haptic interaction with visualization. Mid-air haptics play a important role in supporting users. There are multiple interactive methods for visualizations in a 3D environment, such as in VR or AR applications [103, 114]. However, feedback users receive in mid-air interaction is technically limited at the moment [84]. Haptic feedback has shown potential in mid-air interaction, such as decreasing the interaction time or helping blind people interact with data [125].

Few haptic feedback devices support mid-air interaction. UltraHaptics [29] is a surface device that uses ultrasound to provide multi-point haptic feedback to feel objects in mid-air. HaptoMime [105] also uses ultrasound, enabling users to touch floating images with hands-free tactile feedback. Additionally, the authors show different applications of using HaptoMime, such as implementing a floating touch panel or drawing graphics.

Kim et al. [80] presented a novel mobile haptic device held in the pointing hand that uses an external damping mechanism applying vibration stimuli in a specific direction. They evaluated the device as an assistive technology to facilitate blind users in searching for targets on large wall-mounted displays.

Köpsel et al. [83] conducted two exploratory experiments to investigate the effects of auditory, haptic, and visual feedback on hand gestures. They found that the feedback modality can be given a lower priority and should be chosen by user preference.

In contrast to our work, these devices solely focus on tactile feedback and cannot apply any kinesthetic feedback to the user. Therefore, the devices are limited in steering the user's hand in a specific direction. Additionally, force feedback can give users more options to interact with virtual objects.

2.1.9 Multimodal Haptic Feedback

Wang et al. [153] define multimodal haptics as approaches that simultaneously provide multiple haptic stimuli, such as forces, vibration, and thermal stimuli. The authors highlight three domains involved in multimodal haptic interaction. Firstly, the multi-properties of virtual objects, encompassing aspects like softness, texture, and shape. Secondly, the multi-gesture interactions, including actions like grasp or weight. Lastly, the multi-receptors of the human channel, comprising cutaneous and kinesthetic receptors. They identified the core challenge of providing multimodal haptic stimuli within limited space for actuators. Creating haptic stimuli necessitates using actuators, such as motors, pneumatics, or voice coil actuators. However, a single type of actuator cannot produce different haptic stimuli. For instance, voice coil actuators cannot exert forces on a user.

To tackle this challenge, Park et al. [119] developed a haptic feedback device equipped with a vibration and impact actuator. This handheld device effectively simulates texture and impact feedback. The researchers evaluated the device by examining various types of material with the haptic device, using vibrotactile and impact feedback separately and in combination. The results revealed that participants perceived greater realism with single feedback types than combined ones for specific material types.

Culbertson et al. [36] combined a vibrotactile actuator with the kinesthetic haptic feedback device Phantom Omni. They successfully simulated 15 distinct virtual surfaces based on the model components friction, tapping transient, and texture. Through a user study, they discovered that the importance of these three separate model components varied across the surfaces.

Another approach, introduced by Al-Sada et al. [14], involves Haptic-Snakes. This snakelike robot offers taps, gestures, airflow, brushing, and gripper-based feedback on both the front and back of the body. The results of their user study demonstrated differing opinions regarding the most valuable haptic feedback, but there was a shared consensus on the robot's usefulness.

Wolf et al. [157] pursued a different approach by developing a multimodal haptic feedback device for the head. Utilizing numerous vibration motors and thermal actuators, such as cold winds, could generate temperature and vibration feedback on the head. Their user study revealed higher presence and enjoyment when using their haptic feedback system.

Prior research has demonstrated that different feedback devices can simulate various haptic feedback types on different body parts. Each device faced unique challenges, as there is currently no all-encompassing feedback device offering multiple haptic modalities. In contrast to previous work, our research regarding providing multimodal haptic feedback does not primarily focus on constructing new haptic feedback devices. Instead, it aims to combine existing feedback devices to create a multimodal haptic feedback system. To the best of our knowledge, a multimodal haptic feedback system that encompasses collision simulation, grabbing feedback, and weight simulation does not yet exist.

2.1.10 Summary

There are numerous haptic feedback research devices that employ various technologies. However, each device and technology type has its limitations. The most significant constraints in our problem domain were the lack of free movement, lengthy setup time, high latency, and high complexity. Furthermore, no feedback devices provide stimuli to the user's entire body.

These haptic feedback devices are not suitable for multiple automotive VR use cases. While one device might work for buildability studies use cases where the user needs haptic feedback on their hand, it would not be appropriate for another use case involving head collisions. Employing a new haptic feedback device for each VR use case would be too complex, expensive, and cumbersome. Additionally, most current feedback devices provide only one haptic stimulus and cannot simulate multiple simultaneously.

As we can see, we are still far from having flawless haptic feedback devices without limitations that cover the complete spectrum of haptic stimuli on the whole body. Next, we will demonstrate how haptic feedback devices are used in practice or tested in practical applications.

2.2 Haptics in Practice

This section focuses on haptic technology and its practical applications, specifically within the automotive industry. Furthermore, we will explore how haptic feedback can be utilized in immersive visualization and mid-air interaction. Our first case study demonstrated the potential of our resulting device in this field.

Nowadays, haptics research has become part of many fields, but the movement of haptics into practice is still rare, especially in industry [21]. We can find haptics research in arts [19, 145], education [112, 86], and the entertainment area such as Windblaster [76] or ElastiLinks [154], which demonstrated an improved user experience in VR games. Haptics research has also reached the medical simulation and rehabilitation field, such as for hand rehabilitation [136], robot-assisted surgery for minimally invasive surgical procedures [41], or for training an eye cataract surgery [47]. Most works' focus is technique-driven to inspire readers to develop new haptic feedback devices. However, we do not find them commonly used in museums, schools, or hospitals, so it remains unclear what is needed to move the research prototypes into practice.

In the automotive area, haptics research exists in two different domains. On the one hand, the in-car interaction haptics offers the driver and co-driver haptic feedback to better interact with the car. There is haptics research on a shape-changing car seat [61], mid-air ultrasonic feedback for automotive user interfaces [66], tactile feedback for virtual automotive steering wheel switches [43], or haptic feedback for the transfer of control in autonomous vehicles [42]. Besides these haptic car interfaces, participatory design studies have also been conducted to involve drivers in the design process. Brown et al. [27] conducted an exercise to design and validate an ultrasound-haptic mid-air interface. Pitts et al. [123] did a participatory design study with touchscreen experts from the automotive area to investigate user responses to haptic feedback in touchscreens using a simulated driving scenario with representative use case tasks.

On the other hand, the car engineering process benefits from haptic feedback, such as in assembly, ergonomic tasks, or reachability studies, where our focus lies. Vo et al. [151] evaluated the benefit of haptic feedback in assembly tasks in virtual environments. Compared to only visual feedback, the results showed that haptics has reduced the completion time by achieving higher placement accuracy to position the virtual objects. Berg et al. [21] describe how virtual reality is used in the automotive industry's product design and manufacturing, such as in visibility, ergonomics, reachability, and packaging use cases. They mention that haptic devices could help the engineers in their tasks, but currently, there is a lack of suitable haptic feedback devices. Xia et al. [161] share the opinion that haptics remains more a concept than is used in practice.

However, a few technique-driven applications introduce a string-based haptic feedback workbench that gives users haptic stimuli in assembly tasks [140, 116]. However, they do not conduct user studies and do not involve automotive experts. Richard et al. [127] investigated the effect of tactile feedback in accessibility tasks involving different parts of a mock-up. Results show that the participants could easily and quickly access the specific mock-up parts with haptic feedback. However, they do not focus on automotive experts' requirements and investigate how to move the haptic feedback into their daily work. Chamaret et al. [30] investigated the benefits of haptic feedback in accessibility tasks regarding task completion time and collision avoidance. They used a string-based haptic device to simulate collisions. Results show that haptic stimuli helped the users be more efficient than just the visual stimuli. However, they did not conduct the study with automotive experts or evaluate whether the experts would use such a device. More efficiency does not necessarily imply that automotive experts would use the technique. More requirements have to be met. As opposed to this, in our case studies, we involved automotive engineers in the design process to understand their problems and requirements for using a haptic device in their daily work.

2.2.1 Haptics for Visualization

In our first case study, we took a technique-driven approach to develop a new haptic feedback device called PropellerHand. While PropellerHand has demonstrated promising results in enhancing realism and immersion in VR, we do not believe it has the potential for use in industry. Instead, we see the potential for its use in immersive visualization tasks. Therefore, we aim to provide an overview of related work on haptics for visualization and mid-air interaction.

In data visualization, haptics has become important for users to understand their data more accurately and quickly [45]. Paneels et al. [118] summarized various haptic designs to provide feedback for data visualizations such as charts, maps, signs, networks, diagrams, images, and tables. Their results show that most of the research focused on chart visualization, where they also describe the challenges in the potentials of haptics. In scientific visualization, Avila et al. [17] present a haptic interaction method suitable for volume visualizations. Another area where haptics has a high potential in data visualization is to enable blind persons to observe and understand visualizations. Here, participatory design has shown that haptics was successfully integrated for visual impairments [149, 102, 147, 57, 101, 79] by involving them in their design process. Frith et al. [53] present various methods to observe data with haptics without visual components, such as using texture or forces. Through a study, we evaluated the potential of our newly developed haptic feedback device, PropellerHand, for immersive visualization tasks. Our results showed that PropellerHand offers a novel approach to data interaction and investigation, which is enhanced by force feedback. This finding distinguishes PropellerHand from previous related work in the field.

2.2.2 Summary

We can observe several advantages to using haptics in various practical fields, particularly in the automotive industry. However, current research is mostly concentrated on assessing the advantages of haptics in practical applications rather than integrating them into daily tasks. As a result, haptic feedback devices are used more in research than in practical applications.

In the next section, we aim to demonstrate how other research fields are addressing the issue of translating research into practical use and how their methods inspired us.

2.3 Moving Research into Practice

Research is crucial in solving problems and creating new inventions to benefit the world and its people. However, it is necessary to move that research into practice to ensure that it has a positive and important real-world impact. While some research areas, such as haptics, are in the early stages of development, others, such as medicine, have been extensively explored, with several methods in place for moving research into practice.

In medicine research, for instance, there is a defined process for moving vaccine research into practical usage, demonstrated during the COVID-19 pandemic by developing a new vaccine in a very short time [26]. The process starts with an exploratory stage, where potential targets for vaccine development, such as specific pathogens, are identified. This step is followed by pre-clinical studies to test the vaccine on animals to assess safety and efficacy. Clinical studies with humans are then conducted, followed by regulatory review and approval from official agencies. Finally, the vaccine is manufactured, and its quality is controlled during manufacturing. This strict process and rules are in place to prevent the false usage of vaccine development that could injure people.

In haptics, the risk of injury to people is generally low. However, researchers must still move research into practice to ensure that their work has real-world impact and adheres to the respective requirements. Gold et al. [58] examined the factors that facilitate or hinder the successful application of research to practice and found that developing appropriate products that help users understand the practical relevance of research improves the process. However, the process is hindered if researchers fail to reach the right audience. This fact means considering the right audience and including real-world users in the development process for haptic research.

Visualization is another field that has been motivated to move research into practice, especially in the aftermath of the terrorist attacks of September 11, 2001. Researchers in this field have developed suitable visual analytics to defend the United States against future terrorist attacks [141].

In the field of visualization, Munzner et al. [107] proposed a nested model that includes four layers for designing and validating visualizations. The layers are: 1) characterizing the task and data of the problem, 2) abstracting into operations and data types, 3) designing visual encoding and interaction techniques, and 4) creating algorithms. This model aids designers in developing valuable and appropriate visualizations. We believe this model could also be utilized to design suitable haptic feedback devices. The first layer involves characterizing the domain problem and identifying how haptics can be used to solve the problem, along with defining the tasks and the role of haptics. The second layer, data/operation abstraction design, involves identifying the available data, such as forces, and determining the type and amount of haptic feedback needed, such as kinesthetic or tactile feedback. The third layer, encoding/interaction technique design, is about determining the technical implementation of the haptic feedback, such as the required hardware or actuators, the size and shape of the device, and how the user interacts with the device, such as where it is attached. Finally, the algorithm design layer involves creating the software that controls the haptic feedback device. We were inspired by the nested model, which helped us in our process. However, in haptics, one important part is the hardware. Therefore, some important differences have to be considered, such as the interaction or setup of the haptic system.

Sedlmair et al. [132] investigated the process of integrating information visualization in a large company, highlighting the challenges that arise and providing recommendations for moving visualization research into large companies. In our case studies, we faced similar challenges, such as integrating the tool regarding technical and organizational issues, obtaining necessary data, securing time from experts, and persuading stakeholders. We have also faced these challenges in our efforts to integrate hardware.

Sedlmair et al. also offered several recommendations, including providing smooth installation and technical support, learning from experts, persuading them to use new solutions, and gently reminding them to use the tool. Most of these recommendations are also relevant to our efforts to move haptics research into practical application. However, a haptic system involves software and hardware, which is the most crucial part. Therefore, we must consider additional factors, particularly suitable haptic feedback devices.

In conclusion, moving research into practice has been explored in various research domains, resulting in new methods and recommendations. However, it is still in its infancy in the haptics research domain, particularly in the context of automotive VR use cases. While the outcomes of other research domains inspired us, our focus on hardware and software necessitates unique solutions, particularly concerning developing suitable haptic feedback devices.

Chapter 3

PropellerHand

In our first case study, we used a technique-driven approach to build a suitable device for the industry to move research into practice. Here, we build a new haptic feedback device driven by the inspiration of current research technologies regarding simulating forces to a user. This chapter is based on the author's papers [12] and [13].

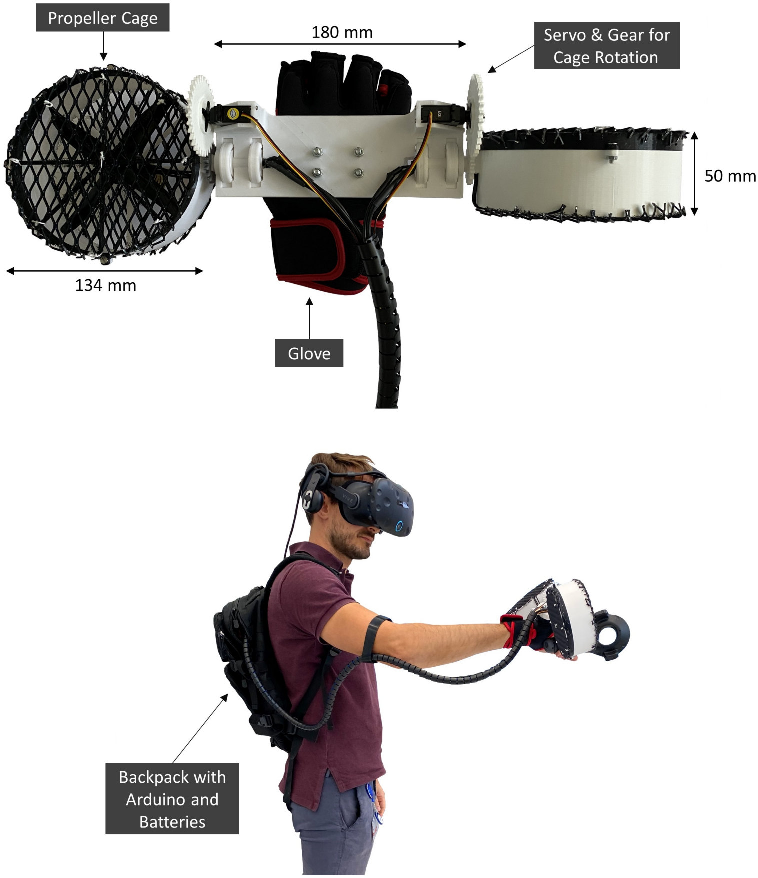


Figure 3.1 — Left: PropellerHand consists of two propellers in rotatable cages attached to a glove. Right: A user wearing the device. The control unit and batteries are placed in a backpack to reduce the weight of the hand-mounted hardware.

3.1 Introduction

VR and AR enable users to inspect and interact directly with 3D data, allowing various applications in education, training, entertainment, immersive analytics, and visualization [165, 156, 118]. Current VR/AR headsets primarily rely on visual and auditory output, sometimes enriched with haptic feedback through vibrating controllers. Other types of haptic feedback, such as force feedback, can be exciting in VR, though, as they allow us to "touch" virtual objects or data. Such devices can produce different force strengths and directions and have shown an improved VR experience in classical VR applications [142, 144], telepresence [87], and also in data visualization [45, 53].

Currently, many tactile haptic feedback devices are available for research purposes, including some commercially available devices like VR controllers [2] that use vibrations. However, kinesthetic feedback devices that can provide force feedback to users are rare and have not been explored extensively. These devices are complex to design and build to become comfortable and suitable for extended use. We believe that kinesthetic feedback devices have more benefits than tactile ones, although tactile feedback can also be combined with kinesthetic feedback to enhance the experience. As a result, we are focusing on developing a new kinesthetic feedback device. While other kinesthetic feedback prototypes are available in the research field, we are taking a technique-driven approach to develop a new haptic feedback device for general use in virtual reality. This approach involves analyzing existing haptic feedback devices, identifying their limitations, and then striving to improve them. Our focus is on ungrounded kinesthetic devices that are cheaper and lighter than grounded ones, making them ideal for use in mobile scenarios.

We extend existing work on ungrounded haptic feedback devices [67, 75, 76, 82, 8, 131] by creating a novel device that for the first time allows generating force and torque directly on the hand via propellers. These two types of feedback are required to resist motion and/or rotation, resulting in a more immersive perception of a virtual environment or in immersive analytics. Example use cases for haptic devices include games, industrial design, virtual collaboration, or data visualization [160, 148]. Here, we can increase the immersion of interactions such as moving or rotating objects or colliding against them. For instance, when opening a door, haptics can simulate the torque of turning the handle and the force of pushing the door open.

We propose PropellerHand, a hand-mounted haptic device that leverages propellers to create kinesthetic feedback through forces and torques in two degrees of freedom (2-DOF) each, directly on the hand. PropellerHand can generate a thrust of up to 11 Newton (N) and a torque of up to 1.87 Newton-metres (Nm) with a weight of 480 g. As our device is mounted to the back of the user's hand, they can still interact with or hold objects, such as VR controllers or physical tools. This design allows more flexible interaction possibilities and usages in various domains. We also allow for more mobile use by integrating Bluetooth communication and batteries into our design. When users hold a VR controller, there is no need for an additional tracking setup, as the controller is already tracked and moves together with the hand. Our user study demonstrates that game mechanics, such as opening a drawer or lifting objects, become more immersive when using PropellerHand. Based on the positive results of using PropellerHand, we see potential in using PropellerHand in immersive analytics as well. Therefore, we conducted a second user study, where participants had to interact with visualization data in VR. Results revealed multiple benefits of using PropellerHand in the field of immersive analytics.

To summarize, we contribute a novel hand-mounted propeller-based force feedback device and details of our design process. This process includes a formative user study evaluating different form factors and measurements investigating the relationship of noise versus thrust of different propellers, both of which we did not find in related work. We performed a qualitative user study to evaluate our final device's usability and increased immersion. Additionally, we conducted a third user study in immersive visualization to evaluate the benefits of using PropellerHand to interact with data in VR.

Core Related Work The first haptic feedback device to use propeller propulsion to generate forces was Thor's Hammer [67]. Thor's Hammer is a handheld device designed in the shape of a hammer, equipped with six propellers to provide forces in three degrees of freedom. Studies indicate that Thor's Hammer successfully enhances immersion and realism in virtual environments.

There are other handheld devices, such as Aero-Plane [75] or Leviopole [131] that also utilize propeller propulsion for haptic feedback. However, these devices have a significant drawback, as users must hold the device in their hands, making it impossible to use VR gloves or state-of-the-art controllers. The design of PropellerHand does not have this problem.

There are also haptic feedback systems that use drones to provide users with haptic feedback [8, 162, 7, 59, 82, 71]. In these systems, a drone flies to the specific space where the user wants to touch a virtual object and simulates the object's resistance. However, the drone's need to fly to a specific location has a high latency and can only provide low forces to the user.

The most closely related work to PropellerHand is Windblaster [76]. Windblaster is a device attached to the user's wrist and consists of two propellers that can produce forces on the user's hand. However, Windblaster cannot rotate the alignment of the propellers, which means it can only provide forces in one degree of freedom. In contrast, PropellerHand can provide forces and torque in two degrees of freedom each, making it a more versatile and practical haptic feedback device.

3.2 Design of PropellerHand

We designed a force-feedback device that consists of two propeller cages attached to a hand-mounted bridge (Figure 6.2). Those cages can be rotated via servo motors to be able to generate thrust and torque in two degrees of freedom (2-DOF) each (4-DOF in total). We used mostly 3D-printed parts and commonly used electronic components to facilitate rapid prototyping and reproducability.

3.2.1 Propeller Cage Design Study

As moving propellers can be dangerous, we encapsulate them in cylindrical cages covered with aluminium meshes to prevent them from getting in contact with fingers or objects in the room, that might be pulled by the airflow. We conducted a small user study to find a cage size that does not obstruct movement of the arm and hand or cause collisions with other body parts. Six people (5m, 1f; 24-27 years) participated in this study.

The participants played one level of a VR game (Tumble VR for PlayStation). In this game, players have to stack objects onto a plate, requiring them to move and rotate their hand while holding a controller. We repeated this procedure six times with differently sized and weighted paper mockups of our approximate device design (Figure 3.2). The mockups' shapes reflect the dimensions of possible propeller choices and we tested cylinders with a height of 60, 65, and 70 mm and diameters of 76, 102, and 127 mm. We added different amounts of weight to the mockups (132, 198, and 290 g) to simulate the small, medium, and large versions of the device. The participants were sitting on a chair, to allow investigating collisions with the legs, and the mockups were fixed to either wrist or hand. To avoid biases, we made sure that the participants did not know which mockup they wore, by attaching those in a random order and only after putting on the head-mounted display. On average, each participant spent about 17 minutes in total playing Tumble VR.

We registered a total of 11 collisions, 5 with the head and HMD and 6 with legs. We asked the participants, if they noticed any difference between

Figure 3.2 — The paper mockup used in our form factor pre-study. Left/right: attached to the wrist/hand.

the sizes and weights of the mockups, if they were restricted in their movement, and if they consciously moved differently. Four participants did not notice any differences in size and three no difference in weight. Only two participants felt slightly restricted in their movements, but only with wrist-mounting. Just one participant reported that s/he consciously moved differently because of the mockup. Overall, the participants' answers to our questionnaires show that even the largest and heaviest model did not obstruct usage. They also preferred mounting the device to their hand instead of their wrist, since this is more stable when moving. The hand-mounted version seems also more comfortable, since two participants reported to sweat less with this configuration.

Based on these results, we chose the biggest of our three candidate shapes, as we assume that this allows for the most thrust. We also decided to mount our device to the hand instead of the wrist.

3.2.2 Hardware

We chose an Arduino UNO micro controller board due to its ease of use and wide support. The brushless motors we use to drive the propellers, are of the type T-Motor F40 PROIII [139] and are similar to the ones used in Thor's Hammer [67], but slightly stronger. To select the servo motors that rotate the propeller cages, we compared about 40 different products to find the best compromise between torque and weight. We chose the Hitec HS-81 Micro Servo. As all servos we found either provide 180 degrees or continuous rotation, we opted to use gears to obtain a larger range (330 degrees). We recommend using metal gear servos, as one of our plastic ones broke during the user study. For batteries, we used the Conrad Energy Lipo with 2400 mAh and 14.8 V, and for the electronic speed controllers (ESCs), we used Pulsar A-50 with 50 A. We chose these components because they match the motors' power requirements. For the communication between a PC and the Arduino we use a HC-05 Bluetooth module.

We compared four propellers with different diameter, shape, and blade count that fit the cage size we found in our pre-study. For this comparison, we performed experiments to measure thrust and noise at different power levels using a custom-built thrust stand. Based on the results of these experiments, we chose a four-bladed propeller with a diameter of 127 mm.

3.2.3 Software

Our software consists of several parts. For controlling motors and measuring thrust with the load cell, we wrote small C/C++ programs for the Arduino. The VR scenarios for our user study and the code for sending commands to the Arduino are written in C# using Unity. We implemented two safety measures: propellers turn off when they get too close to the user's head or when the controller's trigger is double-clicked.

3.2.4 Resulting Device

PropellerHand (including the glove) measures about 470×135×50 mm and weighs about 480 g (Figure 6.2). We are confident that we can further reduce the weight with a more sophisticated 3D design, as the motors, propellers, and cables weigh less than 130 g. The total cost of components amounts to about 225 Euros (about 270 USD), excluding 3D printed parts. Controller, batteries, and Bluetooth module (840 g in total) are placed in a small backpack to minimize the mass attached to the user's hand. With our current battery capacity of 2×2400 mAh, PropellerHand could provide feedback for at least two hours. The actual operating time will vary depending on the duration and strength of feedback, but batteries are quick to change and can be replaced by ones with higher capacities when needed. Our device does not require any calibration or tracking setup prior to use, as we assume that the hand will be tracked anyway in a usual VR use case, via either controller or VR glove, to which PropellerHand could be directly attached.

3.3 Technical Evaluation

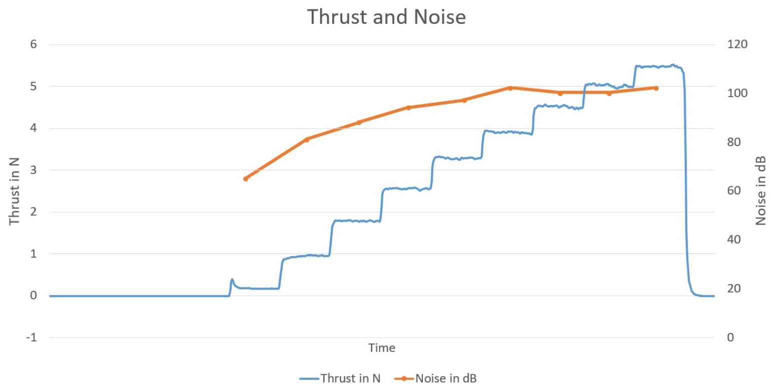


Figure 3.3 — The thrust and noise measurement of one propeller. We increased the power every 5 seconds. Therefore we can see steps in the thrust measurements.

To avoid unnecessary noise, and since the generated thrust seemed already strong enough, we did not use the maximum amount of power, but only 55.6 percent of it (as regulated by pulse-width modulation (PWM)). For our force measurements, we used a load cell from which we suspended one of the propeller cages such that it created a downward thrust. We measured a maximum force of 11 N, a minimum force of 0.17 N, and a maximum torque of 1.87 Nm, see Figure 3.3.

This means that PropellerHand can provide more thrust than Wind-Blaster [76] (1.5 N) and Thor's Hammer [67] (4 N) and less than Aero-Plane [75] (14 N).

Another important metric is the consistency of thrust, since users might notice fluctuations and therefore feel less immersed. When running the propeller for 10 seconds, all measured values were inside a range of 0.03 N (SD: $5.3E^{-5}$ N). We did not perceive these fluctuations ourselves, and they are even smaller when less thrust is generated. This is a low value, which means PropellerHand can produce the same amount of force over a long time, which is important for many use cases.

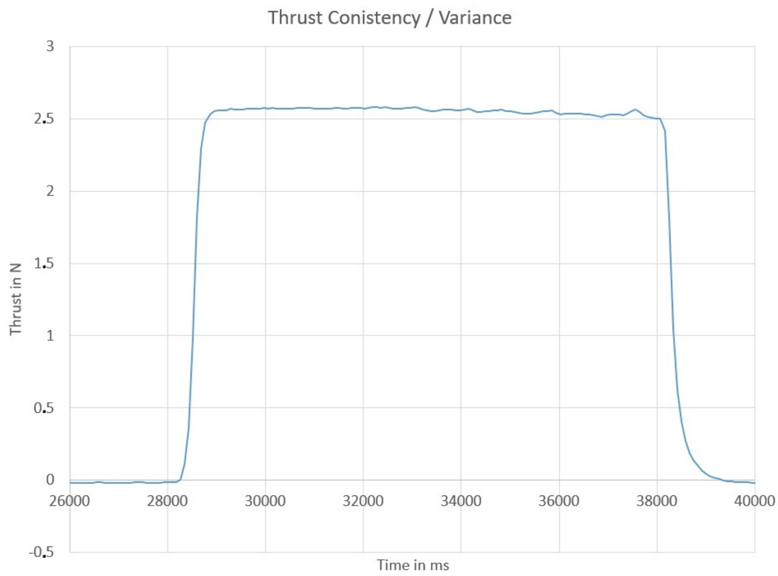


Figure 3.4 — The thrust consistency measured with a single propeller with an intensity of 27%.

As our device can produce varying amounts of thrust as well as rotate the propeller cages, we measured two kinds of latency: the reaction time from a control signal to full target thrust and the time needed to rotate the cage to a target angle. We measured a latency of 683 ms for a still-standing propeller to reach full thrust. Compared to non-propeller-based force feedback devices, this is a high value, therefore we recommend to calculate collision prediction in order to reduce the latency. For a 330 degree rotation of the cage, our device requires 429 ms with standing propellers and 833 ms when running at full thrust.

We measured the noise level of PropellerHand with a decibel meter placed 1 m away, we got a maximum sound pressure of 102 dB and a minimum sound pressure of 65 dB.

3.4 User Study

We evaluated the influence of our device on immersion in a user study with four scenarios that require PropellerHand to simulate force and torque in varying amounts and directions.

3.4.1 Study Design

We recruited six people from our university's campus to participate in the study (5 m, 1 f; 24-34 years). Five assessed their VR experience as beginner and one as advanced. None of them have had previous experience with kinesthetic haptic feedback.

The participants used an HTC Vive Pro head-mounted display (HMD) and its controller and wore earplugs during the study. For increased hygiene, we provided each participant with their own single-use rubber glove and sanitized the HMD after each use. We attached our device to the participant's dominant hand (all were right-handed). The participants were standing and free to move in an area of about 4×4 m. To reduce noise and especially annoying frequencies, we limited the power through PWM to 28 percent of the maximum, limiting thrust to 5.1 N and torque to 0.87 Nm.

We proceeded as follows: After the participant signed a consent form, we gave a brief introduction to the safety features and study procedure. Each participant experienced four scenarios, each of them first without haptic feedback and then with PropellerHand. In each of the scenarios, the participants had to complete a different task, as described in detail in the following subsection. The participants were allowed to familiarize themselves with the virtual environment for as long as they wished, but for at least 30 seconds. After each scenario, the participants answered a questionnaire that included 7-point Likert scale questions (1: very strongly disagree - 7: very strongly agree). The questions asked how far PropellerHand increased the immersion in VR. After all four scenarios, a concluding questionnaire inquired about general feedback for PropellerHand, possible improvements, and which scenario the participants preferred and why.

3.4.2 Scenarios

We created four scenarios that allowed us to evaluate our device with different types of user-object interactions. To provide a more comfortable environment, we situated these scenarios in a virtual room and a grove which we retrieved from the Unity Asset Store [6] (Figure 3.5). The scenarios require PropellerHand to simulate both force and torque separately for the first three scenarios and to switch between them within the last scenario. This differentiates our scenarios from those used in related work, which only tested either force or torque [76, 67, 75].

S1: Moving Objects with Different Weights In order to investigate the simulation of physical weight, we told participants to sort five identical looking pieces of cheese by weight into boxes (Figure 3.5a). We assigned each piece a different weight that PropellerHand then simulated by varying the produced thrust. Once a user grabbed and lifted a piece, PropellerHand oriented its propeller cages such that the produced thrust was directed downwards (airflow upwards), using the HTC controller's pitch value.

S2: Daggers Producing Different Torques In this scenario, participants grabbed identically-looking daggers at their grip and held them horizontally, with the blade pointing to their left (Figure 3.5b). Each blade had a different weight and therefore produced a different torque on the participant's hand. Here, PropellerHand oriented one propeller's thrust downwards and the other one's upwards, creating torque around the arm. As before, the participants sorted the daggers by weight and placed them in empty boxes.

S3: Catching Falling Items To also test torque in another direction, this scenario employs items that fall from the sky and have to be caught by the participant (Figure 3.5c). For this task, we provided a virtual catching device that resembles two pans glued together at their handles. Depending on the items' weight, the torque will be slightly different, allowing the user to perceive collisions with different object weights. We implemented three different falling objects with different weights: a block of cheese, a

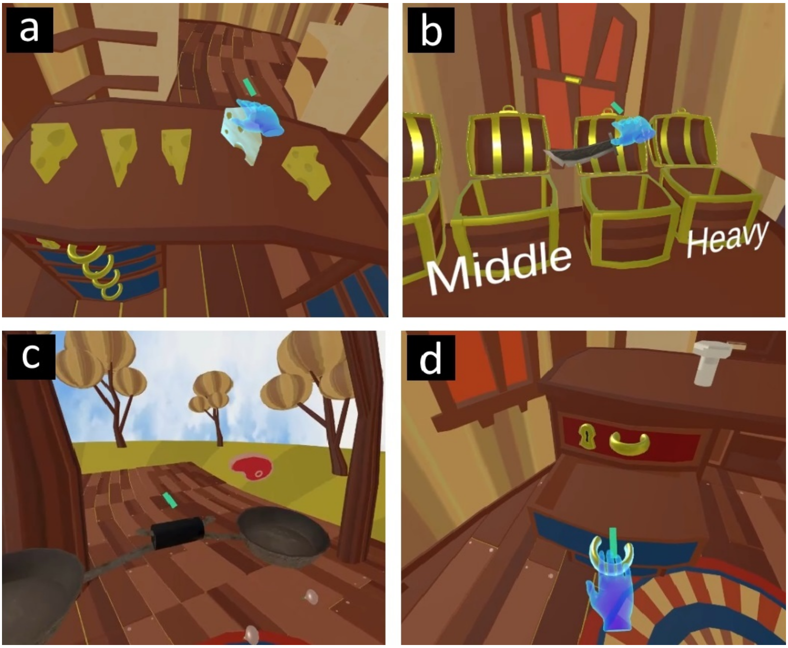


Figure 3.5 — The four scenarios of our user study. (a) and (b) Blocks of cheese and daggers that participants had to sort by weight. (c) A catching device with which items falling from the sky were to be caught. (d) Participants had to unfasten screws and place them in drawers.

piece of meat, and an onion. The catching device itself was not assigned a weight to reduce strain and allow us to measure the effect more clearly.

S4: Multiple Desk Interactions In this scenario, we tasked participants with unfastening three screws and placing them in three drawers (Figure 3.5d). This motion required PropellerHand to quickly switch between producing force and thrust. When the participants grabbed and twisted the screw, the propellers were rotated such that they produced a torque simulating the screw's friction. After removing the screw, PropellerHand simulated its weight by orienting the thrust downwards. Next, the participants had to place each screw in one of the drawers. We simulated the drawers resistance during opening and closing by orienting the thrust against the direction of movement. When completely opened, increased thrust conveyed the drawers being stopped from moving further.

3.4.3 Results

Overall, participants enjoyed using our device. They strongly agreed that PropellerHand increased the immersion in VR (mean (M) of 7-point Likert scale: 5.9).

S1: Moving Objects with Different Weights: We asked the participants whether they felt the weight of the objects and whether they perceived these weights to be different. All of them described the weight perception as very distinct (M: 5.8, SD: 0.8) and easy to distinguish (M: 6, SD: 0.9), see Figure 3.6. One participant reported that s/he noticed louder noise for higher weight values and that the *"lag between picking up things and the fans turning on feels odd"*. All agreed that PropellerHand increased the immersion of the virtual environment (M: 6, SD: 0.9). Everyone sorted the pieces correctly.

S2: Daggers Producing Different Torques: In this scenario, we asked the participants about their perception of torque. All participants stated that they could feel the torque when grabbing the daggers (M: 6.5, SD: 0.5)

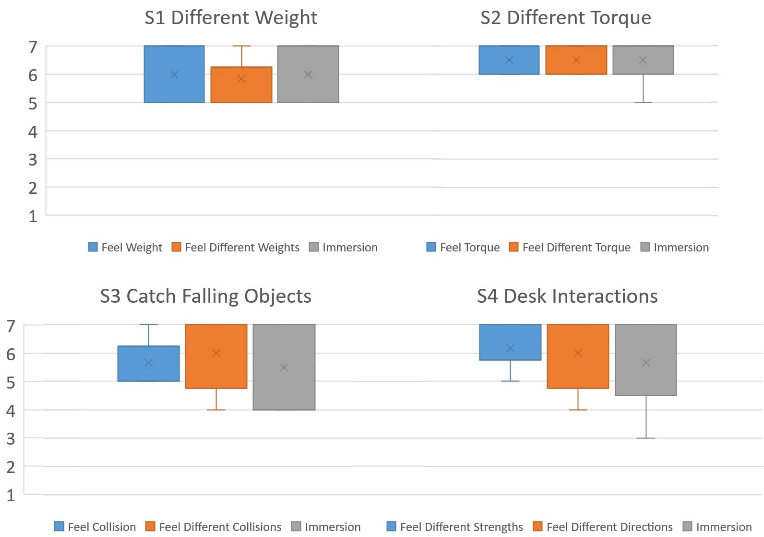


Figure 3.6 — The results of the 7-point Likert Scale of the 6 participants (7 means very strongly agree and 1 very strongly disagree). The boxes indicate the first and third quartile, the lines the minimum and maximum values, and the X-symbols the mean value.

and a torque difference between the different blades (M: 6.5, SD: 0.5), see Figure 3.6. One participant mentioned that some torques did not fit the daggers because they were visually identical, but felt different. However, this was necessary to avoid visual biases from influencing the results. As in the first scenario, all participants reported feeling more immersed when using PropellerHand (M: 6.5, SD: 0.8), with one participant mentioning that the *"torque was captured well"*. Again, all objects were sorted correctly.

S3: Catching Falling Items: After they finished the third scenario, we asked participants whether they were able to feel the impact of falling objects as well as a difference depending on the object's type. Each participant reported to have felt a significant difference between the strength of impacts (M: 6, SD: 1.3), see Figure 3.6. All participants clearly perceived the impact of falling objects (M: 5.7, SD: 0.8), but three mentioned a significant delay between seeing and feeling it. Due to this delay, participants reported less increased immersion than in S1 and S2 (M: 5.5, SD: 1.4). Furthermore, it seems that fast hand movements make it harder to perceive impacts.

S4: Multiple Desk Interactions In this scenario, the participants were asked whether they perceived forces with different strengths and directions depending on the object they interacted with. They strongly agreed that they felt different strengths (M: 6.2, SD: 0.8) and directions (M: 6, SD: 1.3), see Figure 3.6. While interacting with the drawers, one participant said *"oh that is cool"* when he felt the drawer's collision with the stopper. Others described the torques as easier to feel than the forces and stated that there is *"only a slight delay in the haptic feedback when pulling out a drawer to the limit"*. All participants told us they enjoyed this scenario and agreed that PropellerHand made them feel more immersed in the virtual environment (M: 5.7, SD: 1.5).

Concluding Questionnaire and Summary: After participants finished all the scenarios, we asked them to answer a final questionnaire with general questions about PropellerHand. The questions included which use case they prefer, if the noise or wind flow was disturbing, and if the weight of PropellerHand was too heavy. We also asked them to give general feedback about PropellerHand. The participants agreed that the noise was disturbing the immersion (M: 5.7, SD: 0.8), although one said that *"the noise is not that bad since you are distracted"*. When asked whether the airflow negatively impacted the immersion, the average answer was between neutral and disagree (M: 3.5, SD: 1.6).

The answers about PropellerHand's weight were mixed, they neither agreed nor disagreed that our device is too heavy (M: 4.3, SD: 2.2): *"Keeping your arm in the same position for long periods of time is tiring."*, *"The device* *definitely increases immersion. At the same time it is also tiring for your arms, first due to its own weight and second because most forces are generated in the same direction as gravity.*"

The general opinions on PropellerHand were positive: "*Totally awesome to have these haptics, this changes a lot*". Participants described their experience as "*very interesting and immersive*" and said that the "*haptic device emphasises the feeling of actually doing something in reality*". Interestingly, "*torque was more clearly tangible than directional force*". There were also some suggestions and criticisms, for example that "*it would be more realistic if momentum was simulated [as well]*" and that "*picking up things seems more realistic, but the lag feels off*".

Regarding the feedback, participants told us that "*it was extremely helpful to feel the drawer's stopping*" and that they "*like that it gives you more information about the virtual environment*".

When asked for their favorite scenario, participants preferred those including torques: "*I preferred the use case with torques, in that case I found the reaction of forces on the human body (arm) the most appropriate.*" "*The falling object use case was my favorite, because you could feel the impact, even if you did not look at it.*"

One participant suggested to keep the propellers running at all time, such that the device carries itself and the noise is more constant. Further proposals included adding another DOF for rotation, increased forces, and using both hands for the feedback.

3.5 Touching Data with PropellerHand

Regarding the results and benefits of PropellerHand, we see potential in using PropellerHand in other domains, especially in immersive analytics (IA). IA supports users in decision making and data understanding through the use of immersive technologies [46, 52]. However, IA lacks haptic feedback, which counteracts the promise of providing immersive environments.

Current VR/AR headsets primarily rely on visual and auditory output, sometimes enriched with haptic feedback through vibrating controllers. Other types of haptic feedback, such as force feedback, provide more immersive feedback, as they allow to “touch” virtual objects or data.

We conducted a second user study in the field of immersive visualization. We implemented two charts where the user can touch data in order to gain knowledge about it via haptic stimuli. Furthermore, we implemented another chart where the user can interact with and perceive force feedback. We envision potential benefits of PropellerHand in immersive visualization. a second user study illustrating its potential benefits in immersive visualization.

3.5.1 User Study 2

In a second small-scale exploratory user study, we investigated the potential benefits of PropellerHand in immersive visualization scenarios. To that end, we implemented different visualizations where data can be inspected or interacted with using PropellerHand. Touching data via haptic feedback devices is a new and largely unexplored research area. We thus focused on a qualitative and exploratory study design, instead of seeking confirmatory statistical results. Therefore, we follow recommended practices for an early design stage, which caution to not prematurely focus on statistical, comparative evidence to avoid suppressing or even eliminating novel and creative ideas [63]. The same argument has been made for studies in the area of data physicalization [74], which is conceptually related to our endeavor of “touching data”.

3.5.2 Study Design

We decided to follow an exploratory study setup similar to the one used to evaluate Thor's Hammer [67]. To that end, we randomly recruited five people from our university's campus to participate in the study (4m, 1f; 24-34 years). Three assessed their VR experience as beginner, one as experienced, and one as expert.

The study was structured as follows: After the participant signed a consent form, we gave a brief introduction to the safety features and study procedure. Each participant experienced three different immersive visualization scenarios with PropellerHand, as further detailed below. In each scenario, the participants had one minute to explore the data, touch the graph, and experience the haptic feedback. After that, the participants took off the HMD and we asked them questions about the data, such as where the highest slope, what the highest value was. We explained the participants at the beginning of the study that we will ask questions about the data to motivate the participants to inspect the data instead of playing around. After the three scenarios, we asked our main qualitative questions about the haptic experience. Specifically, we asked (i) whether they could imagine PropellerHand to have a benefit in analyzing data graphs and which benefit they would expect. We also wanted to know (ii) whether they felt that PropellerHand supported them in answering questions. Furthermore, we inquired (iii) whether they see potential value in using PropellerHand for analyzing data graphs, (iv) what worked well or not well regarding our scenarios, and (v) how engaging the experience was.

3.5.3 Scenarios

For our user study, we implemented three scenarios with two different chart types. We implemented a line and a bar chart, using Unity, where PropellerHand provides forces to investigate the data. In a third scenario, the user interacts with a bar chart.

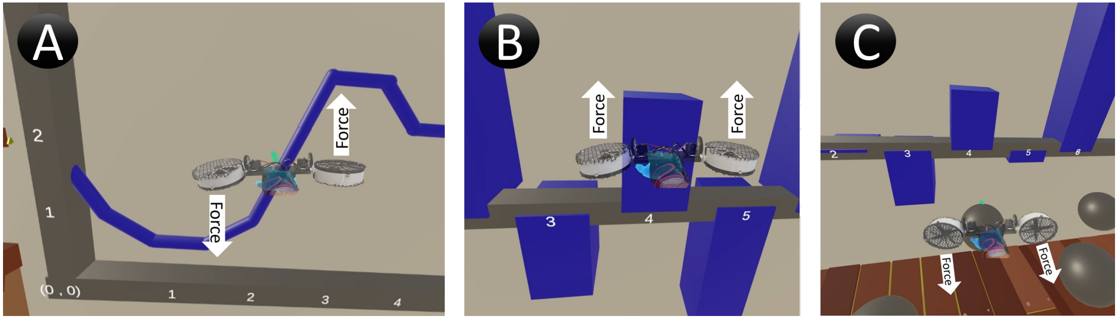


Figure 3.7 — The three implemented charts of the case study. (a) The line chart where PropellerHand generates torque on the user's hand depending on the chart's slope. (b) The bar chart where PropellerHand simulates the height of the bars. (c) The interactive bar chart where the user can move spheres to update the data of the chart.

Line Chart Investigation: In this scenario, we placed a line chart in front of a wall, (Figure 4.7A). The lines consist of a 3D cylinder with a diameter of 5 cm. The whole chart is 2.7 m long with a height of 1 m. When the user holds their virtual hand inside a line, PropellerHand starts to produce forces on the user's physical hand. The force depends on the data the user touches. PropellerHand produces a torque on the roll axis of the user's hand, (Figure 4.7A). Depending on the slope of the touched line, PropellerHand changes the torque direction and strength: the higher the slope, the higher the torque strength. When the slope is positive, the torque direction is applied counterclockwise on the user's hand and vice versa.

Bar Chart Investigation: This scenario contains a bar chart in front of a wall with 6 bars, (Figure 4.7B). The bars' width and depth is 20 cm. When the user touches one bar, PropellerHand produces a force downwards or upwards depending on the corresponding data of the bar: the higher the value of the bar, the stronger the force. For positive values, PropellerHand produces a force upwards and vice versa.

Bar Chart Interaction: In this scenario, we implemented a bar chart that can be interactively updated. The type and size of the bar chart is the same as in the Bar Chart Investigation scenario. We added an interactive slider in front of each bar, (Figure 4.7C). The slider can be moved forward and backward. When the user moves the slider, the data updates and the height of the bars changes accordingly. The slider has an end position in each direction. If the user reaches this position, PropellerHand produces a force in the opposite direction in order to signal that they reached the limit.

3.5.4 Results

In the following, we report our qualitative results collected from our participants for each scenario, as well as general feedback.

Line Chart Investigation: Three participants perceived the scenario with PropellerHand as engaging, because of its novelty and playful experience. However, three participants criticized that PropellerHand distracted them, because they did not get used to it for the first time. Multiple benefits of PropellerHand in the line chart scenario were reported by the participants. Two participants told us that PropellerHand could give them information about an additional dimension, such as the deviation of the function. Another participant explained that PropellerHand is able to represent data more extremely and to present the impact strongly. He said *"you perceive the slope more explicitly via haptic than visually"*. In addition, one person noticed that PropellerHand helped them better orient themselves along the line of the chart. One participant was happy that PropellerHand triggered their explorer instinct and they wanted to compare the data.

However, there were also negative comments about the experience with PropellerHand in the line chart example. Distraction by PropellerHand's noise and airflow were mentioned by two participants. One participant with long hair was scared that PropellerHand's rotors would catch their hair. Another participant was surprised by the force increase jumps, as we used discrete values in our line chart. He said *"sometimes, the jumps in the force increase were a bit surprising, I think continuous data would feel better"*.

Bar Chart Investigation: In the bar chart investigation scenario, four participants described the investigation of the data with PropellerHand as engaging. A benefit of using PropellerHand when comparing data was reported by three participants. One of them could imagine feeling small data differences is easier than only seeing them. The participants mentioned that the force and force directions matched the data well. One person told us that he thinks *"the data peeks are represented more dramatically with haptic feedback and have an emotional impact. Therefore, I have the feeling they are easier to remember."* Compared to the line chart scenario, three participants told us they prefer the bar chart because the bars were easier to touch than the line.

However, two participants criticized that PropellerHand did not help much because they were more focused on the visual feedback. Another participant said *"I was distracted by the noise and the air flow of the device."* One participant mentioned force directed towards the ground when touching negative bars was more dramatic than upward forces.

Bar Chart Interaction: In this scenario, four participants could clearly perceive the maximum value of the slider. Haptic feedback helped two persons in manipulating the data without looking at the slider and stay in the designated space. *"You can manipulate the data without looking at the slider because you feel when you reach the maximum. This is helpful."* Another participant told us they can imagine haptic having a benefit when manipulating complex data, because the eyes can focus on the data instead of the manipulation via the UI.

However, two persons criticized that the latency was too large to simulate a realistic impact. One participant said *"when you reach the end position of the slider, there is a delay of the haptic feedback. Therefore, it does not really feel like an impact"* One participant expected a linear or exponential force increase when getting closer to the sliders' endpoints. Another person perceived the force on the slider's end points as too strong. Additionally, two participants told us that PropellerHand was distracting because interacting with the chart and feeling haptic feedback was too much fun.

General Feedback: The participants told us they see a general benefit in using PropellerHand for immersive visualization because it supports them by adding one additional sense. Therefore, they felt like they might be able to better remember the data and perceive data peaks as *"more dramatic"*. In addition, they told us that PropellerHand could add one additional dimension that cannot be represented visually.

The participants also proposed other graphs where they think PropellerHand could provide benefit. They mentioned 3D plots and multidimensional graphs where haptics can render one dimension. They also suggested graphs with nodes and edges, where the force could be directed to the node with the strongest edge. One person explained us that he can imagine using PropellerHand in flowcharts, where PropellerHand could apply forces in the flow's direction.

We also asked the participants for which users they can imagine PropellerHand providing a benefit in immersive visualizations. Blind or visually impaired users were proposed by two participants, as they could investigate data by touching them. Another participant told us that they think teachers can benefit from PropellerHand by teaching their students mathematics in a more exciting and engaging way. Two persons can imagine that people who want to present data to other people can benefit from PropellerHand. They could use the haptic feedback to present data peaks more dramatically and emotionally in order to keep the data better in mind and to perceive them more clearly.

3.6 Discussion

In the following subsections, we split our discussion based on our two user studies.

3.6.1 User Study 1

There are many use cases where PropellerHand can simulate force and torque convincingly. For example, the participants in our user study enjoyed being able to perceive the stopping of drawers and impact of caught objects, feedback that does not require them to keep their eyes on objects while interacting with them. However, due to the latency and maximum force of PropellerHand, it has limitations in simulating realistic collisions. We see more potential in the simulation of soft resistances than impact forces, such as weight simulation, pressing against soft objects, or simulating current. The noise level increases with the strength of the force, so we recommend reducing the power of the motors, if communication is more important than high forces during the task. We believe PropellerHand can also be used in general mid-air haptics to enable interaction, but we see a limitation when PropellerHand obscures important information due to its size.

In addition, the study results showed that PropellerHand was capable of providing perceivable torque for different abstract use cases. Our studies focused on simple VR scenes and tasks. In the future, we want to use PropellerHand for immersive data analytics and investigate how findings will generalize to this application area.

3.6.2 User Study 2

The benefit and potential of immersive visualization is still relative unexplored. Some research either does not fully exploit the possibility of immersive visualization or overestimates its power. Kraus et al. [85] mention four areas where they see potential of immersive visualization: situated visualizations, spatial data analysis with spatial tasks, collaboration, and presentation. We also see potential in these attributes, especially in the presentation that is mentioned in our immersive visualization user study. The result that PropellerHand makes special data more dramatic is interesting and helpful in the area of presentation. For example, we have a pie chart showing current costs where we want to convince a person that one part of the costs is too high. We can use PropellerHand to render this area of the pie chart with an additional high force to perceive the data more dramatic. We can imagine that haptics can help the person better understand that these costs are too high and should be reduced as soon as possible.

PropellerHand helped the participants follow the line in our line chart. However, in our scenario, we only had a single line visualized. If we had multiple, we would have a problem with distinguishing them. Yu et al. [166] used friction to distinguish lines. We could add an additional modality to distinguish lines such as sound, as Ramloll et al. [126] used to find values of lines.

One idea we had during the immersive visualization user study was to visualize the chart around the user instead on a flat wall. To investigate our charts, we had to walk multiple steps to observe all data. Sometimes, we did not know in which direction to move. If we visualize the chart around the user with a radius of the user's arm length, we could potentially investigate the whole data without needing to walk, at the cost of having to turn.

Comparing the two studies we conducted, we noticed only a few design characteristics that differ. We observed that the delay of the force feedback was more problematic in the first user study than in the second one. We believe that this is caused by the participants, which do not have a clear expectation of the haptic feedback compared to more realistic use cases such as opening a drawer. Additionally, we noticed the force's strength can be lower in the immersive visualization applications than in the scenarios of the first study. In the second user study, participants reported that the force strength fits well also in data peaks. There, we used smaller forces than in our first study, where some participants found the force to be too weak in some situations.

3.7 Limitations

Again, we split our limitations we observed based on our two user studies.

3.7.1 User Study 1

The current version of PropellerHand still has several limitations. Due to its propeller-based design, noise will be an issue even when wearing earplugs or headphones. In practice, users should wear active noise-canceling headphones to further reduce the noise level compared to standard headphones or earplugs. Currently, the device cannot provide thrust in the left-right direction or rotate and move the user's hand in different directions at the same time. This also means that users have to hold their hand in certain ways depending on the intended direction of thrust.

Some participants mentioned that PropellerHand is too heavy, an issue that we plan to address with an improved design. Both force and torque are produced with a certain delay that decreases the immersion in some use cases. This delay between visual and haptic feedback could be reduced by letting the propellers always run at low RPM. Furthermore, software-side methods such as collision prediction could be used. Our user study only had six participants, which means we cannot generalize to a broader population. However, this was not our goal and is left for future work.

3.7.2 User Study 2

We noticed a limitation regarding the high noise level during the second user study again. At the moment, we hope further research will result in more quiet propellers.

The device cannot provide thrust in the left-right direction or rotate and move the user's hand in different directions at the same time. This limitation is present in immersive visualization and game applications. However, in immersive visualization, the interactive charts can be implemented in a constrained way to reduce the DoF limitation.

Both force and torque are produced with a certain delay that decreases the immersion in some use cases, such as in interacting with charts with continuous data. This limitation arose more in the first than second study.

We note that our studies are purely exploratory in nature with small participant numbers. We opted for these qualitative and exploratory study designs, and did not seek confirmatory statistical results. As such, we follow recommended practices for an early design stages, which caution to not prematurely focus on statistical, comparative evidence to avoid suppressing or even eliminating novel and creative ideas [63]. With maturing hardware for haptic feedback, gathering statistical evidence through larger studies will be an interesting line of future work though.

3.8 Conclusion

We propose a new ungrounded force feedback device that is worn on the user's hand. Compared to prior work, we include more powerful motors and propellers. Additionally, PropellerHand can produce thrust and torque and can quickly switch between them. We also contribute our design process, including a user study on form factors and quantitative experiments on propellers.

The user study we conducted to evaluate our final design shows promising results regarding the improved immersion. It also revealed current limitations and provided us with ideas and suggestions for further improvements.

Additionally, we propose a second user study, evaluating PropellerHand in the field of immersive visualization. Results show potential benefits in using PropellerHand in different data visualization tasks.

In the future, we want to further improve our design and evaluate upcoming versions with more extensive user studies.

Chapter 4

STRIVE

Our findings from the PropellerHand in the first case study showed that it did not meet the needs of most industrial use cases. We noticed that we had not adequately focused on the actual industry problems or thoroughly understood and studied them. Thus, we adopted a problem-driven approach and conducted another case study, which resulted in a new haptic feedback device that is better suited for industry and meets the requirements of VR engineers. This chapter is based on the author's paper [10].

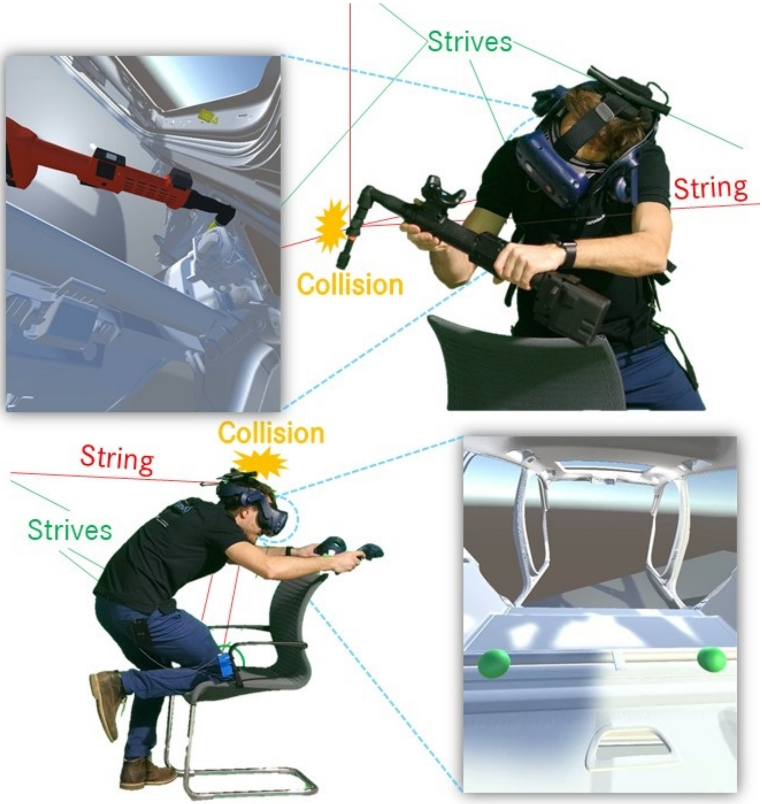


Figure 4.1 — The use of STRIVEs in two automotive use cases. On the left, an assembly task in a trunk in which STRIVEs provide force feedback on the user's head. On the right, a screwdriver task in which the user feels forces acting on the screwdriver. Most of the STRIVEs boxes are not visible in this figure because they were mounted outside the picture.

4.1 Introduction

VR is a rapidly growing research field that has also found practical applications in various industries [21]. Currently, VR technology provides users with useful visual and auditory feedback, but it often lacks force feedback [40]. While several research prototypes offer haptic feedback [154, 67, 81], their practical usage in industry remains limited [21].

It remains unclear how we can move this workstream from research into practice. Depending on the domain application, there are different requirements, such as costs, accuracy, flexibility, or usability. Moving research into practice has been a topic in other areas, such as Visual Analytics, and was successfully conducted over the last one and a half decades, substantially broadening the impact of visualization research [141]. This process is rarely investigated for haptics, especially in industrial settings [21].

In this work, we focus specifically on the automotive industry. There is research on the use of haptics for in-car interaction [61, 66, 43], but the focus is on technique-driven approaches rather than moving research into practice. Another area in the automotive industry is the car development process that partially takes place in VR, where our focus lies. The main goal here is to find issues in the cars' digital version and fix them before the expensive physical prototype phase. VR use cases include assembly validation or accessibility inspections [169]. Some research demonstrates that integrating force feedback devices can help engineers complete their tasks more efficiently [127, 30]. However, the study was not conducted with automotive experts and did not evaluate whether the experts would use such devices. In our experience, the use of force feedback devices in this domain is still rare, as most devices do not meet the requirements of automotive engineers since they are only intended for specific use cases or are expensive and complex to set up.

To fill this gap, we conducted a participatory design study on using haptic feedback devices in the automotive industry. Our design study aimed to investigate the problems of current feedback devices regarding their tasks, to develop a haptic feedback device that meets their requirements, and to evaluate how we can move the device into their daily work. We analyzed requirements with 13 VR experts from an automotive company by interviewing them and observing their daily work for ten months. The requirements analysis shows that the engineers need a force feedback device that can cover multiple use cases and is quick and easy to set up. Based on the results, we built a new string-based haptic feedback device called STRIVE (STRIng-based force feedback for Virtual Environments), which was inspired by the existing haptic feedback devices INCA 6D [122] and Wireality [49]. STRIVE is designed so that it can be used flexibly to cover as many of the engineers' use cases as possible. Depending on the use case, it can be attached to the user's body, to static objects, or both. It can stimulate multiple body parts, allowing engineers to find their trade-offs between forces, comfort, and mobility. We conducted a study with 16 automotive VR experts and let them test STRIVE in five day-to-day automotive VR use cases.

The main results show that STRIVE can be used flexibly in different use cases and supports the experts. It helps users orient themselves more precisely in the virtual environment and perceive the constructed space more realistically. However, some experts mentioned they need more reliability, optimization, and an easy and fast setup, while 14 of 16 experts can imagine using the device in their work.

In summary, our contributions are:

- A requirement analysis based on a 10-month iterative design process with 13 VR experts from the automotive industry
- The design and implementation of STRIVE: A string-based force feedback device that can be used flexibly in various use cases
- An expert study with 16 VR experts from the automotive industry who evaluated STRIVE's usefulness in their work

Core Related Work: Nowadays, haptic technology can be found in various research areas, including arts [19, 145], education [112, 86], entertainment [76], and medicine [136]. However, most haptic research methods use technique-driven approaches to develop new devices, which are rarely used for practical purposes.

This work focuses on the automotive industry. Currently, there are haptic devices used for in-car interaction, such as a shape-changing car seat [61], tactile feedback for virtual automotive steering wheel switches [43], and mid-air ultrasonic feedback for automotive user interfaces [66]. Moreover, haptic feedback devices are also used in the car engineering process, which is our main focus.

Some studies have investigated haptic devices in assembly tasks in VR [151, 140, 116]. Other studies have explored the benefits of haptic feedback in accessibility tasks [127, 30]. However, these studies did not involve automotive industry experts or evaluate haptic technology's suitability in their specific work environment.

In contrast, our case studies involved automotive engineers in the design process to understand their problems and requirements for using haptic devices in their daily work.

4.2 Requirement Analysis

To move haptics research into practice, it is important to involve target users and to understand their tasks and requirements. Therefore, we investigated the VR tasks of 13 experts from the automotive industry by observing them over 10 months and interviewed them each for one hour on average. Additionally, we asked them how haptic feedback could support them in their tasks. Afterwards, we showed and explained to them different feedback devices and asked them to explain the benefits and drawbacks of the devices concerning their tasks and whether they could imagine using them. We chose these devices based on brainstorming sessions with two haptics and one domain researchers. We then selected those devices that they deemed as potentially interesting seed points for the introduction of haptic devices into industrial settings.

4.2.1 Automotive VR Tasks

Results of the interviews and task investigations revealed different VR tasks that could benefit from haptic feedback:

- **Assembly Complexity:** The VR engineers want to check whether they can assemble a component and how fast or simple it is. Sometimes, the component's destination is not visible because of occlusion. Haptic feedback can support them by feeling the collisions with the components and assemble more realistically.
- **Enough Space:** Here, the experts want to know whether the component fits into the target position or whether they have enough space to move, such as the elbow to hold a screwdriver. It is important to feel haptic feedback when colliding with car components.
- **Ergonomics:** It is important to understand the ergonomic behavior of an assembly movement. Is the engineer able to do the movement 100 times a day? If it is an unergonomic movement, they will have physical problems. The engineers want haptic feedback here, because they do not notice any collision or penetration with the car

components. For example, their head could penetrate the car roof, so the realistic pose would be much more uncomfortable.

- **Accessibility:** The experts have to check whether they can access specific components on predefined positions, such as reaching the screw with a screwdriver. Haptic feedback is important to feel whether they reached the specific component, so that they do not have to check it visibly and can feel if their body does not penetrate some components.
- **Visibility Investigation:** The VR engineers want to check whether specific components can be seen on predefined positions, such as: Is the screw visible if the head only has a small movement area? Here, they can benefit from haptic feedback to feel whether their head is penetrating some components.

To sum up the tasks, we can see that haptic feedback has to be stimulated on multiple body parts, such as the hand, arm, head, or elbow. To stop their movement after colliding with a virtual object, the device must provide force feedback, which means it has to provide forces in order to stop the movement instead of giving vibrotactile feedback.

4.2.2 Requirements for Haptic Devices

Next, we have to understand the problems of current existing feedback devices and what we have to modify to make them suitable for the users. Therefore, we showed the experts nine images of different devices: three propeller-based devices (Thor's Hammer [67], Wind-blaster [76], Drone-based [8]), one electrical muscle stimulation (EMS) [92], two string-based devices (Wireality [49], INCA 6D [122]), one arm exoskeleton [56], one Glove [152], and the feedback arm Virtuose 6D [54]. We explained each one's functionality to the experts and asked them where they see problems in using the devices and what they liked about them. Based on these insights, we created the following requirements list, that we split into *usability* **(RU)** and *technical* **(RT)** requirements. The *usability* requirements make sure that the experts can use the device in an enjoyable way.

- **RU-Flexible (flexible usage):** The experts would like to use the device for multiple use cases, so the device should be adaptable to be used in all of them. Most of the presented devices are only suitable for special use cases.
- **RU-Mobile (light and small):** Most VR rooms of the experts are shared with other engineers and sometimes they are switching rooms. So the device should be mobile. They said the INCA 6D is too bulky and blocks a whole room and they liked the mobility of Wireality and Windblaster.
- **RU-Setup (fast setup):** Sometimes the VR sessions are short or involve multiple people, so they have to switch the device quickly. Exoskeleton, EMS, and Wireality were perceived as taking too long to be placed and calibrated, however they liked the quick setup of the drone-based approach.
- **RU-Simple:** They considered INCA 6D, Virtuouse 6D, and exoskeleton too complex to use for non-experts, so that they cannot use it on their own without a lot of know-how. Windblaster was reported as simple.
- **RU-Quiet:** There are usually multiple people during a VR session and they have to talk to each other, so the propeller-based devices would be too loud.
- **RU-Hygiene:** The experts explained that the gloves and the EMS could be too unhygienic.
- **RU-Comfort:** Some of the tasks are about ergonomics, so it is important that free movement is not restricted by the haptic feedback device. They rated the exoskeleton as too uncomfortable, it would influence their ergonomic behavior. Additionally, VR sessions can last up to two hours, so it should be light weight in order to prevent fatigue.

The *technical* requirements ensure that the device has the technical aspects that are needed to provide suitable haptic feedback:

- **RT-Grab (grab objects):** In some use cases it is useful that the experts can realistically grab objects with their own hands. So the feedback device has to provide the functionality or should be able to be combined with a glove. Therefore, they criticized the predefined grab positions of Virtuose 6D, Inca 6D, and Thor's Hammer.

- **RT-DoFF (degrees of force feedback):** When their use cases are complex, they can collide in every direction, so they need multiple degrees of force feedback (DoFF). They said Wireality has too few DoFF.
- **RT-Accuracy:** Depending on the use case, accuracy is important. In assembly tasks there is sometimes an accuracy of a few millimeters required, so they rated the propeller-based devices as too inaccurate.
- **RT-Price:** The device's price should be in relation to the usage. For the experts, the INCA 6D is too expensive.
- **RT-Body (full body feedback):** They reported that gloves are nice to have but they need the feedback on the whole arm, such as stopping their arm after colliding.
- **RT-Impact (low latency & high force):** They have to feel the collision immediately so that they do not penetrate the virtual objects. They criticized that the propeller-based devices have too high latency and too little force.

4.2.3 Requirements Fulfillment of Current Devices

Table 4.1 shows the result of the requirements fulfillment analysis. In the following, we give a brief explanation on how the main approaches work and which devices we focused on for designing our haptic feedback device.

Exoskeletons are mechanical joints that are directly attached to the user's body. With their mechanics, they can prevent the movements of the user. Propeller-based approaches use propeller-induced propulsive forces to provide feedback to the user. In contrast to drones, they have to be grabbed or attached to the user's body. Drones fly to the virtual object's position the user wants to interact or collide with. Thereby, the user perceives the drone's resistance as force feedback. The EMS approach uses electrodes that have to be fixed to the user's skin to trigger the muscles in order to provide force feedback. Feedback arms consist of grounded mechanical arms with breaks. The user interacts with the end of the arm who can be stopped after virtual collision. In contrast to string-based approaches, the medium the user is interacting with is connected to strings. The strings are attached to edges on racks and their retraction can be stopped by brakes or motors. In contrast, elastic string approaches use elastic strings to provide resistive forces.

Regarding the requirements and feedback of the experts, we came to the conclusion to develop a string-based device that is inspired by Wireality and Inca 6D. We see potential regarding the technical aspects in both devices because of the low latency and high forces. In the expert interview, the mobility of Wireality was rated as good, but the inflexible usage and the low DoFF were not acceptable. In contrast, the Inca 6D has a high DoFF but is too bulky and expensive and lacks flexibility in different use cases as well. Our design goal regarding these devices is to optimize the mobility, DoFF, price, and particularly the flexibility in usage.

		Usability Requirements							Technical Requirements					
Main Approach	Device	Flexible	Mobile	Setup	Simple	Quiet	Hygiene	Comfort	Grab	DoFF	Accuracy	Price	Body	Impact
Exoskeleton	Gloves [72, 60, 120]	✗	✓	✗	✗	✓	✗	✓	✓	✗	✓	✓	✗	✓
	Active (VI-Bot) [56]	✓	✓	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓
Propeller-Based	Thor's Hammer [67]	✗	✓	✓	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗
	Aero-Plane [75]	✗	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗
	Wind-Blaster [76]	✗	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✗	✗
Drone-Based	Drones [8, 7, 71, 162]	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓	✗
EMS	EMS [92]	✓	✓	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	✗
Feedback Arm	Phantom [96]	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓
	Virtuose 6D [54]	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗	✓
String-Based	Spidar [68]	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓
	Spidar G [81]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
	Spidar G&G [108]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
	Spidar-W [110]	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓
	INCA 6D [122]	✗	✗	✗	✗	✓	✓	✓	✗	✓	✓	✗	✗	✓
	Wireality [49]	✗	✓	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓
Elastic Strings	ElastiLinks [154]	✗	✓	✓	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
	ElasticVR [143, 144]	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗

Table 4.1 — Current force feedback devices and the experts' requirements fulfillment. However, the experts did not test most of the devices, therefore most of the results are assumptions based on the experts' experience.

4.3 STRIVE

STRIVE is a string-based haptic feedback device that consists of a small wireless box (see Figure 4.2). The box is 3D-printed with Polylactide (PLA) and has a size of 84 mm × 55 mm × 44 mm (length, width, height) and a weight of 110 g (RU-Mobile). The total price for one STRIVE is about 25 USD and it consists of two parts, the solenoid box and the communication box. The solenoid box has a string that can be extracted. The string as well as the entire box can be attached to static objects like tables, rigs, or to moving objects such as controllers, head mounted displays (HMDs), tools, or any part of the body, which is described in Section 4.3.3. Thereby, STRIVE can be used flexibly (RU-Flexible) and can provide forces on the whole body (RT-Body). One STRIVE can provide 1 DoFF in pushing direction, so depending on the use case, the user can use multiple STRIVEs to reach the necessary DoFF (RT-DoFF). For a better usability (RU-Simple), we added a sliding door and soldered connectors to change the battery quickly and simple, and added a switch to turn the device on and off (RU-Simple). We modeled three string outputs in STRIVE (see Figure 4.2) in order to switch the position where the string leaves the case to get a higher flexible usage (RU-Flexible).

4.3.1 Hardware

One challenge was to build STRIVE as small as possible (RU-Mobile), but also enable wireless functionality, have enough battery capacity, provide sufficient forces, and have adequate workspace. A STRIVE is able to stop the string extraction with the same technique that is used in Wireality [49], which demonstrated strong arresting forces (180 N) with low latency (30 ms) and a small, robust, and cheap design (RT-Impact, RU-Mobile, RT-Price). The string is attached on a reel with a mainspring, which is commonly found in retracting badges. The reel is mounted on a ratchet gear that can be blocked by the solenoid which stops the string extraction immediately.

We used one of the smallest batteries that has enough voltage to power up an Arduino Nano and the 5V solenoid (Figure 4.2), but can power also

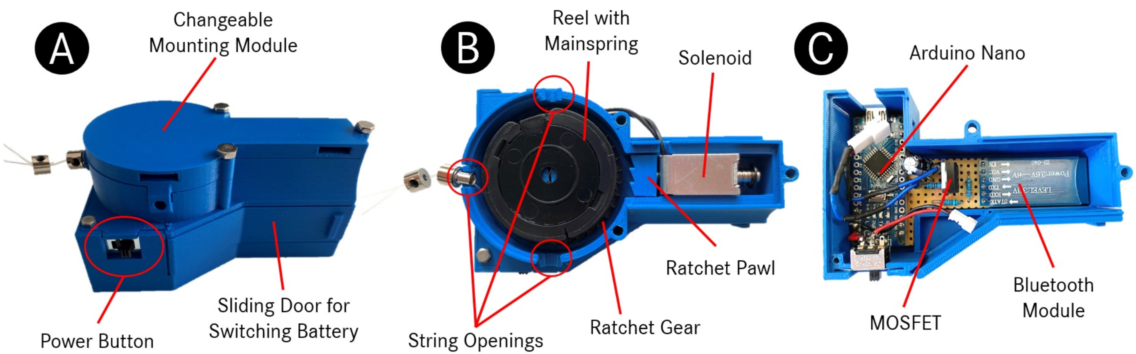


Figure 4.2 — (A) One entire STRIVE. (B) The solenoid box, when the solenoid is activated, pushes the ratchet pawl inside the ratchet gear and blocks the reel, stopping the string extraction. (C) The communication receives commands from the VR application.

up a STRIVE over 1 hour. A HC-05 Bluetooth module provides wireless communication.

4.3.2 String Material and Penetration Distance Evaluation

Using STRIVE, it is important to have a suitable string material that allows for a smooth friction and is thin and robust. We had the hypothesis that strings that can be kinked, like nylon-coated braided steel strings, do have some force peaks when a kink passes the opening. Therefore, we decided to do a small study on three different string materials.

To evaluate the accuracy of STRIVE (RT-Accuracy), we measured the penetration distance by colliding against a virtual wall and measuring the collision speed and the penetration distance.

Procedure

To evaluate the force continuity in different string materials, we measured the traction force with a load cell, that is, the force the users perceive when they are pulling the string. The string of the prototype was attached to the load cell and a STRIVE was attached to a string that is mounted on a continuous rotating servo motor. We moved the prototype with the servo motor and measured the corresponding force. We evaluated three different string materials, a nylon steel wire, a nylon wire, and a fishing wire which have a diameter of about 0.5 mm and can lift 9 kg without ripping, and 45 kg in case of the fishing wire. We used a braided fishing wire made of Dyneema due to its abrasion and tearproof properties. We manually made three kinks in the nylon steel and nylon wire and tried to remove them as good as we could. It is not possible to make kinks in the fishing wire.

The penetration distance depends on the latency of a STRIVE and the stiffness of the string and mounting materials. We mounted one STRIVE on a stable cupboard and attached the string via a velcro strip to the controller. Afterwards, we collided with different velocities and two different string materials against a virtual wall that was placed 1.18 m away from the cupboard.

Results

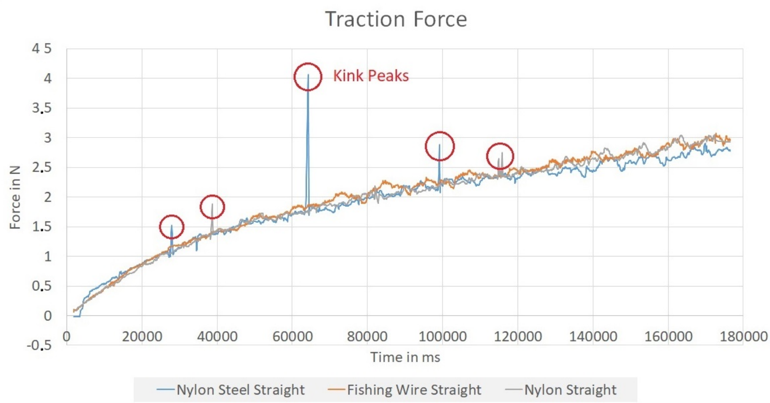


Figure 4.3 — The traction force measurements. The force peaks in the nylon and nylon steel material are highlighted with red circles.

Wireality [49] uses the same traction mechanism and they reported a fixed pull force. However, we cannot confirm this statement because mainsprings do not deliver a uniform torque during unwinding [124]. From Hooke's Law, the torque exerted by the spring decreases linearly to zero as it unwinds.

7 m of our strings fit around the reel, but after 2.00 m the mainspring is fully uncoiled. The minimum lifting force of the strings is 9 kg, however, we assume that this force is still enough to stop most of the body movements without ripping. Figure 4.3 shows the results for the three tested string materials. Measurements show that there is a force peak at the points of the kinks. We measured a maximum peak of force increase in nylon steel with 2.3 N (mean 0.9 N) and in nylon with 1 N (mean 0.4 N). These force increases are definitively perceivable and could lead a user to a false collision detection. After a while of using steel or nylon strings, it is

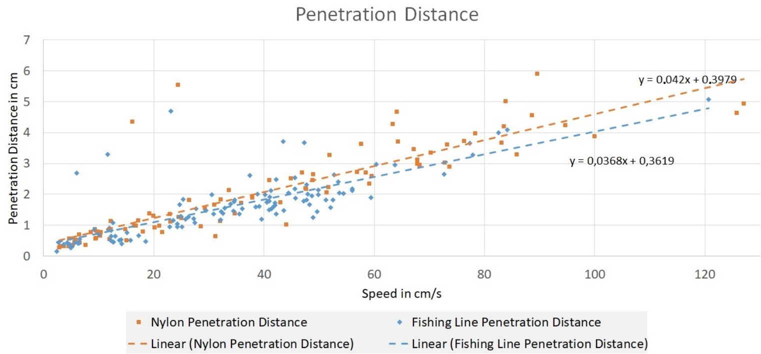


Figure 4.4 — The penetration distance with the nylon string and fishing wire. The distance increases linearly, therefore we added the linear trend lines.

inevitable to create kinks, for example by twisting the string a few times. The retraction force at 1.5 m was 2.8 N, estimating the distance between a STRIVE mounted on the floor and a stretched arm. We measured 2 N at 90 cm, which describes the distance between the stretched arm and shoulder. We estimated these values with a person of 1.80 m height, reflecting our main target audience. If the users position two STRIVEs in the opposite direction, the retraction force on the object to which the STRIVEs are connected decreases, because the second STRIVE exerts the retraction force in the opposite direction. Based on the results and unlike Wireality [49], we recommend fishing wires, because they cannot have kinks.

The penetration distances show a linear increase depending on the speed (see Figure 4.4). From our experience in the automotive VR use cases, we know that their movements are quite slow most of the time (under 20 cm/s), so the average penetration distance will be lower than 1 cm. The fishing wire has a lower penetration increase than the nylon string. This could be due to the higher stiffness of fishing wire compared to nylon string. However, we measured some penetration peaks in the low-speed area. We believe that this is caused by the different forces that are applied to the controller after colliding and stretching the velcro strip. To prevent these peaks, we plan to design more stiff attachments.

4.3.3 Modules and Mounting Locations

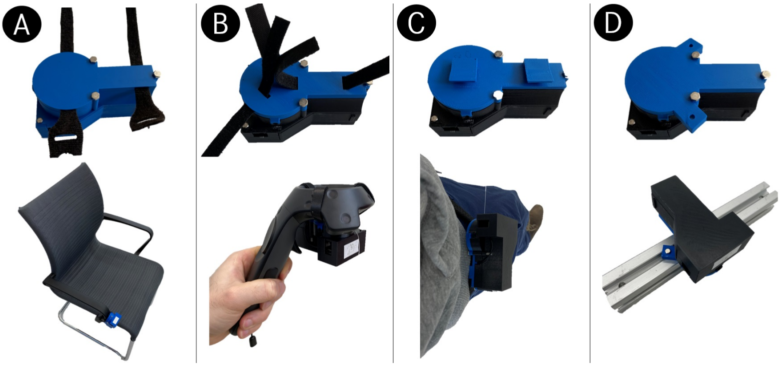


Figure 4.5 — The different mounting modules for STRIVE: (A) The Velcro Strip Module, (B) the Controller Module, (C) the Pants Module, and (D) the Screw Module.

STRIVE should be set up quickly (RU-Setup), comfortable to wear (RU-Comfort), and mountable on as many static objects and body parts as possible (RU-Flexible). The more positions it can be mounted in the better it fits the use cases' needs. We designed four different mounting modules for STRIVE, which can be easily swapped by screwing them to a STRIVE (see Figure 4.5). Our four modules are:

- **Velcro Strip Module:** This module is the most flexible one. It can be attached to cylindrical or rectangular objects (see Figure 4.5 A),

Step	UC1	UC2	UC3	UC4	UC5.1	UC5.2	Mean
S-Mod	55 s	0 s	130 s	140 s	95 s	40 s	77 s
S-Mount	105 s	40 s	170 s	40 s	130 s	35 s	86 s
S-Con	60 s	23 s	60 s	100 s	112 s	85 s	73 s
Total	220 s	63 s	360 s	280 s	337 s	160 s	237 s

Table 4.2 — The measured time that is needed to set up the use cases that are described in Section 4.4

such as chairs, tables, or rigs, but it can also be attached, to the foot, wrist, or the HMD.

- **Controller Module:** In some use cases, two controllers have to be connected, therefore we designed a controller module, in order to attach it in a robust and fast way (see Figure 4.5 B).
- **Pants Module:** One of the most used mounting position is the hip. Thus, we designed this module such that it can be attached to the pants or belt fast and easily (see Figure 4.5 C).
- **Screw Module:** This module has two screw holes to screw it to a flat surface like a wall, desk, or a aluminum profile, which is common in automotive companies (see Figure 4.5 D).

4.3.4 Setup Time

To estimate how long it takes to set up STRIVE, we measured the setup time for our six use cases that are described in Section 4.4. One of the co-authors who knows the positions of the STRIVEs for the specific use cases placed the STRIVEs accordingly. To show that the requirement RU-Simple is met, just this one person prepared the setup, without any external help. We split the setup process into three steps:

- **Module Change Step (S-Mod):** Changing the STRIVE's modules with a cordless screwdriver.
- **Mounting Step (S-Mount):** Mounting the STRIVEs on the objects such as chairs, tables, HMD, or backpack.

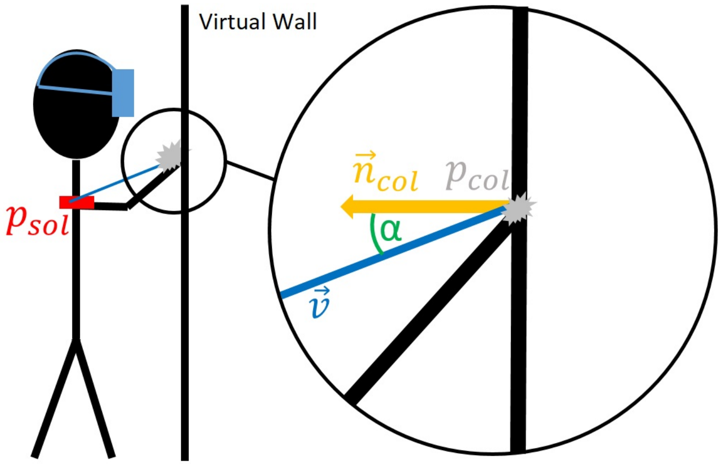


Figure 4.6 — Illustration of parameters that need to be calculated for a solenoid activation.

- **Connecting Step (S-Con):** Connecting the strings to objects such as a 3D printed screwdriver or controller. After this step, the user can start with the use case.

The results can be seen in Table 5.1. Overall, the average setup took 237 s. We can see, however, that the measured time of course differs substantially between the use cases.

4.3.5 Software Implementation

The software and the use cases from Section 4.4 were implemented in Unity. We added default colliders in Unity on objects, to which the STRIVE string is attached, such as a sphere for the head or cubes for the car components. These colliders are tracked depending on the objects, for example, HMD, controller, or Vive tracker and run a method that tells us if they are colliding with an object of the scene. Here, the solenoid position p_{sol} of the STRIVEs are important. The solenoid position is determined in two ways: If the position is static, the user manually defines the coordinates of the device. If the position is dynamically changing, e.g. when mounted on an HMD, the tracking coordinates of that device, plus an offset, are used.

To calculate, whether a solenoid should be activated, we used the following information: Collision point p_{col}, solenoid position p_{sol}, and collision normal $\boldsymbol{n}_{col}$ (see Figure 4.6). We calculate the angle α between $\boldsymbol{n}_{col}$ and the vector $\boldsymbol{v} = p_{sol} - p_{col}$ through the points p_{col} and p_{sol}:

$$\alpha = acos(\frac{\boldsymbol{v} \cdot \boldsymbol{n}_{col}}{|\boldsymbol{v}| \cdot |\boldsymbol{n}_{col}|})$$

The smaller α, the better the collision can be simulated. If α is 90 degrees, the string direction is perpendicular to the collision direction and cannot provide any force feedback in that direction. If α is 180 degrees for example, the string position can simulate a push collision, whereas a pull collision occurred. Therefore we do not activate the solenoids if α is higher than 90 degrees.

4.4 Automotive Use Cases

In Section 4.2, we described the different automotive use cases and why they benefit from haptics. In the following section, we give a brief description of five concrete day-to-day automotive VR use cases, that cover the described use cases above. We implemented these use cases in Unity, integrated STRIVE, and used them in our expert study. Additionally, we describe how many STRIVEs we used, and where they were mounted. The goal with these various use cases is to show STRIVE's flexibility in usage and the application of real automotive use cases.

4.4.1 Reachability (UC1)

In this use case, the users have to inspect the distance of the car dashboard and rate whether the distance to the driver is appropriate (see Figure 4.7 A). They can check whether they can click the radio buttons in a comfortable way. With the haptic feedback, they can better assess the distance in a realistic way, especially if they do not look at the buttons they want to touch. The user is sitting on a chair. One STRIVE is mounted on the right side of the chair and a second one is mounted on the right side of the HMD, so the user can perceive collisions in pushing directions. Both strings are attached to the controller.

4.4.2 Head Collision (UC2)

In this use case, the users have to assemble a pole on the end of a trunk (see Figure 4.7 B). The users do not have much space for their head, so they have to do it ducked, which is uncomfortable. Without the haptic feedback, it is difficult to know whether their head is inside the car roof and to give general statements about the ergonomic behavior. One physical chair is on the position of the trunk's ground such that the user can kneel on it. Two STRIVEs are mounted on the chair and attached to the HMD in order to provide collisions to the top. One STRIVE is mounted on a rack behind the user and attached to the HMD to simulate collisions to the front.

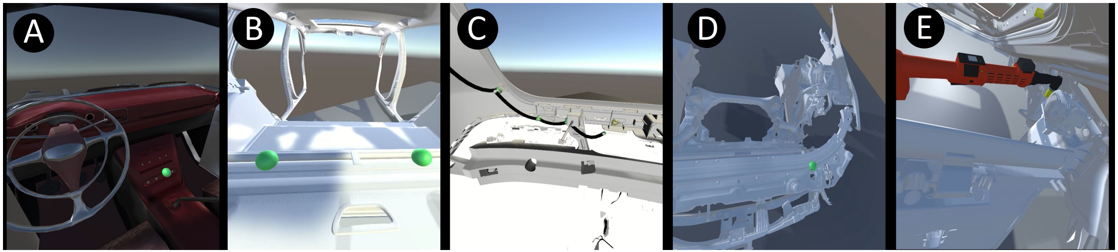


Figure 4.7 — Screenshots of the automotive VR use cases, where the green spheres represent the user's hand positions. (A) The reachability use case, (B) the head collision use case, (C) the cable routing use case, (D) the bi-manual assembly use case, and (E) the screwdriver use case.

4.4.3 Cable Routing (UC3)

In this use case, the engineers have to route cables on a car component (see Figure 4.7 C). One STRIVE is mounted on a controller and attached to the other controller, in a way that if they have a virtual cable in their hand, they cannot stretch it physically more than in the virtual scene. Thus, the cables do behave in a more realistic way. One STRIVE is mounted on a backpack and one on the top of a rig and attached to the controller. Thereby, they feel the collision on the car component in order to not penetrate the components with the cables.

4.4.4 Bi-manual Assembly (UC4)

In this use case, the users have to place a front module onto the front of a car (see Figure 4.7 D). Because of the large size of the component, it has to be grabbed using two hands. Additionally, it cannot completely be seen in the user's field of view, so if a collision occurs on the left and right side of the component, the user can just visually check one side. Therefore, it is important to feel on which side of the component you are colliding. Here, we mounted one STRIVE on the right side of the pants and one on the top of a rig and attached them to the right controller. We used the same constellation with the left side, so the users can perceive collisions to the front and the bottom on each hand.

4.4.5 Screwdriver (UC5.1 & UC5.2)

In this use case, the users have to check whether they can reach a screw that they cannot see (see Figure 4.7 E). Here they use a 3D printed automotive screwdriver that is tracked via an HTC Vive Tracker. We split this use case into two parts. First, the collision free moving space of the screwdriver has to be explored. Second, the ergonomic movement of the users has to be investigated, because their working space is very limited. We placed a physical chair at the position of the virtual rear bench seat such that the users can sit and lean against it. In the first part, we mounted one STRIVE on the backpack, one on the top of a rig and two on shelves and attached it to the tip of the screwdriver to provide feedback to the front, right, bottom, and back. In the second part, we mounted two STRIVEs on the chair, one on the HMD and one on the top of a rig, and attached it to the user's elbow, which was tracked with an HTC Vive Tacker.

4.5 Expert Study

We conducted an expert study to check whether the experts would integrate STRIVE in their VR tasks and where they still see problems using it.

4.5.1 Participants

We had 16 (14 male, 2 female) VR specialists from an automotive company who tested STRIVE in the 5 use cases we described above. On average they are between 38 and 50 years old and work in VR once a week. 7 participants have 1 to 4 years and 5 participants have more than 10 years of VR working experience. The experts were from different teams. Combined, they cover all VR tasks that were described in Section 4.2. Thereby, we made sure to get feedback from different engineering areas and to verify the flexible usage of STRIVE (RU-Flexible). We asked the experts whether they had experience with haptic feedback devices before. Six experts had experience with the force feedback arm Virtuose 6D [54], diverse haptic gloves, or used tables to simulate collisions with car components.

4.5.2 Procedure

The participants conducted the study under a VR rig and used the HTC Vive and its controllers. Each participants performed the tasks of the five use cases described above, after an explanation of the task. Each use case was done twice, first without haptic feedback and then with STRIVE. They could experience and test each use case as long as they wished to freely explore the environment as well as the haptic feedback.

After each use case, we interviewed the participant. To measure the **haptic experience**, we orientated our questions on *Defining Haptic Experience* [78], which guides design and research of haptic systems. Therefore, we only asked the questions after the second trial with the haptic feedback. We asked about utility, consistency, saliency (*Is it appropriately noticeable?*), harmony (*Does it fit with other senses?*), realism, immersion, and restriction

(*Were you restricted in your free movement?*). Additionally, we asked them to rate each answer on a 7-point Likert scale.

At the end of the study, we asked them **general questions** about STRIVE regarding their own automotive use cases. We asked them about whether they would use STRIVE in their work, about problems, suggestions for improvements, what they like, how satisfied they are with the string-based technology, and whether they can think of a more helpful device regarding their use cases. On average, the study lasted 90 minutes and the interview recordings about 40 minutes for each participant.

4.5.3 Results

In total, we recorded over 11 hours of audio during the study, which we transcribed and coded. Figure 4.8 shows the results of the 7-point Likert scales. We checked the requirements based on the qualitative responses to our questions, such as RT-Accuracy with questions on consistency and utility. We opted for this choice as it allowed for a more holistic understanding.

Haptic Experience Questions

The mean utility rating over all use cases was 5.1 (SD: 1.6, 7: very useful, 1: not useful). Head collision feedback was clearly rated the most useful and the cable routing the least. 13 of 16 experts reported that with the haptic feedback they were able to perceive the installation space better and whether they had enough space to do the required movements. One expert mentioned: "*It gives me the opportunity to see how tight it is in my physical and ergonomic space*". 10 experts stated that they have an improved orientation in the virtual environment and a better feeling for their ergonomic behavior. 8 experts reported a mental relief because they no longer have to visually check collisions of components and concentrate on avoiding errors. With STRIVE, they can better focus on the main task. One expert said: "*With the force feedback, I have the feeling that I am almost hitting the surface and that means I don't have to worry about my eyes first, that takes the strain off me*". 6 experts told us that the haptic feedback

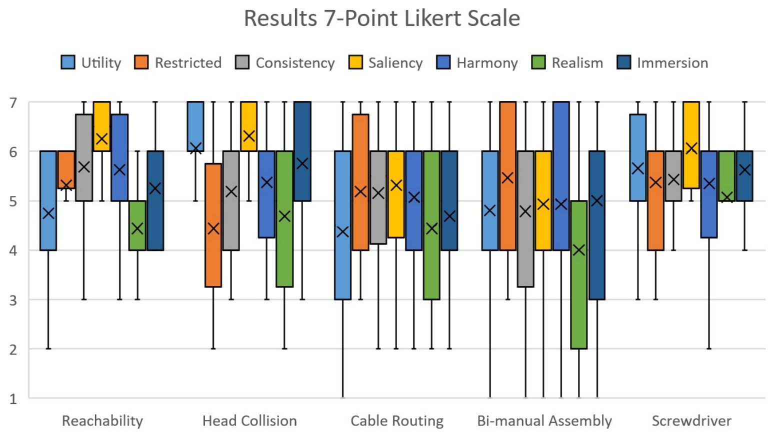


Figure 4.8 — The results of the 7-point Likert scale of the 16 automotive experts (7: strongly agree - 1: strongly disagree). The boxes indicate the first and third quartile, the lines the minimum and maximum values, and the X-symbols the mean value.

gave them more trust and confidence in their task results. For instance, when the result of the VR session says that it is possible to assemble the car component in this installation space, but in the real physical car it does not work because their elbow does not have enough space to complete the movements, which are necessary to use the screwdriver, it will cause expensive consequences. One expert explained: "*Without this haptic feeling, you simply have less feedback and that also feels spurious, I'll just say now, you don't know whether that is actually possible now, so that makes the statement more difficult in any case without haptic feedback*".

We were surprised about the restriction results in the free movement. The experts felt less restricted than we expected. In total, they rated the mean restriction at 5.1 (SD: 1.4, 7: not restricted, 1: very restricted). The highest restriction was perceived in the head collision use case. There, they crossed the strings with the controller and 3 of 16 experts had to reach around with their hand. 13 experts mentioned that they could perceive a collision between the strings and their body. However, they did not feel restricted after a string collision and 3 experts told us, they just have to get used to it. Furthermore, they noticed some other negative secondary effects of STRIVE. 10 experts told us that they perceived the noise of STRIVE as vexing and annoying, especially when it was placed near the ears. Every time the solenoid is activated or deactivated, it causes a 'clack' noise. Another side effect was the pulling force, which was noticed by 8 experts, but most of them rated it as low and not restricting. 4 experts reported that they felt a yank, when a STRIVE was attached to the HMD.

The average consistency value was rated at 5.3 (SD: 1.4, 7: very consistent, 1: not consistent). However, there were some optimization requests and criticism regarding the consistency. 11 experts reported that they missed some DoFF, such as in the accessibility use case where they missed the collision on the side points of the steering wheel. 10 experts noticed a component penetration, especially in the cable routing and screwdriver use cases and therefore criticized the accuracy and reliability. 5 experts moved their body during the bi-manual assembly task and therefore moved the position of the STRIVEs attached to the pants. This implied that they did not feel a collision, they just heard a 'clack' and could penetrate the objects. Therefore, there is a large standard deviation in the bi-manual assembly task, because the experts who moved did not receive a noticeable force feedback. These problems also negatively influenced the realism.

In most use cases, the experts sensed the haptic feedback as appropriately noticeable, they rated it at 5.8 (SD: 1.3, 7: very appropriately noticeable, 1: not appropriately noticeable). However, 4 experts felt the feedback too hard, because they had to do a subtle task, and 5 experts said the feedback was too soft, when they are interacting with a large car component.

Regarding the harmony of the haptic feedback, they mostly thought it suited their visual and auditory sense, rating it an average of 5.3 (SD: 1.5, 7: fits very good, 1: does not fit). In some cases they were irritated by the device's noise or collisions with the strings.

Compared to the other questions, the realism was rated worst, in average 4.5 (SD: 1.5, 7: realism has improved, 1: realism has degraded). 8 experts criticized that the visual presentation did not match with the feedback they felt, such as they felt a collision on the hand but the virtual representation was a sphere or they felt that the head collider was a different size than their real head. Additionally, they reported that the head collision did not feel realistic because they did not feel any pain. However, 7 experts mentioned that they prefer the unrealistic head collision. 4 experts missed the feeling of weight, which negatively influenced their sense for realism.

The experts rated the immersion at 5.3 (SD: 1.4, 7: immersion has improved, 1: immersion has degraded). The object penetration and the irritating noises by STRIVE reduced their immersion, however, most of them felt more immersed when using STRIVE.

General Questions

The answers to the final questions showed us, that 14 out of 16 experts would use STRIVE in their daily work, especially in the head collision and screwdriver use cases. The other 2 experts are from the same team and mentioned that they only have visual tasks and do not interact in the virtual environment and therefore need no force feedback. However, some of the 14 experts mentioned some optimizations and requirements in order to integrate and use STRIVE in their daily work. The most important requirement that they mentioned was that the setup has to be fast and simple. They will not use it otherwise.

Regarding the setup, 4 experts could imagine that the setup could possibly be too complex for them and 6 participants mentioned that the setup time could be too long and they would have to plan the positions of the STRIVEs first. One expert said: "*Such a system has to be up and running fairly quickly, it doesn't help if the thing is great, nobody books you if the thing really needs a week for setup*". However, this was an assumption as they did not prepare the setup but it is definitively a very important aspect. 9 experts could believe that in some cases there are too many strings that could collide with the body and restrict the free movement. 5 experts reported that STRIVE has to be optimized regarding the accuracy and reliability.

The experts had some good suggestions for improvements. 5 experts gave some ideas regarding the mounting of the STRIVEs, such as a movable rotating column or a jacket to which the strings could be attached. Some experts mentioned extension ideas, such as simulating weight, sliding along surfaces or simulating material properties like texture or softness, or combining the feedback with vibration or visual information. One expert came up with the idea of recording the movements during a task without feedback and using this data to calculate the best positions for the STRIVEs.

We asked the experts what they liked regarding STRIVE. 7 experts reported that they liked the simplicity of STRIVE. One expert said: "*Considering its simplicity, it fulfills a lot of purposes really well.*". 4 experts praised STRIVE's price, mobility and the fast setup. The most important thing they liked is the additional benefit which was mentioned by 5 experts.

To evaluate the pros and cons of using strings to provide forces, we asked the experts for their opinion on the matter. 14 experts liked the technology and 2 experts were neutral and mentioned the technology does not matter, only the results count. However, some experts see a drawback regarding the complexity and collisions when using many strings.

In the last question, we gave the experts the chance to compare STRIVE with existing feedback devices they know. Here some said that the advantage of STRIVE is its high flexibility in usage. One expert told us: "*There is only the multi-axis force feedback arm for limited installation spaces ... but it has very serious disadvantages that it can only work in certain cases ... and that's why it has never been operated any further*". In addition, some described the price-performance ratio as very good.

4.6 Discussion and Limitations

In the following, we discuss in how far STRIVE met the initial requirements from Section 4.2, as well as potential alternative approaches, further application areas, and its limitations.

4.6.1 Usability Requirements

Based on the study results, the experts confirmed that we met most of the requirements. They reported that they liked the simplicity (RU-Simple) and that it could offer useful feedback in very various use cases (RU-Flexible). In addition, the design of STRIVE allows a high mobility (RU-Mobile) and they were not restricted in their free movements (RU-Comfort).

The most important requirement the experts mentioned was the fast and simple setup (RU-Setup). No expert would use STRIVE if setup takes too long, regardless of the added value it has. We could not verify that we met the requirement, as we did the setup ourselves. However, some experts mentioned that they believe the setup could be quick and easy, especially because they understand the simple functionality of STRIVE, which is a plus. Nevertheless, we received useful information for a quick setup, such as new mounting options or the calculation of STRIVEs' positions.

4.6.2 Technical Requirements

Regarding the technical requirements, they reported that it is very cheap (RT-Price), that they could perceive forces on different body parts (RT-Body) and that it was appropriately noticed (RT-Impact).

However, some optimizations have to be done to meet the remaining requirements. One problem the experts mentioned was the STRIVE's noise (RT-Quiet). The noise does not disturb so much that the experts cannot talk to other colleagues, but it was described as annoying and irritating. As a result, we want to use noiseless solenoids and a more noise-insulated case in the future.

Regarding the accuracy (RT-Accuracy), we need to make some optimizations here, as the experts have criticized this in some use cases. During the study, we observed three problems that influenced the accuracy. The first problem is the latency of STRIVE which is low but depending on the colliding speed, so the user is able to penetrate the objects a few centimeters into an object, which is too much for some of their use cases. Here, we can use the measured linear ratio between speed and penetration distance (see Section 4.3.2) to predict the collision and reduce the penetration distance. The second problem is the string and mounting flexibility. Here we have to make sure to use a stiff string material, such as fishing wire and stiff mounting materials. We used velcro strips, which were too flexible and caused object penetrations. The third problem was that some virtual objects were too thin, like the car component in the cable routing use case. In this case, the user can break through the whole object. So we have to thicken these objects before usage.

The more STRIVEs we use, the more DoFF we get, but the more string-body collisions can occur and restrict their free movement (RT-DoFF). So, the experts need to carefully consider how many STRIVEs to use. Some experts mentioned, they also play around in the virtual environment during the task, so they need more DoFF than necessary. For instance, in the accessibility use case, they actually need one DoFF to complete the task, but some experts wanted additional DoFF to feel the collision on the side of the steering wheel. So, before the experts prepare the setup, they have to reflect whether they want to focus on the task or also want a free exploration. Additionally, we saw some problems when the experts moved the whole body during collisions when a STRIVE was attached to the body. Here, the experts have to think about attaching it to a static object or they have to concentrate on not moving their whole body during the collisions. Overall, there are a few things for the experts to think about before preparing the setup. Thus, we would like to give them a guideline in the next step.

We also noticed that we have to take care of the representations, such as the hand and the head collider. The experts wanted to have the feedback in their hands instead of on a controller. In future, we would like to combine

STRIVE with existing VR gloves (RT-Grab).

4.6.3 Other Haptic Approaches

There are other techniques to perceive collisions than haptic feedback, such as environment color codes or gradual audio as the body gets closer to the virtual objects. So, the question is, is haptic feedback really the best choice?

We believe that haptics, alone or combined with visualization as mentioned by some experts, is at least a very good choice. The problem with using color alone is that collisions might be occluded from the user. Users also reported a mental relief that they do not have to use their eyes for collision detection. Further, we hypothesized that audio feedback could irritate them, as they often speak to other experts while doing the tasks. Another approach would be to use some haptic proxies in combination with haptic retargeting [33]. We think this is a good idea in some cases, such as dashboard interaction. But we see limitations in the RT-DoFF and there would be a difference between the virtual and real movement, which would be insufficient in some use cases. To improve the accuracy, there are techniques such as adapted rendering for penetration compensation [20]. Here, we also see potential in some use cases, where the exact ergonomic behavior is not that important. Otherwise, the difference between real and virtual position could be insufficient.

4.6.4 Other Applications

We hypothesize that STRIVE is also of interest to other application areas, specifically due to its price and flexibility. For example, we developed a VR drum simulator that utilizes STRIVE to provide haptic feedback (see Figure 4.9). To achieve this, we attached two STRIVE devices to physical drumsticks. We employed the Sense Glove Nova Gloves for hand tracking, which allowed us to synchronize the physical and virtual drumsticks. When the virtual drumstick collides with the drum, STRIVE provides haptic feedback that simulates the sensation of hitting a physical object.

Figure 4.9 — STRIVE for haptic feedback in drums simulation. Two STRIVEs are attached on physical drum sticks and simulate the collision with the drum.

Using STRIVE made the VR drumming experience more immersive, and we experienced more fun.

We believe that STRIVE has potential applications in other areas as well, such as in entertainment. For example, gamers could mount STRIVE devices on furniture like tables, chairs, or cupboards to enhance their gaming experience. Another potential use case could be in AR, where STRIVE could be attached to an AR headset and connected to the user's hand, providing haptic feedback when touching UI buttons.

Finally, we also had the idea of attaching STRIVE devices to the user's hip to prevent them from colliding with physical obstacles when they move outside of the tracking area. This could be useful in training simulations or real-world scenarios where users need to navigate complex environments. For the field of haptic communication, we believe STRIVE could have problems because it is a passive haptic feedback device.

4.6.5 Limitations

One limitation that arose is the ability to slide along surfaces. With the current technique, a smooth sliding is not possible. In a next step, we will try to extend STRIVE to allow smooth sliding. Another limitation is the missing torque. Torque is not as important as directional forces, but in some use cases it helps the experts. Another limitation is that we did not use vibration as a baseline condition in our study. To provide vibration in every use case, we would have had to insert vibration systems into the HMD, the 3D printed screwdriver and the Vive tracker for the elbow. This was deemed as technically too complex and was left for future work.

4.7 Conclusion

In this chapter, we addressed the challenge of moving haptics research into practice by conducting a detailed requirement analysis in the automotive industry, designing and implementing STRIVE, a suitable force feedback device, and evaluating the device in an expert study. The main results show that STRIVE could support the experts and most of them can imagine using it in their daily work. However, the engineers also mentioned some optimization problems and limitations which we discussed.

CHAPTER 5

STROE

After reviewing the results of STRIVE's user study, we found that VR engineers missed weight simulation. Unfortunately, STRIVE's technical design precludes weight simulation. To solve this issue, we conducted another case study where we built a new haptic feedback device. Our research showed that no existing device met the industry's requirements, so we chose a problem-driven approach. This approach proved more effective than a technique-driven one, as it gave us a detailed understanding of the problem and enabled us to develop a solution that specifically addressed it. This chapter is based on the author's paper [9], © 2022 IEEE. Reprinted, with permission, from Alexander Achberger, STROE: An ungrounded string-based weight simulation device, 04/2022.

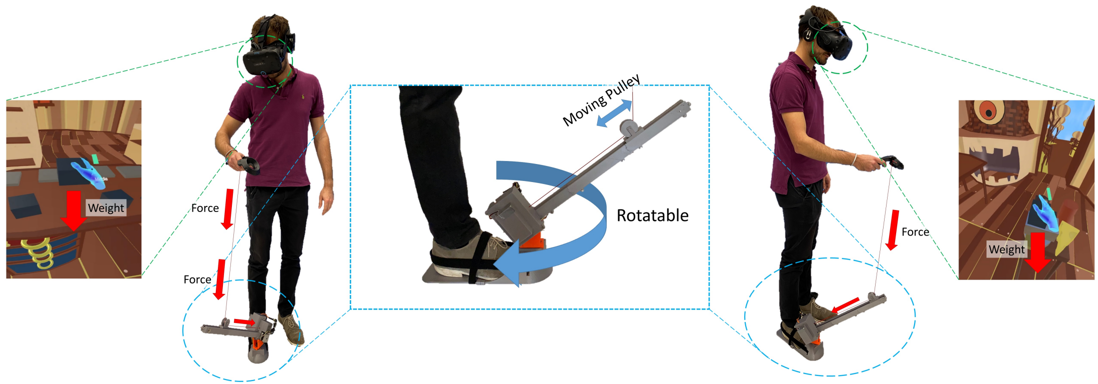


Figure 5.1 — The use of STROE in two VR scenarios. STROE is strapped to a shoe and generates downward forces on the user's controller to simulate the weight of objects. A motor pulls a string attached to the user's controller. This string is guided by a movable pulley that is mounted on a rotatable rod, allowing it to generate the force downwards independent of the user's controller position.

5.1 Introduction

In addition to simulating collisions in VR, another crucial haptic sensation often lacking is weight simulation. Without haptic feedback, virtual objects in VR lack physical weight when held, allowing users to effortlessly lift objects that would be heavier in the real world without experiencing muscle fatigue. This absence of a weight sensation can reduce the overall realism and immersion of the VR experience.

Furthermore, weight simulation can prove beneficial in various VR applications, particularly in industries like the automotive industry, which is our area of expertise. Engineers can benefit from weight simulation in VR tasks, such as evaluating how ergonomically a specific car component can be assembled. Weight simulation of the car component can yield results similar to those of the same physical task. Research has shown that current weight simulation devices with haptic feedback can enhance the sense of realism and increase immersion in interacting with virtual objects [75, 67].

Nevertheless, existing weight simulation prototypes do come with certain drawbacks. Grounded devices, permanently connected to the physical environment like the INCA 6D [122] or Virtuose 6D [54], are limited in their workspace coverage and are often expensive and challenging to implement. In contrast, ungrounded devices, such as drones [8], or those attached to the user's body for free movement during weight simulation, face issues like disturbing sound [8, 67, 75], high latency [32], and weak forces [67]. To address these challenges, we propose STROE, a new ungrounded string-based weight simulation device. STROE is worn as an add-on to a shoe and consists of a motor with a pulley. One side of the string is connected to the pulley, and the other side to the user's controller, hand, or tool. When the motor generates torque, the string pulls, and the user experiences a force that simulates weight. STROE's design directs the force towards the floor, regardless of the user's movement, to create a more realistic weight simulation. STROE can simulate weights up to 720 g and has a latency of only 250 ms, with minimal sound disturbance.

In a user study, we evaluated the precision and realism of STROE in simulating weight and users' ability to walk while weight is simulated. The results show that all participants could perceive different weights with STROE. Using STROE, participants had more enjoyable and immersive VR experiences. Despite being an early prototype, STROE shows promise regarding mobility. However, there are still some limitations regarding ergonomics that we will discuss further in the paper.

In sum, our contributions are:

- The design and implementation of STROE: A new ungrounded force feedback device for weight simulation
- Design decisions and a technical evaluation to measure STROE's specifications
- A user study with 12 participants who evaluated STROE in four different VR scenarios

Core Related Work Weight simulation devices are relatively rare in haptic research, but a few prototypes exist that can simulate weight using different technical approaches. However, these devices come with several limitations.

For instance, some devices use liquid pumped into a container attached to a VR controller to increase its weight to match the corresponding virtual weight [32, 111]. Unfortunately, these devices suffer from high latency compared to STROE, and users must be tethered to a compressor, restricting their movements.

Lopes et al. [92] utilize electric muscle stimulation to simulate forces in VR. Their system creates a counterforce on the muscles that must be used to simulate the force, requiring users to activate the opposing muscles. However, this system takes a long time to set up, and users are connected with multiple cables, limiting their movement. Apart from providing forces to simulate weight, some devices focus on simulating the center of mass of a virtual object, such as Transcalibur [137] and Shifty [167]. These devices have a fixed total weight but can change their center of mass by changing their shape. However, they are unsuitable for VR applications where users hold objects with different weights.

Finally, there is an approach that only gives the illusion of weight simulation instead of generating real forces. For example, Grabity [34] and Gravity Grabber [104] create a virtual force tangential to each finger pad through asymmetric skin deformation. Samad et al. [129] create a force sensation by manipulating the control-display ratio. However, weight illusion does not provide any real forces and, therefore, does not generate fatigue, which may be insufficient in some VR scenarios, such as automotive buildability studies, compared to STROE.

5.2 Design Requirements

As a preliminary step, we conducted a requirements analysis by interviewing 12 VR experts who work in an automotive company. We asked them to rate the importance of weight simulation and weight shift in their VR tasks using a 7-point Likert scale.

We also questioned the experts on the maximum weight they need to simulate and the minimum weight affecting their VR tasks. They also indicated the device's maximum acceptable latency and simulatable weight deviation.

Next, we demonstrated various weight simulation devices in the literature to the experts. The devices included:

- Gravity Grabber [104] (weight illusion-based)
- Transcalibur [137] and Shifty [167] (moving mass-based)
- GravityCup [32] (liquid-based)
- Lopes et al.'s electro muscle stimulation system [92]
- Virtuose 6D [54] (mechanical)
- PropellerHand [12] and Thor's Hammer [67] (propeller-based)
- A sketch of our string-based device prototype, STROE

The experts rated each device type based on its suitability for their VR tasks and shared their pros and cons for each device.

Results The experts rated the importance of weight simulation in their VR tasks at 4.75 (SD: 1.8) on a scale of 1 to 7, with 7 being very important and 1 being not important. The weight shifting feature was rated at 4.3 (SD: 1.5). On average, the maximum weight the device needs to simulate was indicated as 10 kg (SD: 4.2). Some experts noted that in some tasks, they use a handling device that helps them with heavy weights, so they do not require further weight simulation. The minimum weight simulation that impacts the VR tasks was rated at 610 g (SD: 230 g), and the average maximum weight deviation the device has to meet was 11% (SD: 4.7%). The experts rated the maximum latency at 2.1 s (SD: 1.9 s).

Regarding the different types of weight simulation devices, the weight illusion-based device was rated at 2.6 (SD: 1.5) on a scale of 1 to 7, with 7 being very appropriate for VR tasks and 1 being inappropriate. The experts criticized this device for not inducing muscle fatigue and only providing tactile feedback but appreciated its small size.

The weight-shifting devices were rated at 4 (SD: 1.2) on average. The experts appreciated the ability to simulate a weight shift but criticized the limited weight simulation options and the need to physically hold the device.

The liquid-based device was rated at 3.1 (SD: 1.2) and was criticized for its high complexity, latency, and the presence of tubes. However, the ability to simulate different weights was appreciated.

The electro muscle stimulation device was rated at 3.6 (SD: 1.6). The experts liked not having to hold anything but expressed concerns about potential health risks if something goes wrong. They also noted a low acceptance rate for this type of device and negatively mentioned the cable connections.

The mechanical device was rated at 5.1 (SD: 1.7) and was described as quickly usable by the experts but criticized for its small working area and self-weight.

The propeller-based devices were rated at 4.5 (SD: 1.2). The experts appreciated the flexible usage but criticized the audible noise and latency.

Our sketch and explanation of the string-based device were rated at 5.1 (SD: 1.2). The experts positively mentioned its quick usage but criticized the possibility of the string hindering the user and restricting movement.

We identified several key requirements for designing a weight simulation device based on our findings. These requirements were derived from our research results and two years of automotive industry experience. Our requirements are as follows:

- **R-Mobility**: The device should allow users to move freely and have a large workspace for VR scenarios.
- **R-Quiet**: To enhance realism and immersion, the device should be quiet and not create disruptive noise, especially when people need to communicate.
- **R-Simple**: The device should be user-friendly and easy to set up and use.
- **R-Price**: The price should be appropriate and fit to the benefit the device provides.
- **R-Hygiene**: The device should be designed to enable easy cleaning, with a minimal area in direct contact with the user's skin.

After reviewing existing weight simulation devices and consulting with VR experts, we found none meeting these requirements. As a result, we developed our own new weight simulation device called STROE.

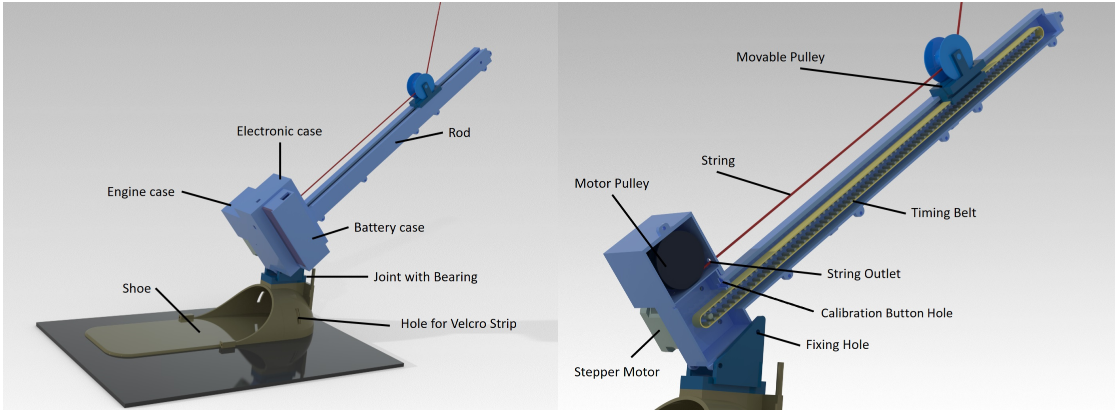


Figure 5.2 — Left: An overview of STROE and its hardware components. Right: A close up view inside of STROE's rod.

5.3 STROE

STROE is a string-based weight simulation device, that can be attached to the user's shoe to allow free moving while perceiving weight simulation, see Figure 5.2. The length of STROE's rod is 50 cm and its height is 42 cm. The total weight of STROE is 1090 g. The total cost of all hardware components is about 150 USD. The users can place their shoe into the device and use Velcro strips to tighten it, see Figure 5.1. STROE is designed in a way for different shoe sizes to fit into it. Most of the components are 3D printed. The device consists of a rotatable rod where two motors are mounted on. One motor has a pulley where a string is wrapped around. The end of this string goes through a second movable pulley and is connected to the user's controller, hand, or tool, depending on what they need. When STROE applies a weight simulation to the user, it rotates the motor to generate a retraction force to the string. In order to simulate a realistic weight simulation, the force must be directed downward. Therefore, the second motor can position the second movable pulley.

5.3.1 Hardware

We used the iPower GM3506 Brushless Gimbal Motor [3] for the force simulation where the magnetic sensor AS5048A is attached to, in order to track the position of the motor's coils. To control the motor, we used as motor driver board the Simple FOC Shield V2.0.3 [4] with an Arduino Due as Microcontroller. To control it wirelessly via the computer VR program, we used a Bluetooth communication with the HC-05 module. We used a 3 cell Lipo battery with 1300 mAh to power up STROE wirelessly for about 45 minutes. The motor that moves the pulley along the rod is an ordinary bipolar stepper motor commonly used in 3D printers. We used a timing belt to move the pulley with the stepper motor, see Figure 5.2.

5.3.2 Pulley Positioning

To determine where to position the pulley, we attach an HTC Vive Tracker to the user's foot and measure the distance between the foot and the user's controller. In the distance calculation, we only calculate a 2D distance and ignore the height dimension and subtract an offset that is the distance between tracker and the beginning of the rod. In a first step, the pulley position calibrates by moving to the start position until it collides against a button and triggers it. To position the pulley, we used a stepper motor, where we measured 2750 steps that the motor needs to move the pulley from the start position to the end position. The distance between start and end position is 40 cm and mounted with an angle of 40 degrees, therefore the length of the rod on the 2D ground plane is $\frac{40 \cdot sin(40°)}{sin(90°)} = 30.64\ cm$.

Now we can calculate the ratio between steps and distance on the 2D ground plane with $\frac{2750}{30.64} = 89.57$ steps/cm. We use this ratio to move the pulley, for example, to position the pulley to a distance of 20 cm. In order to do this, we calculate $20 \cdot 89.57 = 1795$ steps. So the motor has to do 1795 steps when the pulley is at the start position. We save this step position and update it accordingly to the controller position. Additionally, the properties of the stepper motor allow the system to hold the pulley in one position, even when a force is applied to the pulley.

5.3.3 Design Choices

During STROE's design and development process, many challenges arose that we had to solve. Here, we list our most important design choices.

Constant Torque

The most difficult challenge was producing a constant torque in order to feel a smooth weight simulation, even while moving the weight. To generate constant torque, we had to consider many aspects. The first one was the choice of a suitable motor with high torque, high precision, and low initial mechanical resistance. With initial mechanical resistance, we mean the minimal resistance to rotate the motor when it is turned off.

There are many different motor types such as stepper motors, servo motors, DC motors or brushless DC motors (BLDC). Stepper motors and servo motors have a high initial mechanical resistance, which would restrict the user's freedom of movement, since they have to apply a high force to rotate the motor, even when it is turned off. Normal DC motors do have a low torque, therefore our choice fell on BLDC motors. We chose a gimbal BLDC motor that can provide a high torque with lower speed.

If we want to control a low speed but high torque BLDC motor, we need a position encoder that tracks the position of the motor coils to provide constant torque. Otherwise, the controller would not know where the coils are and would cause an undesirable cogging effect. The position encoder needs to track the coils fast enough for the user's movements. Therefore, a fast communication between encoder and microcontroller is necessary, where we chose the serial peripheral interface (SPI) communication.

After we found a suitable motor and encoder, the next important step was to use a suitable motor driver board that can control the motor with a constant torque. To do so, we used the field oriented control technique (FOC) [90]. Simply explained, FOC generates an optimal pushing effect on the motor's rotor, by calculating the phase voltage which creates the magnetic field that is exactly perpendicular to the magnetic field of the permanent magnets. We chose this technique, because it provides a precise torque control. In order to get the best torque control, we used inline current sensing, where we measure the current on two shunt resistors to regulate the current the motor receives. This approach causes an accurate torque control. We used the code of the open source library SimpleFOC [1]. The simple FOC algorithm with the inline current sensing method uses a PID controller to steer the torque of the motor. Therefore, the last step was to set the PID parameters in order that the motor's torque behavior suits to our weight simulation. We set the parameters such that STROE reacts quickly to the user's movement.

Lift Object

We found that it does not feel realistic when we simulate the full weight of an object that is resting on a support, immediately after people lift it. If the object is heavy, it immediately pushes the user's hand down a few inches, which can result in a collision with the ground that stops the weight simulation. This behavior causes a cogging effect and feels unrealistic. When we look into the real physical lifting process, we see that users tense their muscles until the muscle strength outweighs the physical weight.

To simulate this behavior, we implemented a *weight increasing function* for the first centimeters of the lifting process. We increase the simulated weight in the first four centimeters from zero to the object weight. To do so, we tried different weight functions f to investigate which one feels the most realistic, where K is the offset with which we increase the force, in our case 4 cm. $x \in [0 < x < K]$ is the distance between the object's height and the start height, M the current of the object that is proportional to its mass, D the default current we defined to tighten the string, and f the resulting current that has to be send to the motor. We tried the following:

- Linear: $f_L = \frac{M-D}{K}x + D$
- Quadratic: $f_Q = \frac{M-D}{K^2}x^2 + D$
- Sine: $f_S = sin(\frac{0.5\pi x}{K}) \cdot (M - D) + D$

We empirically tested the functions ourselves. We tested the different functions multiple times with different object weights and immediately switched between the functions to reduce the time between distinguishing changes. We perceived the linear function as the most realistic one. With the sine function, we had a cogging effect with heavy objects as well and with the quadratic function, the weight sensation came with a short delay, which felt unrealistic.

Design of Rod

We designed STROE's rod with a length of 50 cm. To calculate the length of the pole, we held a string horizontally in front of us with an outstretched arm. Where the string touched the ground, we measured the distance to the toes. Additionally, we mount the rod on the shoe oblique to avoid collisions between the rod's end and the ground the user is walking on. We empirically tested different angles of the rod ourselves, to get the minimum angle that users can walk without colliding with the ground. With 40 degrees, we experienced good results. The rod is connected with the shoe by bearings. Because there is always a tension in the string between the pulley and the user's controller, the rod rotates automatically with the controller's movement without any mechanical actuation support. We decided against a rotational actuator to rotate the rod to keep STROE's design simple and reduce costs.

5.4 Technical Evaluation

In order to understand the technical limits of STROE, to know what weights it can simulate, and to further improve the technical aspects, we carried out a technical assessment. We measured the maximum force it can simulate, its latency, consistency, and the force during lifting and walking with a weight. To measure the generated force of STROE in different behaviors, we connected STROE's string to a load cell. We positioned the load cell straight above the second pulley in order to measure the force directed towards ground.

Maximum Force To measure the maximum weight STROE can simulate, we increased the current to the motor linearly. To do so, the load cell is connected to the ground. Here, a force of 1 N means a weight simulation of 100 g. We began with 0.3 A that we chose as default force to strain the string and increase to 2.0 A, which is the motor's current limit. Results can be seen in Figure 5.3. The default force was about 0.5 N and we measured the maximum force as 7.2 N. Compared to other haptic feedback devices we can produce more force than Windblaster [76] (1.5 N), and Thor's Hammer [67] (4 N), but less than Aero-Plane [75] (14 N). However, we can easily increase the maximum force by using stronger motors, without increasing the hearable noise level, in contrast to these other devices. Figure 5.3 also shows a current-dependent linear force increase that we use to calculate the current to simulate specific weights.

Latency and Consistency We also measured the time STROE needs to produce a force (Latency Up) of 3.5 N (50 % current) and 7.0 N (100 % current) and back to the default force (Latency Down), see Figure 5.4. Additionally we measured how consistently STROE can hold the force over 10 seconds. Table 5.1 shows the results. In Figure 5.4, we can also see a small overshoot in the force generation when the current is 100%. This is caused by the PID parameters we set, as we wanted to have a small latency. However, this overshoot is not an issue because of how we lift objects that we described in Section 5.3.3. Here, the force is increasing

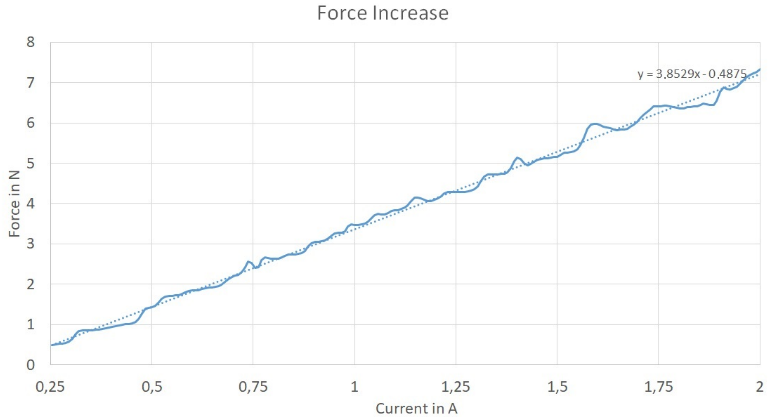


Figure 5.3 — The measured force of STROE's motor with its corresponding current value. We chose 0.3 A as default current to tighten the string and increased the current to the motor's limit to 2 A.

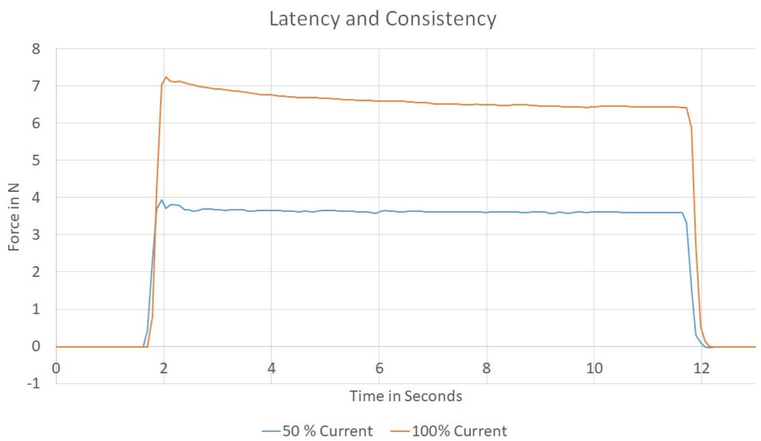


Figure 5.4 — The measured latency and consistency over 10 seconds with 50% and 100% of the motor's maximum current.

Current	Force	Latency Up	Latency Down	Cons.
50 %	3.5 N	250 ms	200 ms	0.02 N
100 %	7.2 N	250 ms	250 ms	0.2 N

Table 5.1 — The measured force, latency to reach the corresponding force (Latency Up), the latency from corresponding force to default force (Latency Down), and the force consistency over 10 seconds.

depending on the speed of the user's lifting behavior. The user would have to lift the object very fast in order to feel the overshoot.

Lift Weight In the real world, when users lift a weight and accelerate it, they perceive a force that is greater than the real weight of the object due to its inertia. We measured the force STROE exerted on the users while lifting a weight to see if we can simulate inertia. Figure 5.5 shows the result of lifting a simulated weight of 7N by STROE for 60 cm. The figure shows the effect of the inertia, that increase the weight during acceleration. When the user moves a weight in the opposite direction of the gravity vector, the force to move the weight is more than the original weight because of the inertia and vice versa. We can see this effect by looking at the measured data.

Walking with Weight STROE's design allows to simulate weight while walking. However, moving STROE during walking can affect the force the users receive. Therefore, it is important to produce a constant force while walking. We measured the force consistency while the user is moving multiple steps. While walking, the user holds a handle where the load cell is mounted on, while walking. The user tried to keep his hands steady. We measured the force for the walking direction forward, backward, right, and left. Figure 5.6 shows the result of one user walking forward while STROE produced a force of 7 N. We measured a deviation of 0.64 N while moving forward, 0.50 N backwards, 0.48 N right, and 0.51 N left. The step length was about 37.5 cm forward, 25 cm backward, and 32 cm for left and right steps. Additionally, we can recognize a pattern for each step,

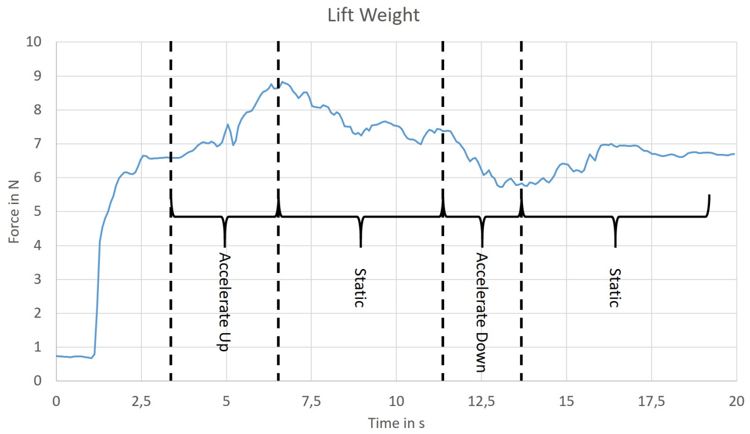


Figure 5.5 — The measured force in one lifting process. The lifting process contains the following steps: Move the object up (Accelerate Up), hold one height with the object (Static), move the object down to the start height (Accelerate Down), and let the object go (static). Here, we can see that the inertia is also simulated by STROE.

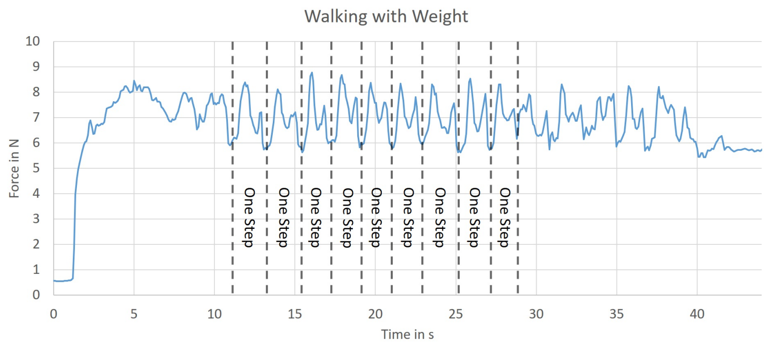


Figure 5.6 — The measured force during walking multiple steps with a current of 2 A. Here we can see a repeating pattern for each step.

that can be used to decrease the deviation with signal processing in future work.

5.5 Study

We conducted a proof-of-concept study in order to evaluate the potential of STROE and its performance in different scenarios.

5.5.1 Scenarios

We have implemented four different VR scenarios in Unity, which we described below. In Unity, we assign a weight to every object that can be grabbed. If the user grabs one object, the *weight increasing function* is called and the resulting weight is sent via Bluetooth to STROE's Microcontroller. Here, the FOC algorithm generates the torque according to the weight it received.

We ordered the scenarios according to the how much participants have to walk in each scenario. From static scenarios to walk-intensive scenarios.

Sort Objects

In this scenario, the participants have to sort five cubes by their weight, see Figure 5.7 A. The cubes look the same but have different weights (180 g, 325 g, 440 g, 580 g and 730 g). We chose this scenario to investigate how well STROE can offer various weight simulations. In this scenario, participants usually do not move their feet. We measured how many cubes were sorted correctly and how long participants needed.

Catch Objects

Here, the participants had to catch objects with a small container and throw them into a chest, see Figure 5.7 B. We assigned this container a weight of 275 g and the objects they have to catch 200 g. Here, STROE simulates the weight of the container and the weight of a caught object while it lies in the container. This scenario requires quick upper body movements but is mostly stationary. Here, we evaluate whether STROE's string limits the fast movements and whether the delay is acceptable.

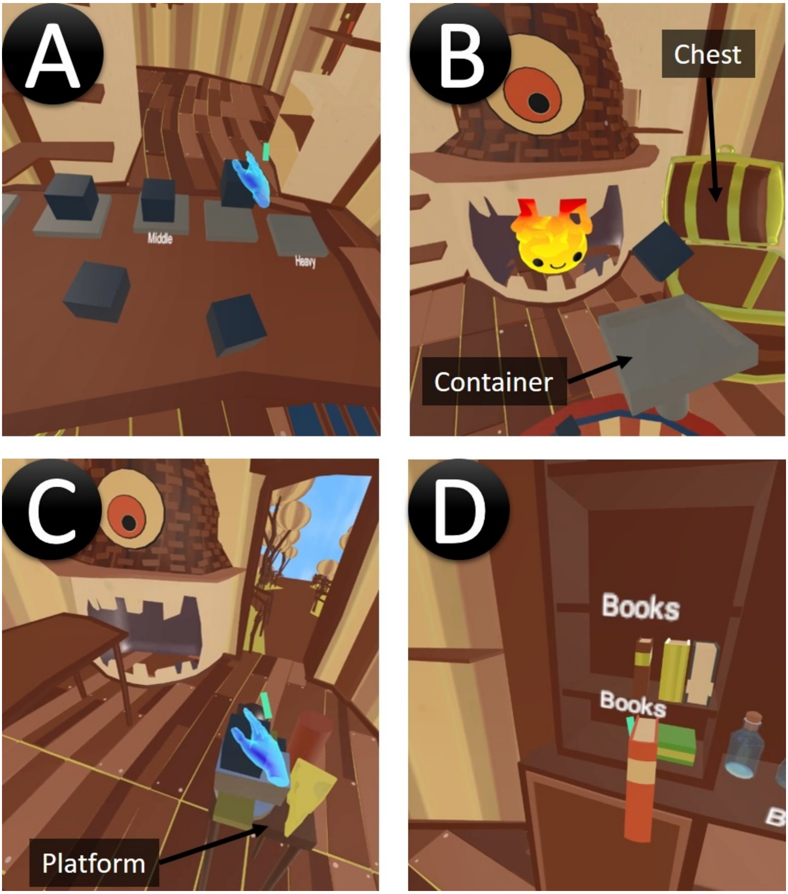


Figure 5.7 — The four scenarios we implemented for our user study. (A) the Sort Objects scenario, (B) the Catch Objects scenario, (C) the Place Objects scenario and (D) the Tidy Up scenario.

We measured the number of dropped and caught objects and the time participants spent there.

Place Objects

In this scenario, participants need to place different blocks on a small platform without knocking the other items down, see Figure 5.7 C. The shape, size, and weight of the objects are different. We choose simple shapes such as cubes, cylinders, cones or pyramids. The weights of the objects were between 180 g and 730 g. The items are placed on tables next to the platform, so participants have to move around a lot while holding the items. We chose this scenario because we wanted to find out how well the participants can move while holding the objects and whether the weight of the objects influences their decision on where to place the objects on the platform. We measured how many items were accidentally dropped from the platform and the time they needed.

Tidy Up

This scenario is about tidying up a room, see Figure 5.7 D. The participants have to grab objects on the desks and position them in the designated place. In this use case, the participants have to walk the most. The room they have to tidy up has an area of $3\ m \times\ 3.5m$. Here we measured the time they spent in this scenario.

5.5.2 Participants

We had 12 participants (10 male, 2 female) with an average age of 25.4 (SD: 3.7) years. 8 participants were experienced in VR, 4 were beginners or had not had contact with VR before. 5 participants had experience with haptic devices in VR. Additionally, 11 participants were interested in VR applications.

5.5.3 Procedure

Participants conducted the study under a VR rig and used the HTC Vive and its controllers. The VR rig is approximately $4\ m \times 4\ m$ in size and gives participants the opportunity to walk freely. We conducted a within-subject study with two conditions, the **visual-only** condition and the **visual-haptic** condition. For the visual-haptic condition, we attached STROE to the shoe on the side of the dominant hand and connected it to the corresponding controller. Only the Sort Object Scenario was done with just the visual-haptic condition, because the participants cannot solve the task without haptic feedback. The order of the conditions were randomized to avoid learning effects. The participants first explored a training scenario with STROE in order to get used to it. In the training scenario, they could freely walk in a virtual room and lift different objects.

Our main intention in this study is to measure the potential increase in realism and immersion, which is essential for our application domain. We did that using the respective questionnaires. To further enrich this data, we also measured **quantitative task performance** as described in the scenario descriptions. Note, that the quantitative task performance measures are not our main focus though. In fact, we expect that haptic feedback conditions will even lower the quantitative task performance measures, as tasks are becoming more realistic and as such harder to conduct. For instance, if the task is to assemble a car component, the heavier the car component is the more challenging the task, and therefore we would expect the task performance to decrease. This realism is essential for domain tasks such as automotive build-ability studies. The main purpose is to simulate in VR how hard these tasks are in reality; the goal is not to make the VR experience as easy and fast as possible.

After each condition, we gave the participants a questionnaire about the **user experience**. Here, they had to rate fun, realism, and immersion of the scenario on a 5-point Likert scale. After each scenario, we interviewed the participants and asked only about the **haptic experience**. Our questions were partially based on the questions from Kim et al. [78], which provide guidelines for building haptic feedback devices. We asked to rate consistency (Is it reliable?), sailency (Is it appropriately noticeable?), and harmony (Does it fit with the other senses?) on an 5-point Likert scale. In addition, we asked whether STROE restricts their movement and how realistic the weight feels when walking. At the end of the study, we collected additional qualitative feedback by asking **general questions** about which scenario they prefer and why, if they prefer with or without haptic feedback, whether they have suggestions for improvement and what they liked and did not like about STROE. We audiorecorded, transcribed, and coded these interview parts.

5.5.4 Results

We split our results corresponding to the questions we asked. First, we report the overall experience to see which effect STROE has on the overall VR experience. Afterwards, we report the haptic experience to find out which aspects of the haptic feedback worked well and which not. At the end, we present qualitative feedback of the participants. Our results is based on an exploratory proof of concept study. Therefore, we used an estimation-based approach with effect sizes and confidence intervals to interpret our results. This approach is recommended by statistical analysis practices [16] and overcomes several limitations and biases of classical null hypothesis testing with p-values (NHST) [38, 44]. Cumming and Finch provide guidance on how p-values can be eye-balled from 95% CI plots [39].

User Experience

In the overall experience, we can see that on average the participants had more fun and perceived the VR scenarios with STROE more realistically and immersively, see Figure 5.8. The highest increase were in the realism from 3.2 without STROE to 3.8 with STROE. Afterwards, the immersion increased from 3.9 to 4.2 and the lowest increase was the fun experience from 4.2 to 4.4. In Figure 5.9 we can see the fun, realism, and immersion ratings per scenario. Here, we notice that perceived fun decreases with

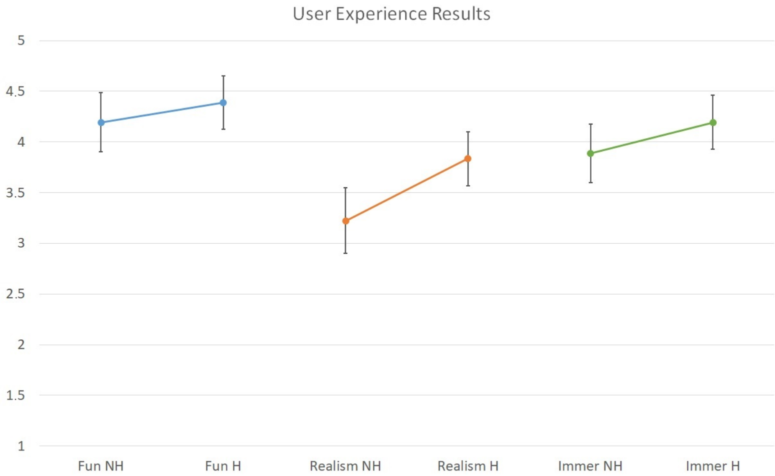


Figure 5.8 — The results and their 95% confidence interval of the overall experience questions about fun, realism and immersion with none haptic feedback (NH) and with haptic feedback (H).

the scenario order, which we assume also depends on the amount the participants had to walk.

Haptic Experience

Overall, we were satisfied with the results of the haptic experience question, which shows a potential in the technical aspects of STROE. Figure 5.10 shows the results of the questions of the 5-point Likert scale for each scenario.

On average, the results about the consistency were 4.3 (SD: 0.78) which demonstrates the reliability of the technical design. The consistency was rated the lowest in the *Catch Objects* scenario, because 8 participants reported a judder in the feedback when the block was jumping on the container. This can be explained by the implemented collision behavior.

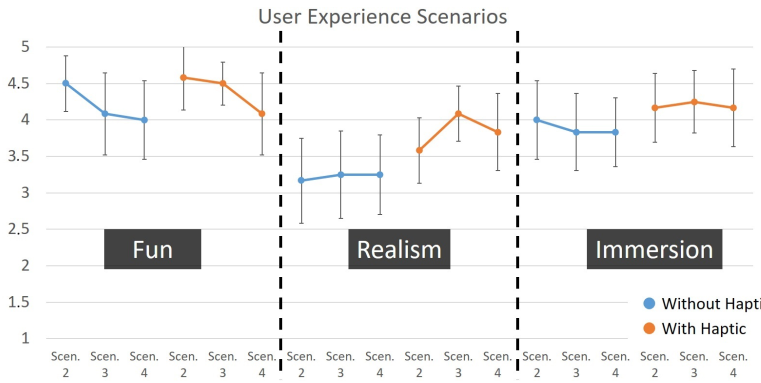


Figure 5.9 — The results and their 95% confidence interval of the overall experience questions about fun, realism, and immersion for the second, third, and fourth scenario with and without haptic feedback.

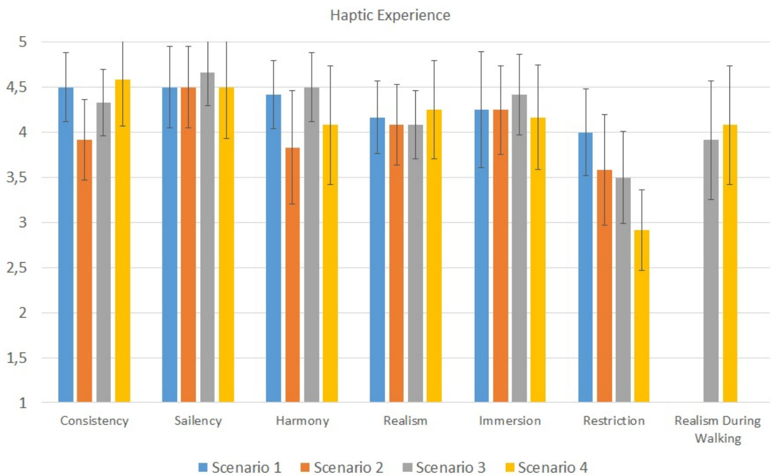


Figure 5.10 — The results and their 95% confidence interval of the haptic experience questions for each scenario.

Every time the block collided with the container, STROE simulates the weight of the block. When the block bounces on the container, STROE will trigger multiple force stimuli in a short time. Most of the participants perceived this behavior as too extreme. However, one participant described this behavior as very realistic. 4 participants criticized the consistency, because sometimes the force was not perceived fully downward, since they leaned their upper body too much to the front and STROE's rod was too short.

The sailency was rated 4.5 (SD: 0.8) on average and the harmony 4.2 (SD: 0.94) which showed us sufficient results. One participant mentioned, that they missed a weight shifting when the block jumped from one side of the container to another.

The realism was scored 4.2 (SD: 0.77) on average and the immersion 4.3 (SD: 0.94), which showed us that the idea to simulate weight with the motor attached on a shoe feels realistic. One participant told us in the *Catch Objects* scenario: "*So in comparison without haptic feedback, it was much, much more real, so it felt really real and even when I let [the block] go, it really felt like I was catching something with a container and throwing it away again, that was really good*". However, 5 participants reported that placing the objects on another object or platform feels unrealistic, because the weight simulation stops too immediately. Here, we have to use the same weight increase function that we implemented for the lift object that we explained in section 5.3.3. Another criticism about the realism, which was mentioned by 2 participants, was that the feedback is triggered on the controller and not directly on the user's hand.

On average, the restriction was rated the lowest with 3.5 (SD: 0.97) where 5 means no restriction in your movement and 1 means very high restriction. In Figure 5.10, we can see that the restriction ratings increase depending on the scenario. The participants felt less restricted when they had a more static scenario and more restricted if they had to walk a lot. Some participants described the restriction of walking due to STROE like wearing a "skier", "flipper", or "bandage". Additionally, 3 participants reported that their other foot collided against STROE's rod, which irritated them a little. However, other participants told us they just had to used to it, one explained: "*If you have tested it for a while and you can see that it can withstand fast movements, then you can move with it without being restricted*".

We were surprised about the positive ratings on the felt realism during walking. We were not sure how much the connection between foot and hand will effect the perceived weight sensation during walking. One participant explained about the force sensation during walking: "*If you concentrate on your hand you don't notice any difference between walking and standing*". The participants rated the realism during walking with 4.0 (SD: 1.14) and reported that the perceived weight did not change during walking.

Quantitative Task Performance

In the *Sort Objects* scenario, we were positively surprised about the successful sorting results. Each participant correctly sorted all objects according to their weight. On average, they needed 80 seconds (SD: 17.5). In the *Catch Object* scenario, the participants without haptic feedback caught on average 59% (SD: 13%) of the objects and threw them in the chest and 43% (SD: 13%) with haptic feedback. On average, participants dropped 0.7 (SD 0.8) objects without haptic feedback in the *Place Objects* scenario and 1.9 (SD: 2.4) with STROE. They needed on average 101 seconds (SD 14) to complete the task without haptic feedback and 141 seconds (SD: 39) with haptic feedback. In the *Tidy Up* scenario, the participants needed on average 180 seconds (SD: 39) to complete the task without haptic feedback and 256 seconds (SD: 39) with haptic feedback. As expected the task performance got harder with haptic feedback, which we see in the increased time and error measures.

General Question

We were happy that 9 of 12 participants preferred their favorite scenario with STROE. 8 participants liked the *Catch Objects* scenario the most where 5 participants prefer the scenario with using STROE. 2 Participants preferred the *Tidy Up* scenario with haptic feedback and 2 participants preferred the *Place Objects* and *Sort Objects* scenario each, both with haptic feedback.

The suggestions for improvements were mostly about ergonomics and wearing comfort. The participants came up with the idea of placing STROE's heavy hardware components more centrally on the shoe in order to better balance the weight and enable better movement. In addition, they wished for a smaller and lighter design of STROE and a better mechanism to attach it tighter to the user's shoe. Some participants suggested to glue rubber onto STROE's sole in order to decrease the hearable noise that arises when the users make a step with the current plastic sole. One participant had the idea to insert a damper for the rod rotation to decrease the swing effect of the rod. Another idea was to increase the length of the rod to prevent forces that are not directed to the ground. One participant suggested to attach the string directly to the hand instead of the controller in order to get a more realistic weight sensation.

Regarding the question what they liked, some participants mentioned the arm freedom and the mobility. One participant said: "*That's the first step into mobility, it's very mobile compared to other things I know*". Other participants liked the increased realism. One participants told us: "*It just feels much more realistic. So in comparison to without [haptics], something is really missing if it is not included*". One participant explained us that he liked the idea to attach the hardware on the shoe, he said: "*I don't notice that the pulling that is causing the feedback on my hand is coming from my foot, I didn't even notice that. I think that was very good*".

Most of the participants agreed on what they did not like about STROE. They mentioned the movement restriction caused by the unergonomic design of STROE and the wearing comfort. None of the participants raised concerns about the technology STROE uses to exert forces on users.

5.6 Discussion

In the following, we discuss whether STROE meets the design requirements we collected from related work and our experience with VR engineers from the automotive industry. Additionally, we discuss the limitations of STROE.

5.6.1 Design Requirements

Based on our study results, we showed that the users can walk with STROE (**R-Mobility**). We were surprised about the positive feedback how realistic the weight sensation is during walking. Therefore, we belief that our design idea has potential for ungrounded weight simulation. However, they criticized the wearing comfort and the ergonomic behavior, which we are confident to improve with design adaptions. Our technical method to generate a force does not create hearable noise (**R-Quiet**). However, some participants were annoyed by the sound that was generated by the contact between STROE's plastic sole and the ground. The participants were able to put the shoe on in less than 30 seconds (**R-Simple**) and the only skin contact it has is with the controller, therefore we just had to clean the controller before giving STROE to the next user (**R-Hygiene**). In total, our hardware costs about 150 USD, whereby we are satisfied as our costs are comparable with a new HTC Vive controller that costs about 140 USD (**R-Price**).

5.6.2 Design Improvements

Some participants reported, that they perceived a slight mechanical noise in the weight sensation, when they do fast and large arm movements. This is caused by the design of the rod's rotation. When a user moves their arm fast for a longer distance, the rod begins to rotate and there is an overshoot in the rotation when the user stops their arm immediately. To fix this problem, we can use a motor that controls the rotation of the rod. For that, we would recommend a brushless DC motor, with a high velocity.

The major problem the participants mentioned was the constraint in walking caused by STROE's design. To improve this behavior, we have multiple ideas, that we want to test in the next prototype. One idea is to round the shape of STROE's sole and to attach rubber material on it. The design would then allow the user's foot to roll and it would decrease the hearable noise. Additionally, we want to create a better weight distribution in the design. At the moment, most of the weight of STROE is in the front of the shoe, which causes problems during walking. We have two different ideas to solve this issue. First, we can place the battery, Arduino, and the driver board further back on the outer side of the shoe, to distribute the weight more equally. Second, we can attach the battery, Arduino, and the driver board on the user's calf and place the motor with the string on the side and back of the shoe, and connect the string with the movable pulley via additional rolls. Another idea that reduces the walking restriction is, to redesign the device to directly attach the rod to the user's shin instead of the foot. Thus, the users would have no restriction on their foot.

In the walking with weight section 5.4, we saw that the force magnitude depends on the direction of the user's step. The study results showed that the participant did not notice a force variation during their walking. However, increasing the maximum force STROE can apply will increase the force magnitude variation and we assume participants will notice it when the force is strong enough. A next step is to track the step direction and use this information to control the force magnitude. For this purpose, we want to use the tracker's orientation that is attached on the user's foot.

5.6.3 Limitations

A limitation that arose is the ability of simulating the center of mass. With one string it is currently not possible to simulate any weight shift. However, there are already some devices that can simulate weight shift, such as Shifty [167]. In a next step, we want to combine both devices. Another limitation is the restriction of free walking. Our study shows that the users could walk during weight simulation but in a restricted way. One limitation that came up was the speed of the pulley that was controlled by the stepper motor. The stepper motor is good in holding one position even when external forces were applied. However, stepper motors are not as fast as brushless motors. In the next prototype, we therefore want to further control the pulley position with a brushless motor. Another limitation is the usage of two STROEs at the same time. When users cross their hands, the rods of the STROEs could collide with each other. Therefore, we want to include a mechanical stopper that stops the rods rotation in the case of using two STROEs. In addition, there are limitations in the current control system that can be improved to increase accuracy. For example, in the next prototype we want to use a tension sensor in the control system.

5.7 Conclusion

We introduce STROE, a new ungrounded string-based haptic feedback device. STROE can be attached to the user's shoe for mobile usage. It consists of an motor with a string that is connected to the user's controller in order to simulate weight in VR applications. We conducted a user study with 12 participants. The main results show that STROE can simulate weight precisely and reliably even during walking. It increased the participants perceived fun, realism, and immersion in the VR scenarios. Although the participants could walk with STROE, they mentioned some optimization problems and limitations, which we discussed.

Chapter 6

Multimodal Haptics for Automotive Engineering

Our previous devices have demonstrated positive results in simulating collision and weight in various use cases. However, during discussions with automotive VR experts, they presented new automotive VR scenarios requiring simultaneous weight and collision feedback. Additionally, they highlighted the importance of grabbing feedback to realistically interact with virtual objects.

Currently, we face the challenge of switching between devices to simulate these different types of feedback, which hinders users from experiencing multiple haptic feedback types simultaneously. To address this issue, we recognize the need for multimodal haptic feedback in these specific VR use cases, and in the following chapter, we will delve into this topic further.

6.1 Introduction

At the moment, engineers predominantly rely on unimodal haptic feedback devices. This approach has shortcomings: Firstly, users must switch between different devices when different types of haptic feedback are needed. Secondly, unimodal devices are inadequate for more complex VR tasks involving simultaneous simulation of multiple senses. In maintenance tasks, for example, where engineers assess the feasibility of replacing a car component, three distinct sensations are necessary. Firstly, a realistic "grabbing" sensation is required to ensure a secure hold on the component and sufficient hand space. Secondly, engineers need to feel any potential "collisions" with the car to prevent scratches during the replacement process. Lastly, they should be able to accurately perceive the "weight" of the components they handle, ensuring safe task repetition without the risk of injuries.

Multimodal haptics provides a potential remedy for this problem. Wang et al. [153] define multimodal haptic as approaches that simultaneously provide multiple haptic stimuli, such as forces, vibration, and thermal stimuli. The authors highlight three domains involved in multimodal haptic interaction: multi-properties, multi-gesture, and multi-receptors.

A significant challenge in developing multimodal haptic systems lies in managing spatial interference among different actuators [153]. For instance, HaptX Inc. has introduced the HaptX Glove, which consists of many tactile actuators and can also provide force feedback [65]. However, the device's size and price are considerable, and certain sensations like temperature are absent. Park et al. [119] developed a multimodal haptic feedback device to simulate impact feedback with vibration and impact actuators. Their user study demonstrated an expanded dynamic range for virtual collision simulation, although it was found that, for specific material simulations, a single haptic modality yielded the best results. However, to the best of our knowledge, there is no haptic feedback device that can simulate weight, grabbing, and collision forces simultaneously.

Our research objective was to explore the feasibility of combining existing devices into a multimodal haptic feedback setup that specifically caters to the integration of weight, grabbing, and collision forces. While individual devices have demonstrated effectiveness in simpler tasks, the extent to which they can be utilized for more complex tasks, for instance, as faced in the automotive domain, remains uncertain. Our investigation sought to address questions regarding the combination of different devices and their overall effectiveness. We aimed to determine how well these combinations could enhance the user experience and task performance in more intricate VR scenarios.

Combining all the possibilities of haptic feedback devices is primarily impossible and is not covered in this chapter. Instead, we wanted to do a deep dive into a specific problem, for which we needed to combine three types of haptic feedback: *Collision*, *weight*, and *grabbing*. At first, we looked for affordable haptic feedback devices which could cover these feedback types separately. Next, we investigated which of these devices can be combined to simulate all three feedback types simultaneously. Afterward, we selected the most suitable feedback devices and combined them into a multimodal setup. We then conducted two user studies, a smaller pilot study to collect formative feedback from 4 participants, and an expert study with 12 VR experts from the automotive industry with two automotive VR tasks. In the pilot study, we collected feedback to improve the setup of our multimodal feedback system. In the expert study, we compared different setup combinations to find out where current practical boundaries lie, which combinations already work well, which do not, and which combination has the highest benefit for automotive experts with and without technical device limitations.

Results show that the combination of *weight* and *collision* has the most considerable benefit compared to the other combinations. However, based on speculative assumptions that the devices do not have technical limitations, approximately half of the participants rated *grabbing* as the most crucial feedback. This suggests that the devices' benefits are currently overshadowed by the technical limitations associated with their grabbing functionality. Additionally, we draw implications for future work on multimodal haptic feedback systems.

In summary, our research makes the following contributions:

- Investigation of Combinable Haptic Feedback Devices: We explored and determined which haptic feedback devices could be effectively combined, leading to the development of a justified multimodal setup.
- User Studies: We conducted two user studies to evaluate the performance and effectiveness of different combinations of haptic modalities within our feedback system when applied to automotive VR tasks.

Core Related Work In contrast to our research, related work on multimodal feedback mostly focuses on developing new devices that can provide multimodal feedback. For example, Park et al. [119] developed a handheld haptic feedback device with vibration and impact actuators, effectively simulating texture and impact feedback. Their study showed that participants perceived more realism with single feedback types for specific materials than combined ones. Culbertson et al. [36] combined a vibrotactile actuator with the Phantom Omni, simulating 15 virtual surfaces. User study results revealed varying importance of model components across surfaces. Wolf et al. [157] pursued a different approach, developing a multimodal head haptic feedback device with vibration motors and thermal actuators. Their user study reported higher presence and enjoyment with their system. Unlike prior work, our focus is not on constructing new devices but on combining collision simulation, grabbing feedback, and weight simulation devices. Such a system does not yet exist.

6.2 Automotive VR Task Requirements

To begin, we provide a description of the automotive VR tasks to gain insight into the necessity and application of *grabbing*, *weight*, and *collision* feedback. Subsequently, we outline the requirements we have compiled for the devices to effectively simulate these three types of feedback.

As for the tasks, we have selected two automotive VR tasks that utilize real automotive car data. These tasks involve replacement and packaging tasks, as depicted in Figure 6.1. In a broader context, these tasks fall under assembly and maintenance categories. Experts evaluate various aspects, including ergonomic posture, reachability, accessibility, and object fitting within target locations. Hence, these specific tasks can also be generalized to other automotive scenarios. We have chosen these task types because they encompass diverse interactions with virtual objects. Tasks in the automotive VR domain that solely focus on design investigations do not necessitate object interaction and, thus, do not present a significant interest in haptic feedback.

The first task involved replacing a faulty hose beneath the cooling water reservoir with a new one. This task included removing the water reservoir, unscrewing the corresponding screws, detaching the holder, replacing the hose, reattaching the holder, screwing the screws back in, and finally, replacing the water reservoir. All the necessary materials, including the power drill, were placed on the table within the participant's reach, eliminating the need for the participant to move from their initial standing position.

Following completing the first task, a five-second break was provided before the scene was rotated by 180 degrees. The rotation was implemented to facilitate the second task on the opposite side of the engine compartment. This approach eliminated the requirement for users to rotate physically, which could hinder their experience with the haptic feedback system. The second task involved a single objective: placing the brake vacuum servo into the engine compartment and evaluating the available space for its placement.

In the following, we list the requirements we collected for each haptic

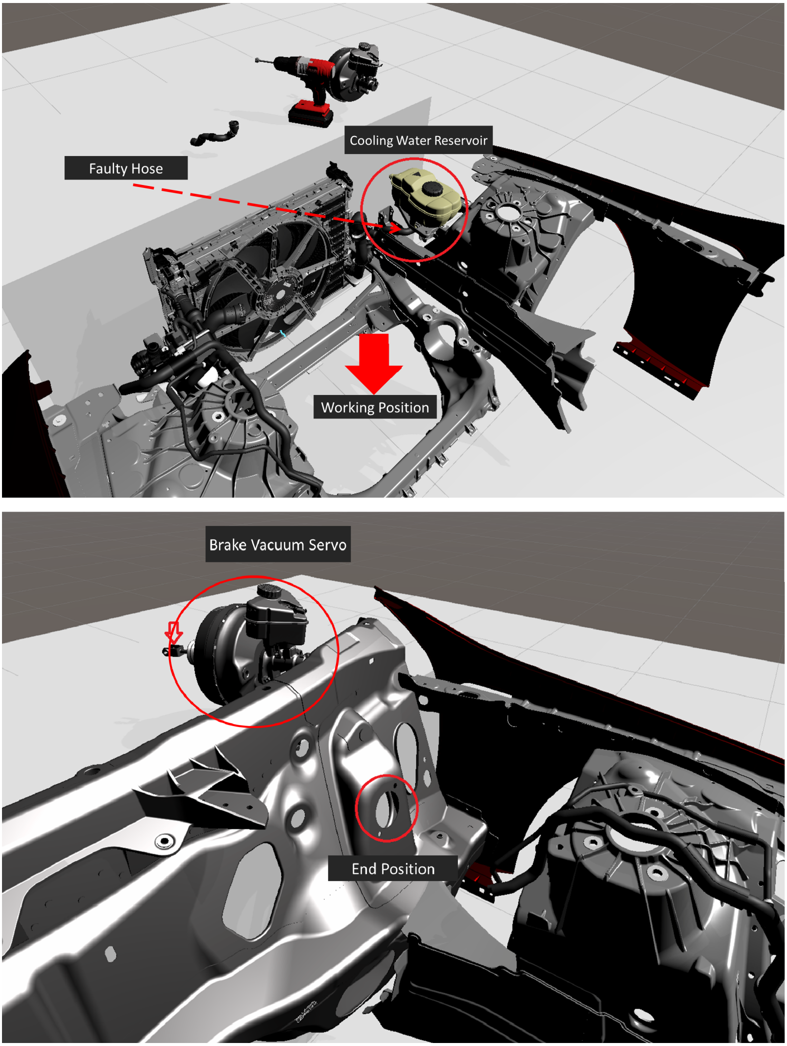


Figure 6.1 — Left: The first automotive VR task involves replacing a faulty hose. Right: The second task requires placing the brake vacuum servo in the end position.

feedback type:

Grabbing Feedback Requirements In both tasks, participants are required to *grab* various objects, such as the cooling water reservoir, the brake vacuum servo, or the power drill. Including a realistic virtual hand pose allows the experts to assess whether there is sufficient space within the virtual environment for participants to maneuver their hands comfortably during the grasping process.

Consequently, one of the requirements for the grabbing feedback is the provision of kinesthetic feedback to ensure accurate hand positioning. Conversely, tactile feedback, which enables the perception of material properties of the grasped objects, is not necessary for our VR tasks.

Furthermore, our observations indicated that a minimum of four fingers, including the thumb, needed to be involved in the grasping interactions. As a result, our focus lies solely on haptic feedback gloves that support a minimum of four fingers.

Collision Feedback Requirements It is essential to incorporate collision simulation to determine if the experts encounter *collisions* with objects. Achberger et al. [10] demonstrated that implementing haptic collision simulation in automotive tasks yields several advantages, including a better perception of the workspace and increased confidence in task outcomes.

Regarding our specific automotive task, we now clarify what we mean by *collision* feedback. Collision feedback involves halting the movement of our virtual hand or the object being held when a collision occurs with the virtual environment. To achieve this, we require a kinesthetic haptic feedback device capable of physically impeding hand movement.

After evaluating our task's virtual environment, we have determined that three degrees of freedom are necessary to arrest our movement effectively. While simulating torque can be beneficial, it is not a mandatory requirement. Hence, our focus lies exclusively on kinesthetic feedback devices that offer at least three degrees of freedom of force output.

Weight Feedback Requirements To assess the ergonomics of the task, it is crucial to simulate the *weight* of the objects. The weight of an object directly impacts the complexity and physical exertion involved in performing the task.

When we refer to *weight* simulation, we mean replicating the actual force exerted on users' hands when they hold a virtual object. Our focus is on force feedback that induces muscle fatigue to simulate the feeling of weight. Muscle fatigue is an important aspect to consider in automotive scenarios, as engineers need to evaluate the ergonomic implications of the task.

Weight shift devices are unsuitable for our use cases since they cannot simulate varying weights. More than simply attaching a single weight to the user's hand during the VR task is required, as they need to handle objects with different weights. Furthermore, if the user places the grabbed object down or encounters a collision that affects the object's weight, the weight simulation must cease.

Hence, we require an active force feedback device capable of dynamically simulating different weights. In our use case, the heaviest virtual object is the brake vacuum servo, weighing approximately one kilogram. Consequently, the weight simulation device we seek does not need to simulate heavy weights.

In contrast to *collision* simulation, we only require force feedback in one degree of freedom, specifically directed downwards.

6.3 Combination of Haptic Feedback Devices

In this section, we provide a list of devices capable of generating haptic feedback for *grabbing*, *weight*, and *collision*. These devices have been carefully selected to meet our specific requirements. We do not cover all existing feedback devices that meet our requirements, as there are many similar devices. Instead, we focus on devices where we see the highest benefits.

Finally, we outline the combinations of haptic feedback devices that can be utilized and reveal the final devices we have chosen for our user studies. It is important to note that we only include haptic feedback devices that are either commercially available or can be replicated. By replication, we mean sufficient information is available to reproduce the device accurately.

6.3.1 Grabbing Feedback

Feix et al. [50] identified 33 distinct types of human grasping, which are based on the shape of the object being grasped and the task at hand. However, when we interacted with the virtual objects in our tasks, we predominantly utilized finger-opposition power grasps, which are the primary focus of most haptic feedback devices.

In a review of kinesthetic haptic feedback research prototypes, Pacchierotti et al. [117] examined 21 prototypes, of which ten supported haptic feedback for at least four fingers. We studied these ten feedback gloves and assessed their compatibility with other haptic feedback devices regarding attachment methods and bulkiness.

These feedback devices are hand exoskeletons, which involve mechanical components attached to the fingers and hand. However, the size of these devices varies, ranging from bulky designs (Sarakoglou et al., [130]) to more compact alternatives (Nycz et al., [113]). The approaches for attaching these feedback devices to the hand and fingers are similar, including direct attachment of mechanical parts to the fingers, holding the device in hand, or wearing gloves with attached mechanical parts.

Upon evaluating the commercial market for feedback devices, it becomes apparent that the options are somewhat limited. Caeiro et al. [28] conducted a systematic review covering 2015 to 2021 and identified 24 smart gloves. Surprisingly, only ten of these gloves offer tactile feedback, while three provide kinesthetic feedback additionally. The remaining gloves solely support finger tracking, lacking the capability to provide haptic feedback.

The three gloves that offer kinesthetic feedback are the initial version of SenseGlove (SenseGlove DK1), the current version (SenseGlove Nova), and the Dexmo glove (Dexta Robotics, Hong Kong, China). We found minimal differences compared to the research prototypes regarding their compatibility with other haptic feedback devices. They all function as exoskeletons and follow a similar approach for donning. We examined that it is impossible to wear an extra glove, like the PropellerHand [12], on top of the feedback gloves to add weight sensation or other haptic feedback. As a result, if one glove can be connected to a haptic feedback system, other gloves can be connected as well.

6.3.2 Collision Feedback

When considering the combination of *collision* feedback devices with other haptic feedback devices, it is important to distinguish between grounded devices connected to the physical environment and ungrounded devices attached to the user's body.

In the case of grounded feedback devices that meet our requirements, we have identified three different approaches to user interaction.

The first approach involves encountered-type devices. Mercado et al. [100] define them as devices which position themselves or a part of themselves in specific locations to provide haptic feedback when the user reaches that point. Since they are not attached to the user's body and do not require grabbing, they do not restrict other haptic feedback devices, such as gloves. Examples of encountered-type devices include drones [8] and movable walls [25, 164]. For instance, Abtahi et al.'s drone [8] flies to the position where the user collides with a virtual surface. Depending on the texture of the surface, the drone rotates, simulating the corresponding texture. Therefore, when it comes to compatibility, we will generalize the encountered-type devices and assume they have equal compatibility.

The second approach involves grounded devices where the user needs to grab a predefined handle. Examples of such devices include the mechanical arm Virtuose 6D [54] and string-based devices like INCA 6D [122]. In the case of INCA 6D, strings are attached to the predefined handle, and forces are controlled by string tension. In this category, the predefined handles prevent users from grabbing other objects while using feedback gloves.

The third approach we found is grounded string-based devices like STRIVE [10], which are directly attached to the user. These devices use strings to stop the user's movement without restricting their grabbing gestures. Grounded devices generally have limited mobility as the feedback device is fixed in place. However, our automotive tasks require only minimal movement.

Turning to ungrounded devices, the device itself and its end effector (the part that simulates haptic sensation to the users) are attached to the user's body. We have identified four types in this category.

The first type are handheld devices such as Thor's Hammer [67], which utilize propeller propulsion to generate forces on the hand. Similar to grounded devices, these handheld devices have predefined handles that restrict grabbing.

The second type includes devices where the end effector and the device are in the same position and attached to the user. Electric muscle stimulation-based systems (EMS) [92] are an example of this type, using electric muscle stimulation to simulate forces. Here, electrodes are stuck to the users' bodies triggering their muscles.

The third type consists of devices attached to different body parts, such as Spidar-W [110] or Mantis [18], which are rigs connected to the user's back. The end effector is then grabbed by the user's hand, allowing them to feel the haptic sensation.

Lastly, there are devices attached to different body parts, with the end effector also connected to the user's body without a predefined handle.

An example of such a device is the feedback device Naviarm [93], which functions as an exoskeleton attached to the user's back, simulating forces on the hand.

It is important to note that except for handheld devices, the compatibility of these devices for combination depends on where the device and the end effector are attached, which varies for each device.

6.3.3 Weight Feedback

In contrast to collision simulation devices, we need to consider an active haptic feedback device capable of exerting forces on the hand. Unlike passive feedback devices like STRIVE [10], these active devices can generate forces independently of the user's movement.

In our literature review, we came across devices that can simulate collision and weight sensations. These include Virtuose 6D [54], Inca 6D [122], Mantis [18], Naviarm [93], Thor's Hammer [67], and the EMS System [92], which were briefly described in the previous subsection.

Furthermore, we found active haptic feedback devices focusing on weight simulation. For instance, Gravitycup [32] is a handheld controller with a tank that allows the flow of liquid to create the sensation of weight. Another device, Aeroplane [75], employs two propellers to simulate weight and the center of mass. However, both Gravitycup and Aeroplane have predefined handles.

The device PropellerHand [12] operates similarly to Aeroplane, using two propellers for weight simulation but without restricting grasping gestures. However, PropellerHand can only simulate weight when the users hold their hands horizontally.

Another weight simulation device we encountered is STROE [9], a string-based force feedback device attached to the user's shoe. It is connected via a string to the user's hand, allowing weight simulation through string tension.

6.3.4 Combination of Feedback Devices

In our search for a suitable combination of haptic feedback devices, we examined devices that met our requirements and were either reproducible or commercially available. We considered gloves and encountered-type devices equally compatible, as their combinability did not significantly differ. We evaluated the devices based on their visual representations or videos, and our results are presented in Table 6.1.

From our findings, we observed that most combinable devices were either focused on weight or collision feedback, with some capable of simulating both types of feedback. Only a few devices could be effectively combined with haptic feedback gloves. The main challenge is that many collision and weight feedback devices come with predefined handles, making it impractical to use them in conjunction with gloves. However, we identified a few combinations that could simultaneously simulate grabbing, collision, and weight sensations.

One simple setup involves using the EMS system [92] in combination with the gloves to simulate all three sensations. However, feedback from participants in the EMS study revealed that collisions against rigid objects did not feel realistic. Additionally, we consulted VR experts from the automotive industry to gauge their opinion on using an EMS system for their work. They expressed hygiene concerns, the time-consuming setup process involving electrode attachments, and the potential risk of health injuries if technical issues arise. Another straightforward approach would be to combine the Naviarm device [93], which provides weight and collision feedback, with feedback gloves. However, Naviarm's weight of 5.75 kg, attached to the user's back, could impact the participants' ergonomics during the task, particularly when leaning forward. Consequently, we opted for STROE [9] as the weight simulation device, as its string-based design allows for easy integration with other haptic feedback devices while minimizing ergonomic concerns.

For collision feedback simulation, various encountered-type devices [8, 25, 164] could be combined with STROE and the gloves. However, encountered-type devices face limitations in simulating collisions between complex geometries. They exhibit latency due to the need for swift movement to a new collision position, which may not align well with our tasks involving frequent changes in collision directions.

Consequently, we selected STRIVE [10] as our collision simulation device. Its flexible design enables collision feedback with low latency in three degrees of freedom. Like STROE, its string-based design facilitates straightforward integration with other haptic feedback devices.

As for grabbing feedback devices, we opted for the commercially available SenseGlove Nova Gloves [135]. These gloves provide kinesthetic feedback on four fingers and have been successfully utilized in a previous study [48]. In the following section, we will give a more detailed description of the devices we chose and how we combined them.

		Grabbing	Collision Feedback								
	Devices	Gloves	Encountered-Type [8, 25, 164]	Virtuose 6D [54]	STRIVE [10]	INCA 6D [122]	Thor's Hammer [67]	EMS [92]	SPIDAR-W [110]	Mantis [18]	Naviarm [93]
Grabbing	Gloves [135]		✓		✓			✓			✓
Weight	GravityCup [32]		✓		✓			✓			✓
	Aero-Plane [75]		✓		✓			✓			✓
	Thor's Hammer [67]		✓		✓		✓	✓			✓
	PropellerHand [12]		✓	✓	✓	✓	✓	✓	✓	✓	✓
	Virtuose 6D [54]		✓	✓	✓			✓			✓
	STROE [9]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	INCA 6D [122]		✓		✓	✓		✓			✓
	Mantis [18]		✓		✓			✓		✓	
	Naviarm [93]	✓	✓	✓	✓	✓	✓	✓			✓
	EMS [92]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 6.1 — Devices for Grabbing, Collision, and Weight Feedback and if they can be used combined.

6.4 The Multimodal Haptic Feedback System

Our haptic feedback system integrates three distinct haptic feedback devices (Figure 6.2 D) to provide the user with tactile sensations of grabbing, weight, and collision impact in a single hand. For the simulation of grabbing and interaction with virtual objects, we employ the commercially available SenseGlove Nova device [135] (Figure 6.2 C), which was introduced in 2019. These gloves can exert up to 20 N force on each finger and deliver vibrotactile feedback through a voice coil actuator.

To simulate the sensation of weight, we utilize the string-based device STROE (Figure 6.2 A). STROE is worn as an extension attached to a shoe, which is then connected to the user's hand via a controllable string. A motor applies force to the string to simulate the desired weight. With its rotatable rod and automatically movable pulley, STROE can generate downward forces independently of the user's hand position. While it can simulate weights up to 720 g, slightly lower than our defined requirement, we found that the limitations of other weight simulation devices outweighed this drawback. As STROE operates based on strings, we can attach its string to the bottom of the SenseGlove.

For simulating collisions with the hand, we employ the haptic feedback system STRIVE (Figure 6.2 B). STRIVE consists of multiple small string-based haptic feedback devices that simulate collision by halting the extraction of the attached strings connected to the user's body. The STRIVE setup offers great flexibility, allowing the placement of STRIVE devices in various locations and connection to different body parts or tools. Similar to STROE, we attach the strings of STRIVE to the SenseGlove. However, it's worth noting that STRIVE devices are fixed to the physical environment, which restricts user movement to a confined area of approximately $1.5\ m \times 1.5\ m$ in our setup. User body rotations are also limited to around 90 degrees in both directions to prevent entanglement of the strings.

We have designed the overall system to be modular, enabling any combination of two of the three devices. Previous research [119] has shown benefits in specific scenarios when using only one type of feedback, reducing complexity when unnecessary. It is also possible to utilize each device

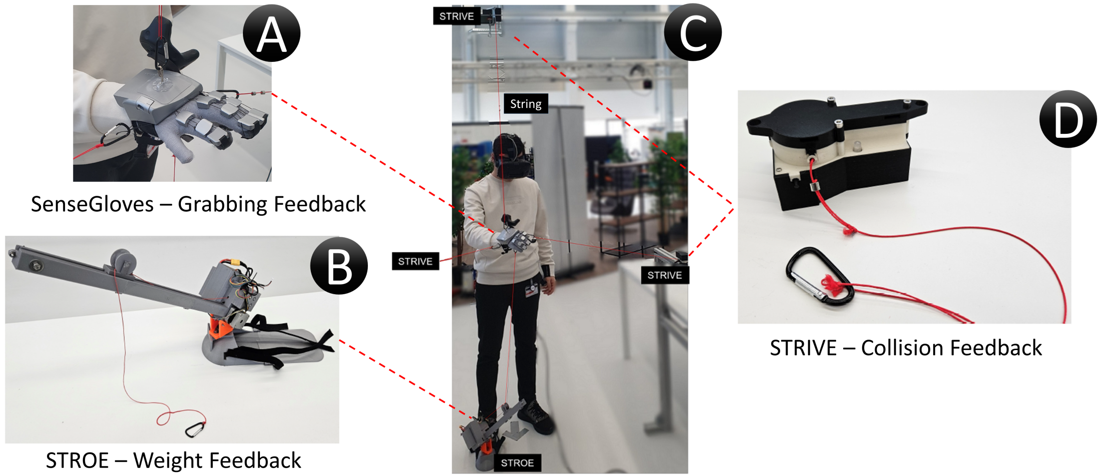


Figure 6.2 — (A) The SenseGlove was used to simulate grabbing feedback. (B) STROE, a string-based device, was employed for weight simulation. (C) The multimodal haptic feedback system incorporated the combination of all three haptic devices. (D) STRIVE, another string-based device, was utilized to provide force feedback and simulate collisions with the user's hand.

individually. However, since existing evaluations of each device exist, we did not consider employing just one device in our system. Instead, we focused on combinations such as STRIVE and the SenseGlove, STROE and the SenseGlove, and STROE and STRIVE. In the last combination, an interaction device is still required. For this purpose, we employed a state-of-the-art VR controller, the HTC Vive controller. We combined all the components by connecting the strings from STRIVE and STROE to either the SenseGlove or the VR controller. Henceforth, we will refer to the SenseGlove as the *grabbing* simulation device, STRIVE as the *collision* simulation device, and STROE as the *weight* simulation device.

6.5 Pilot Study

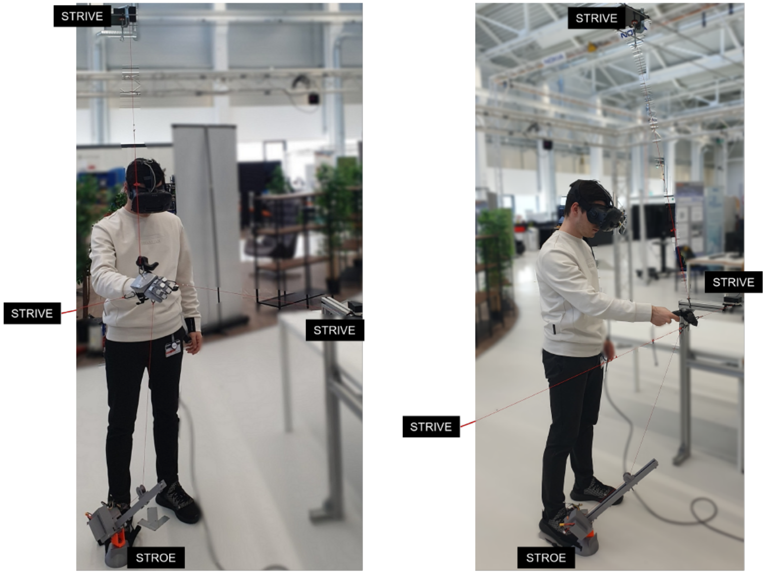
Before conducting the expert study, we conducted a pilot study to validate and refine our haptic feedback system, serving as a proof-of-concept and identifying areas for potential improvement. Four employees from our department participated in the pilot study, providing valuable feedback that encompassed both positive and negative aspects. We utilized this feedback to make necessary enhancements and adjustments to ensure a smooth execution of the subsequent expert study. In the following section, we outline the setup of the pilot study, which mirrors the setup of the expert study.

6.5.1 Study Setup

In our setup, we arranged the collision feedback devices in a triangular configuration, with one module positioned above the user's head and two on the left and right sides. To ensure stability, we securely mounted these modules on an aluminum profile. The distance between the left and right collision feedback devices was approximately 1.5 meters, with a mounting height of around 1.20 meters. This configuration provided a working space of roughly 1.5 meters by 1.5 meters, allowing ample movement during the tasks.

For participants whose dominant hand was on the right, we attached the weight simulation device to their right foot, and vice versa for those with a dominant left hand. To establish the necessary connections, we linked the strings of collision simulation and weight simulation devices to the carabiners on either the grabbing feedback device or the VR controller.

Our setup used the HTC Vive Pro as the VR headset. The tasks assigned to the participants were described in detail in Section 6.2. The software and scenes were developed and implemented using Unity, as depicted in Figure 6.1.



(a) (b)

Figure 6.3 — Left: The study setup with SenseGlove, STROE and STRIVE. Right: The study setup with a HTC Vive Conroller, STROE and STRIVE.

6.5.2 Results

We observed that all participants encountered difficulties with the *grabbing* device when grasping small objects like screws, primarily due to the limited finger tracking accuracy. However, we noticed that the participants achieved better results when employing a tweezer-like motion for grasping. Additionally, the participants mentioned that they required some time to become accustomed to using the *grabbing* device. As a result, we incorporated a brief training session at the beginning of the expert study to familiarize them with the optimal technique for grasping small objects to mitigate the impact of the device's technical limitations.

Two out of the four participants reported experiencing constraints caused by the strings of the *collision* and *weight* devices when rotating their hands. For instance, they encountered difficulties with the *collision* device attached to their left palm while attempting to grasp objects, as the carabiner slipped between their thumb and index finger. In response to this feedback, we developed customized attachment options for each string, considering their directions. Previously, we had used a single attachment position for all strings. Figure 6.2 A illustrates the attachment options.

Another issue highlighted by the participants was the performance of the software simulation. The imported models of the car parts had complex underlying meshes, resulting in a high number of vertices involved in collision calculations. This complexity led to a low frame rate and significant latency in the haptic feedback devices. Consequently, participants could penetrate virtual objects with other objects because the *collision* device halted the interaction too late. To address this problem, we remodeled all tangible objects and other chassis parts using primitive shapes such as boxes, spheres, and cylinders. We tried to ensure the precision of the remodeled objects, thereby enhancing the overall accuracy of the simulation.

6.6 Expert Study

We conducted a user study involving experts from the automotive industry who regularly utilize VR in their work. The selection of automotive VR experts as participants was deliberate, as they are familiar with haptics and are more task-focused than VR beginners, who tend to engage in exploratory activities within the virtual environment. The primary objective of this expert study was to evaluate the advantages, disadvantages, and technical limitations of our multimodal haptic feedback system in the context of a real automotive use case. Additionally, we aimed to determine which setup combinations yield the greatest benefits in performing the assigned tasks, considering that utilizing all three haptic feedback devices simultaneously could potentially introduce complexities in specific scenarios. We employed the same setup and tasks as those used in the pilot study, albeit with improvements implemented based on the insights gained from the pilot study results, as discussed earlier in section 6.5.2.

6.6.1 Participants

We conducted a study involving 12 automotive VR experts, consisting of ten male and two female participants. The age of the experts ranged from 25 to 60 years. All participants were actively employed in the automotive industry and utilized VR technology as part of their work. Among the participants, one had less than one year of VR experience, seven had between 1 and 4 years of VR experience, and four had more than ten years of experience with VR.

Regarding the frequency of VR usage, five participants reported using VR several times a day, two participants used it multiple times per week, three participants used it once a week, and two participants used it once a month.

Furthermore, out of the 12 participants, 11 had prior experience with haptic feedback devices before the study. All 11 participants who had previous experience with haptic feedback devices had used STRIVE at least once in their work environment. Additionally, one participant had previous experience with STROE.

6.6.2 Measurements

In total, we had four conditions: *Weight* (**Wei**) + *Grabbing* (**Grab**) + *Collision* (**Col**) (Figure 6.3 (a)), **Wei + Grab**, **Wei + Col** (Figure 6.3 (b)), and **Grab + Col**. We did not evaluate only one device, as there are already evaluations about the devices and their benefits.

We conducted the user study using a within-subject design because it was necessary for each participant to test all four conditions to get a complete impression of the different combinations of haptic feedback devices. To minimize learning effects, we used a Latin square to shuffle the order of the conditions for each participant during the study.

Since the user study focused primarily on haptic feedback, we based our questions on *Defining Haptic Experience* [78], which guides the design and research of haptic systems. We did not fully query the questionnaire, as some questions were redundant. We asked about **intensity** (the overall perceived strength of feedback), **timbre** (overall tone, texture, color, or quality of the feedback), **utility** (the ability of haptics to benefit user experience), **causality** (how easily a user can relate haptic feedback to the source of interaction), **consistency** (ability to provide reliable haptic feedback), **saliency** (noticeability of the haptic feedback as it relates to its purpose), **harmony** (how well the haptic impressions fit together), **immersion**, and **realism**. We made notes of their answers. Additionally, they had to answer each question on a 7-point Likert scale, where 7 was the most positive result, and 1 was the most negative.

At the end of the study, we asked for their positive or negative impressions, suggestions for improvement, which haptic feedback was individually most important for completing the tasks, and which combination of devices seemed to make the most practical use. These questions were related to the current state of the devices. Additionally, we asked the participants to imagine the same setup but with no technical device limitations or problems. We asked them again which combination and device would have the highest benefit. These speculative study questions can inspire new design ideas, concepts, and directions and are common in the human-computer interaction community [158]. By envisioning future scenarios, designers can push the boundaries of what is possible, explore unconventional interactions, and think creatively about user experiences that may not exist yet. We added these speculative questions to reduce the bias of technical limitations and to find out how strongly the technical limitations influenced the participants.

Our results are based on an exploratory proof-of-concept study and mainly focused on the qualitative feedback of the experts. Qualitative analysis is common in the human-computer interaction (HCI) community [89], which desires to gain an in-depth understanding, contextualize user behavior, explore new phenomena, and maintain a human-centered approach. By harnessing the power of qualitative research methods, HCI researchers seek to uncover valuable insights that inform the development of user-centric technologies and enhance the overall user experience. We used an estimation-based approach with effect sizes and confidence intervals for the quantitative survey data to interpret our results. Statistical analysis practices recommend this approach [16], which overcomes several limitations and biases of classical null hypothesis testing with p-values (NHST) [38, 44]. Cumming and Finch guide how p-values can be estimated from 95% CI plots [39].

6.6.3 Results and Discussion

The results were divided into two categories: haptic questions and additional questions. Given that our study was exploratory, our primary emphasis was on gathering qualitative feedback in cross-relation to the results of the questionnaires.

Haptic Questions

Figure 6.4 presents the results of the average 7-point Likert scale answers for each condition. The average values for each question in each condition are as follows: 5.0 (SD: 0.38) for **Wei + Col**, 4.1 (SD: 0.37) for **Grab + Col**, 4.2 (SD: 0.35) for **Wei + Grab**, and 4.0 (SD: 0.28) for **Wei + Grab +**

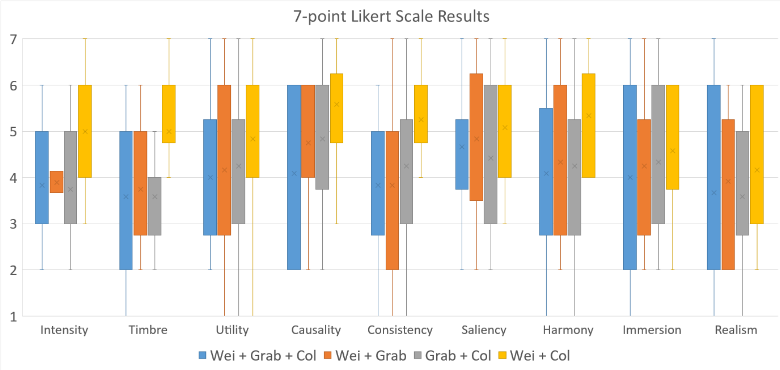


Figure 6.4 — The average values on the 7-point Likert scale for the haptic questions.

Col. Notably, the condition **Wei + Col** performed the best in each haptic question. In the following, we will list our major findings, mostly based on the qualitative feedback of the experts.

The grabbing device caused issues, particularly when handling small objects. The experts highlighted problems related to grasping, which impacted all haptic-related aspects we inquired about. This problem was evident through consistently lower average scores whenever grasping was involved. The **Wei + Col** condition that does not involve the grabbing device received ratings of 0.8 to 1.0 higher than the others. Moreover, we collected substantial qualitative feedback that provided evidence of participants struggling with grasping and how it influenced their experience across different haptic dimensions.

Of the 12 experts, ten criticized grabbing in various conditions requiring grasping. Regarding realism, four participants in the **Wei + Grab** condition criticized the feedback associated with grabbing, as it compromised the sense of realism. Regarding the question related to timbre, one participant explained, *"It was very difficult to grasp screws but easier with larger objects."*

However, in the **Grab + Col** condition, two participants mentioned that they perceived haptic feedback as unnecessary when dealing with larger objects since *"the spatial impression was already well-established."* Participants expressed that compared to the condition without grabbing, the intensity was *"much more pleasant because the strong influence of grabbing was not present,"* and the *"controller gave a more accurate impression due to its simplicity."*

Additionally, some participants shared their experiences with the controller and stated that when *"the focus was not on grabbing, the immersion was higher, although it felt more technical, making it less immersive but more practical."* Other participants compared the usefulness of grabbing with other haptic feedback sensations and mentioned that *"the more frequently grabbing was used, the more evident it became that it was not as useful, and that weight was actually more important."* However, we also received positive feedback about grabbing, where two participants noted the absence of grabbing, expressing that *"at times, adjusting the grip on other objects added to the realism."*

The main problem reported about the grabbing feedback device was that the expert's finger pose did not match the virtual finger pose. They expressed discomfort and explained that it became more distracting than helpful. Chen et al. surveyed hand pose estimation, exploring wearable sensors and computer vision-based methods [31]. They also encountered challenges with data gloves and wearable sensors, particularly in cases where there were variations in user hand sizes—a concern we can corroborate. Computer vision-based tracking methods show promising potential but face difficulties when occlusion occurs or the hand is outside the camera's field of view. One possible improvement we envision is combining both methods to enhance accuracy.

Simultaneous usage of all feedback types was often assessed as excessive. When we combined all feedback types, most experts agreed that there were *"too many impressions at once."* We observed that there were various reasons behind this sentiment.

One negative aspect mentioned by the experts was that they described the setup as *"too distracting and restrictive."* One participant suggested that *"reduced individual feedback would be better."* Two of the three haptic feedback devices were string-based, resulting in four strings when using them together. In the **Wei + Grab + Col**, this was considered to restrict the necessary movements partially. Interestingly, however, the **Wei + Col** condition, which also utilized four strings, was rated as the best feedback combination. This fact might indicate that the strings alone might not be the main problem. Instead, the additional effort required for grasping feedback might have resulted in mental overload, making them feel restricted and distracted.

Another negative aspect mentioned by the experts was the setup effort. Some experts explained that this combination is *"theoretically super useful in the ideal case, but in the current case, it required too much effort to get it almost right."*

Regarding the causality questions, the experts had difficulty identifying the source of haptic feedback due to the multitude of impressions and the need to evaluate each feedback type individually, which was challenging due to the combined feedback's confusing nature. However, two participants did not perceive the problem of identifying the source as negative and did not have any issues with the combination of all three feedback types. They stated that *"it was not bad because it all worked together so well that they could no longer identify the individual devices."*

Weight and collision feedback in combination yielded the best results across all haptic dimensions. Regarding the results obtained from the 7-point Likert scale, the average values of the **Wei + Col** condition were consistently the highest for each haptic question. We previously mentioned that participants encountered difficulties with the grabbing device. However, when considering the qualitative feedback from participants, it becomes clear that the absence of grabbing feedback was not the sole reason for the positive feedback in the **Wei + Col** condition.

Many participants stated that the haptic feedback *"complemented each other very well,"* and nine participants expressed that this form of multimodal haptic feedback felt useful. One participant provided further insight into the benefits of collision and weight simulation in the VR task, explaining that it provides *"an impression of the component and more information about what you are actually doing."* Another participant highlighted why they rated the **Wei + Col** combination as the best, stating that *"the direction can be estimated, and the weight force gives an impression of realistic holding while still allowing free movement in the hand."*

Regarding the causality question, six participants in the **Wei + Col** condition reported reliably identifying the source. One participant mentioned that the weight sensation initially felt very realistic but criticized that it lost its realism during movements.

Interestingly, four participants criticized the realism in the **Wei + Col** condition due to the absence of grabbing feedback. However, we observed in other conditions that grabbing feedback reduced realism, emphasizing the importance of the feedback type and indicating that it is not yet adequately simulated.

The combination of haptic feedback devices with continuous and abrupt feedback was perceived negatively. Our weight simulation feedback device continuously applies forces to users when they hold objects, allowing for different levels of force strength. On the other hand, the collision device only provides abrupt impact feedback, which participants referred to as on/off feedback.

During our study, we observed that participants criticized the combination of these two different approaches. Three participants faced difficulties due to the distinct nature of the feedback devices, as indicated by the comment: *"very different in that one is continuous, and one is collision on/off."*

As a result, the harmony of the **Wei** and **Col** combination was criticized, and the combination of **Wei** and **Grab** was preferred in terms of harmony because *"the two feedback types go well together as they do not have on/off forces but provide a consistent feeling."*

Regarding causality, some participants mentioned that the **Wei + Col** condition was slightly more distinguishable than the **Wei + Grab + Col** condition because the overall impression was lower. Still, the devices felt more intense individually because of their continuous and abrupt feedback types.

Nevertheless, the **Wei + Col** condition was still rated as the best. Although participants criticized the difference between continuous and abrupt feedback types, they still recognized more benefits in this condition than the others.

Weight simulation was perceived different among conditions We observed variations in the participants' perception of weight simulation depending on the condition. In the **Wei + Grab** condition, three participants felt that the intensity of the weight simulation was too weak, despite the weight of the objects remaining unchanged across conditions.

In the **Wei + Col** condition, where participants used a controller connected to the weight feedback device, we noticed that a few participants perceived the weight of the objects as heavier compared to the other condition. One participant mentioned that the weight simulation *"felt too pronounced despite being lighter than reality."*

One possible reason for this behavior could be the different attachment points of the weight simulation device to the user's hand or controller. One participant suggested that *"the weight of the controller may be applied too far forward, causing it to tip over."* We believe this variation in attachment points could influence the participants' perceptions of weight simulation.

Additional Questions

Regarding our additional questions, we collected further major findings:

Collision feedback is perceived as the most important and useful feedback type in our current setup. We first addressed whether the experts would use the haptic feedback system in their daily work. Of the 12 participants, nine stated that they would utilize collision feedback, while four experts would also opt for weight simulation in certain special use cases. However, it was noted that weight simulation is only applicable in specific and less frequent scenarios, as expressed in the following quote: *"It depends on the use case. For accessibility and general tasks, collision and controller feedback are sufficient. For achieving realism, weight simulation becomes important. However, precise grabbing is not as crucial. Regarding interactions with interior components, grabbing feedback can provide more specific feedback."* Only one participant preferred using the **Grab** feedback, particularly when dealing with larger objects.

We also inquired which device assisted participants in their tasks most. Every participant agreed that collision feedback offered the highest benefit. They mentioned that collision feedback enhanced their spatial perception and gave them a better understanding of the component, stating: *"I get an impression of the component and more information about what I am actually doing."*

The importance and usefulness of grabbing feedback are influenced by technical limitations. We revisited the question regarding which haptic feedback types the experts would use in their work, assuming there are no technical limitations in the haptic feedback devices. The results revealed some differences compared to the previous responses. All 12 participants would utilize collision feedback without any technical constraints. Nine participants would also incorporate weight and grabbing feedback if there were no technical limitations, diverging from their previous responses. One participant mentioned considering a combination of two devices depending on the specific use case.

Furthermore, we repeated the question about which feedback type was most helpful, instructing participants to assume that the devices do not have technical limitations. The results varied from the previous responses. Six participants rated collision feedback as the most important. Five preferred grab feedback, and one person favored weight feedback.

The findings indicate that grabbing feedback emerged as one of the most important types of feedback without technical limitations. However, it is worth noting that our grabbing device, SenseGlove, currently stands as one of the leading commercial devices, with few alternatives offering kinesthetic feedback [28]. We observed that the primary issue with feedback gloves primarily stemmed from inaccurate tracking rather than the overall kinesthetic feedback.

The fast and easy setup of the system was a major positive aspect. When we asked the experts about the positive aspects of the haptic feedback system, four participants emphasized the fast and easy setup of the system, particularly highlighting the benefits of collision feedback. While the experts did not change the setup between each condition themselves, they observed us making the necessary adjustments.

On average, the setup change took less than one minute, as we only had to attach the strings of the devices accordingly. This quick and simple setup process was in stark contrast to feedback devices like exoskeletons [56] or other wearable feedback devices [14, 110, 117]. The experts highly rated the efficiency and ease of the haptic feedback system setup. However, a few experts described the setup of all three feedback types as requiring too much effort compared to the combination of two feedback types.

Technical limitations influence the utility of combining haptic feedback The final question aimed to determine the most useful combination of haptic feedback devices. Nine participants agreed that the combination of collision and weight feedback was the most important. Two participants perceived the combination of all three feedback devices as crucial, while one favored collision feedback with grab feedback.

When asked the same question without technical limitations, the responses varied. In this case, 10 participants indicated that combining all three devices would be the most useful. One participant explained that they would exclusively use the system for advanced VR workers, as they mentioned that *"inexperienced people tend to have an 'aha' experience with VR and then engage in unwanted actions like walking around the car, which is not possible with this system."* Two participants rated the combination of collision and weight feedback as the best choice without technical limitations.

Obviously, the more haptic feedback modalities available without technical limitations, the better. However, it is important to note that technical limitations currently constrain our haptic feedback devices and others. Therefore, employing a flexible multimodal feedback system proves advantageous, as users can choose the specific haptic feedback modalities based on their respective limitations. Users must consider the *"relationship between effort and benefits,"* a point emphasized by one of the participants, which may vary depending on the specific use case.

Therefore, we believe that our flexible feedback system could apply to the automotive industry and other domains, such as the gaming sector. Games that involve extensive movement and object interaction may not be compatible with the combination of all three devices. However, the weight and grabbing simulation device, or their combination, could prove effective in such games. Additionally, there are scenarios, such as surgery simulations, where users predominantly remain in a fixed position or move within a limited area. In such cases, the entire system could also function seamlessly.

6.7 Limitations

During our study, we encountered different limitations. First, our study only focused on a one-handed use case, which could pose challenges for tasks requiring bi-manual interaction. The strings of the collision and weight simulation device could become entangled in such scenarios. This limitation should be considered when extrapolating our findings to bi-manual tasks.

Another technical limitation of our system is limited mobility. Participants were restricted to walking within a confined area measuring approximately $1.5m \times 1.5m$. Moreover, complete body rotations were constrained due to the string-based technology. However, it is important to acknowledge that movement is predefined in most automotive use cases and requires less variation in different directions.

It is important to highlight that our investigation primarily focused on the devices' hardware, neglecting the software aspect of combining feedback devices. We believe most of the devices can be combined in their software, but detailed information about the code is often lacking.

Additionally, it is worth mentioning that most participants had prior experience with the collision simulation device STRIVE, which could introduce a bias. However, we do not believe this experience influenced our results, as the STRIVE device does not have a training or learning effect.

6.8 Conclusion

Our research was focused on developing a multimodal haptic feedback system specifically designed for automotive VR tasks. The main objective was to combine suitable haptic feedback devices to provide simultaneous weight, grabbing, and collision sensations. The chosen devices were carefully selected as the most suitable options for our study.

We conducted two user studies to ensure optimal feedback and refined our concept. An initial pilot study aimed to fine-tune the haptic feedback setup and validate our approach. Building on the insights gained from the pilot study, the second study involved twelve VR experts from the automotive industry. The primary goal of this study was to determine practical limitations and identify the combinations of haptic feedback that delivered the most significant benefits in the context of automotive VR tasks.

The results of our study indicated a clear preference for the combination of weight and collision feedback, primarily due to technical limitations associated with the grabbing device. However, it was evident that the participants recognized the importance of grabbing feedback without such limitations. These findings underscore the need to address and overcome technical constraints to enhance the haptic experience.

CHAPTER 7

Discussion and Limitations

We conducted four case studies to evaluate the practical usage of haptic research in VR environments. These studies allowed us to abstract and clarify the problems and requirements, leading to the evaluation of three new different haptic feedback devices and SenseGlove for industrial applications.

We found that the PropellerHand device was the least suitable for industry use, as its technique-driven approach did not consider the specific environment and requirements in which it would be utilized. In contrast, the problem-driven approach led to two devices with better results. Although we applied the same approach for both, we discovered that STRIVE was more suitable than STROE for industrial use. STRIVE was praised for its simplicity and flexibility in usage, resulting in more than 15 automotive VR experts using it for their daily VR tasks. Additionally, STRIVE is currently installed at 5 locations within a large automotive company. One key aspect that contributed to STRIVE's success was that the VR experts derived more benefits from collision feedback than weight simulation based on their automotive VR use cases.

Throughout our three-year research experience in the automotive VR field, we identified several other aspects to consider when building haptic feedback devices suitable for industrial use and integrating them into practical usage. Drawing from this knowledge, we have compiled a list of considerations to aid other researchers in developing more suitable haptic feedback devices and effectively integrating them into real-world applications. These considerations were derived from case studies, interviews, demos, and observations and are likely applicable to other industries. Lastly, we describe the limitations of our work.

7.1 Considerations for Moving Haptics Research into Practice

Over three years, we researched how to implement haptics research in practical settings. During this time, we interviewed over 25 virtual reality experts from the automotive industry, observed more than 45 use cases, demonstrated our haptic feedback devices to over 200 individuals and collected their feedback, and analyzed 105 kinesthetic haptic feedback devices through literature reviews.

We divided our research into case studies, which included the stages of requirement analysis, haptic feedback device development, user studies, and integration into a larger company. Throughout our research, we gathered considerations for each stage to support other researchers in implementing haptic research in practical settings. These considerations helped us in our process.

7.1.1 Considerations for Requirement Analysis

The initial stage of our approach involved conducting a requirement analysis. This analysis aimed to gain a thorough understanding of the problem and the tasks involved and to gather the necessary requirements for developing an appropriate haptic feedback device. This stage is important, as it sets the foundation for the entire process. There is a lot of research on requirement analysis. For example the ISO 13407, which provides guidelines for human-centered design processes in interactive systems [73], helped us with our requirement analysis process. During this phase, we gathered considerations. On the one hand, we want to highlight aspects of the state-of-the-art requirement analysis process that supported us. On the other hand, we want to summarize aspects that are focused on haptic feedback systems.

Use Cases Observations: There are various approaches to gather information and derive requirements for building suitable haptic feedback devices for the industry, such as focus groups, interviews, or observations [55]. Each method has its benefits and drawbacks.

Through interviews, we noticed that experts sometimes struggle to provide accurate answers or express a need for a perfect haptic feedback system. For example, when we asked if they frequently turned around during their use cases, most replied with a "yes." However, our observations revealed that they did not rotate that much in reality. As a result, observing them during their use cases yielded more reliable information than solely relying on interviews.

To gather as much information as possible, we observed experts during their use cases and took notes on their actions. Additionally, we encouraged them to think aloud [150] during their tasks to gain insights into their decision-making process.

Moreover, we collected data by recording their movements, collisions, and interactions. This involved measuring various parameters in 32 different use cases, such as hand velocity and acceleration, the distance between the head and hands, the distance between both hands, view direction, hand position, rotations, and the amount and duration of collisions and interactions (e.g., holding and moving objects). This data helped formulate part of our requirements. For example, movement speed data was used to determine the required minimal latency of the device, and collision duration influenced the choice of the solenoid for STRIVE, as it has temperature limitations during activation.

In the literature, several aspects are considered for conducting successful observations [55]. Below, we list these aspects and describe the configurations we chose to provide some considerations:

- **Structured vs. unstructured:** Structured observations are specific and planned, using a fixed structure to reduce subjectivity. However, we opted for unstructured observation to be more exploratory and find insights we had not planned for.
- **Participative vs. non-participative:** During our observations, we focused on being observers without actively participating in the

tasks. This way, the experts performed the tasks independently, free from external influence.

- **Open vs. hidden:** There is an option to not reveal the observer's identity to the participants. However, we explained to the experts that we were observers so they would feel comfortable explaining their steps and problem-solving approaches.
- **Field vs. lab:** The observation can occur in a laboratory or working environment. For evaluating a hardware prototype, we used the laboratory setup to reduce bias and focus on the technical proof-of-concept. When observing the experts' tasks, we chose the field environment, as the real-world environment, such as available space for free movement, also influenced the requirements.

Understandable and Right Questions: Between use case observations, expert interviews are a common method to collect requirements [95]. We noticed that using both methods gave us a better picture of the users' needs and problems. In contrast to observations, we collected new requirements we could not observe, such as the wish for a small contact area to reduce hygienic problems.

Interviewing experts about requirements may seem simple, but we have noticed that asking the wrong questions or asking them in an unclear manner can lead to incorrect or unhelpful answers. It helped us to ask questions clearly and understandably because, on the one hand, industry experts may not be familiar with haptics, and on the other hand, they may not know the answers if the questions are not clear.

We found out that, instead of asking for haptic feedback properties directly, it often worked better if we used the user's language, e.g., by asking if the texture of objects is important or if they apply forces to objects. Doing so gave us more concrete problem descriptions and we could translate them into a requirement collection.

Additionally, it helped us to provide examples that match their use cases. For example, in the automotive industry, we explained the difference between passive and active feedback by asking if they want to feel when a door hits their legs when it gets opened (active) or just feel the resistance of closing the door (passive).

In our experience, asking the following questions helped us collect the requirements and understand the problem more clearly.

- Is the texture of an object important?
- Do you have to feel the temperature of objects?
- Do you need to feel the softness of objects?
- Do you apply forces to objects or do objects apply forces to you?
- How much do you have to walk?
- Do you have to rotate?
- Do you interact with both hands?
- Where do you have to feel haptic stimulation?
- Is torque stimulation required?
- How long are you planning to use the haptic device in one session?
- What is the maximum velocity of your movement?
- How many degrees of force feedback are necessary?
- Does your movement have to be stopped?
- Do you need to feel the resistance of objects or interactions?

We discovered that experts often provided maximum values instead of average ones. For instance, when we inquired about the number of degrees of force feedback they required, their consistent response was either three or six degrees. However, upon observing their use cases, we noticed that they needed less than three degrees of force feedback in most instances. To ensure the accuracy of the requirements, we conducted additional use case observations, allowing us to gather more details and better understand their actual needs.

Different Haptic Solutions: During the initial stage of our requirement analysis, we observed that most of the involved experts were unfamiliar with haptic devices and were unaware of the possibilities they could offer. To address this, we introduced the experts to various haptic feedback devices, preferably by demonstrating a prototype. However, demonstrating a prototype may not always be feasible, so pictures or videos effectively explained the devices to them. Additionally, showing mockups of the prototype we planned to develop and comparing them with existing devices proved helpful. This approach allowed us to comprehensively understand what would work and what would not. For example, initially, we believed that the experts would highly appreciate an electric muscle stimulation (EMS) feedback system, similar to the one presented in Lopes et al. [92]. However, when we showed them the EMS system, they highlighted several drawbacks, such as the long calibration and setup time, making the system unsuitable for practical use. They also raised hygiene concerns, which we had not considered before. Compared to other approaches for collecting requirements, our method led us to identify new requirements that we could not have gathered with other methods. For instance, we discovered that experts considered some devices unhygienic, uncomfortable, or too complex for their needs.

Requirements-Prioritizing and Focusing: Currently, haptic research is still far from developing a perfect haptic feedback device that can simulate all haptic stimuli across the entire body without any restrictions. We discovered a desire for such an ideal haptic feedback device through interviews with experts. However, given the current technological limitations and the extensive time required to achieve it, our primary objective was not to create this perfect device. Instead, we focused on building a haptic feedback device that can cover most use cases while providing substantial benefits. We recognized that meeting certain requirements may mean sacrificing some other attributes. For example, during STRIVE's development, we decided not to use motors for active haptic feedback to maintain mobility.

Prioritizing requirements is a common approach in human-centered design processes for interactive systems [55]. This approach helps determine which requirements should be implemented immediately, soon, in the future, or which are out of scope. We used a similar approach to prioritize our requirements, focusing on maximizing the number of users who benefit from our haptic feedback system. Therefore, ensuring flexible usage was our most important requirement, as it enables more experts to use the haptic feedback system. This prioritization guided us in developing an early prototype that could be used by more users, allowing us to collect early feedback for further improvements.

Additionally, when considering technical requirements, we found that concentrating on average values of quantitative requirements rather than the maximum values was helpful. For instance, we observed that the average hand velocity was 36 cm/s, whereas the maximum value was 120 cm/s. Focusing on the average value gave us a higher tolerance for the actuator's performance. If it is impossible to observe use cases, we recommend rephrasing the questions in paragraph 7.1.1 to implicitly inquire about the average values.

7.1.2 Considerations Device Development

Once we collected the experts' requirements, we proceeded with the development of the haptic feedback devices. Given the technical nature of this step, we refrain from considering technical aspects, as they may vary depending on the specific haptic feedback device being built. Nevertheless, we provide considerations on the process that aided us in developing a suitable haptic feedback device.

Flexible Device Usage: After collecting the requirements from different teams of experts, we observed that each had unique use cases with distinct requirements. However, creating multiple haptic feedback devices for each use case was not feasible. The experts emphasized that they did not want multiple devices due to increased complexity and cost. Therefore, during our device development, we focused on keeping the technology flexible, allowing it to be used for different use cases.

In other research areas, keeping systems flexible is already explored. Such as in software engineering, where flexibility means the ability to allow conducting certain changes to a system with acceptable effort [109]. There, solutions exist, such as modifications via metadata or component parameterization. However, we noticed we achieved flexibility during our STRIVE development when STRIVE could cover different use cases. We achieved this by designing STRIVE to be portable and adaptable, allowing it to be placed anywhere, and allowing the user to choose which body parts should receive haptic stimulation.

Rapid Prototyping: Modern technologies like 3D printing and CAD development enable developers to quickly construct and assemble devices. Adopting this approach to focus on rapid prototypes proved beneficial, as presenting early versions allowed us to receive valuable feedback sooner. Rapid prototyping is now a common method in product development and has been widely used in interactive systems development [51, 23]. However, when showing the experts early prototype versions, we encountered the challenge of the uncanny valley. The uncanny valley refers to the human response that shifts from empathy to revulsion when encountering a robot or haptic feedback that mimics human-like behavior but fails to achieve authenticity [106, 22]. One example occurred during an automotive VR use case with experts using STRIVE. The task was to ensure the visibility of a screw in a specific position where the head had limited space. We used an early prototype of STRIVE. Therefore, the VR software had a bug that caused the virtual head position to have an offset from the real head position. Consequently, the experts felt collisions too early and had the sensation of having a gigantic head. This bug hindered the effectiveness of STRIVE and confused the experts, resulting in negative feedback and rejection of STRIVE. To avoid this issue, we carefully considered the timing of presenting prototypes to users, ensuring that the haptic feedback they experienced did not fall into the uncanny valley.

During the early stages of STRIVE's development, we noticed that some participants became disturbed rather than supported due to high latency and feedback mismatches. To avoid this, we refrained from showing very early prototypes to users to prevent negative experiences that might not offer meaningful feedback. Moreover, when providing the haptic feedback device to the experts, we clarified that it was an early prototype and that some issues might arise. This transparent approach encouraged the experts to be more understanding and cooperative when providing feedback, leading to more valuable insights and suggestions instead of becoming frustrated with potential limitations.

Fast and Simple Usage: Currently, vibration feedback is the most commonly used haptic feedback approach due to its easy integration into devices like VR controllers and its simple usage, requiring no setup time compared to complex haptic feedback systems like exoskeletons. However, in our problem domain, vibration feedback falls short, and we need alternative solutions. Therefore, prioritizing a simple and fast user experience has been crucial, as most VR experts have emphasized their preference for a less perfect haptic feedback device over one with a long setup time or a complicated interface.

To achieve a streamlined and efficient usage experience, we have tried to simplify the haptic feedback system as much as possible, and even small changes have made a substantial difference. For instance, optimizing the calibration process is essential in reducing setup time. The simpler and quicker the process, the more likely the haptic device will be used. Simple adjustments, such as replacing Velcro strips with clips to attach the strings of STRIVE to objects more swiftly, have reduced our setup time and enhanced the user experience. Several add-ons have been implemented to further reduce the setup time for STRIVE. For instance, we incorporated a button in the setup tool that allows users to power off all STRIVE devices simultaneously, eliminating the need to manually turn off each device. This straightforward addition has substantially improved the setup process. Additionally, we have utilized Bluetooth Low Energy instead of Bluetooth Classic, simplifying the connectivity process between STRIVE devices. With this feature, users no longer need to go through a manual pairing process, resulting in a faster and more efficient setup.

Effort vs. Benefit: During our research, we observed that considering the relationship between the effort required to use a feedback device and its benefits has been instrumental in our design process. If the effort required to use the device is high, its benefits must be substantial, and vice versa. Therefore, we consistently compared the effort required to the benefits gained when developing a haptic feedback device.

For example, using one STRIVE attached to a user's belt requires minimal effort. However, its benefit is limited since it can only offer haptic feedback in one degree of freedom. Nevertheless, with one STRIVE, we were able to strike a balance between the effort and benefit ratio, which convinced some users to adopt the device for their specific use cases.

In general, when building a haptic feedback device that may be complex, its benefits must be substantial. Otherwise, users may not see the value in using the device.

7.1.3 Considerations for User Studies

To proceed, we gathered considerations for the user studies. During these studies, we tested and evaluated our haptic feedback devices to gain new insights that could help us improve them.

Pilot Studies with Non-Experts: During our early development stage of STRIVE, we noticed that it helped us to early test our current prototype with real users to evaluate its proof of concept and technical limitations. However, asking experts for every new prototype version is nearly impossible or inefficient, as the experts only have little time. Nevertheless, we could quickly recruit non-experts sufficient for general feedback to improve the prototype further.

Qualitative Feedback Based on Real World Use Cases: After reviewing the literature, we noticed that most studies evaluating new haptic feedback devices rely on quantitative data to describe their benefits. Currently, several haptic questionnaires are available to assess such devices, such as those developed by Kim et al. [78] or Maggioni et al. [94]. While these questionnaires provide a comprehensive overview of general feedback, they fail to determine the device's effectiveness in real-world industrial use cases.

We observed that obtaining qualitative expert feedback provided us with more useful information. In particular, engaging them in conversations that allowed them to relate the device to their actual work resulted in even more valuable feedback. For example, in our case with STRIVE, we asked the experts for feedback about its usefulness in their real use cases. One expert told us: "In reality, when I want to bolt this part, I would lean myself on the object. Here, I know I could not do that." This feedback helped us identify a new improvement for STRIVE - the ability to lean on virtual objects.

VR Beginners vs. VR Experts During our studies and observations, particularly when VR users used our haptic feedback devices, especially STRIVE, we noticed a difference in device usage between VR beginners and VR experts.

When VR beginners used STRIVE for the first time, especially if it was their first time using a VR headset, we observed that they were often impressed by the virtual feedback and tended to explore the VR environment extensively. Even if they had an automotive VR task, they sometimes got distracted by the VR experience's novelty and played around in the virtual space without fully focusing on the actual task. This behavior presented a challenge with STRIVE because we had set it up to provide haptic feedback for the VR task and not for additional haptic simulations, such as on other body parts or additional degrees of freedom. As a result, this behavior influenced their impression of STRIVE, as they wanted to feel haptic feedback that was not being provided.

On the other hand, VR experts tended to be more task-focused and did only what was required for the specific task at hand. In this case, the feedback was generally more positive, as STRIVE was set up to provide precise feedback for the exact task they were performing. Therefore, it is crucial to consider whether a participant is a VR beginner or expert, as their opinion about the haptic feedback device could depend on their VR experience and familiarity with such devices.

Expert Data for Studies: We found that gathering extensive feedback from various sources is essential to enhance the haptic feedback device. During our research, we discovered that even team members with identical tasks provided differing feedback, emphasizing the importance of considering multiple perspectives. We also observed that testing the prototype using engineers' specific use cases and data yielded valuable insights. It was evident that attempting to generalize feedback from one use case to others posed challenges for the users.

Furthermore, we found that experts' feedback was more precious when the data pertained to their own work. For instance, in our company, experts were responsible for specific car models. When we demonstrated our haptic feedback device, which they used in a use case related to their car, their feedback on its usefulness was much more detailed than a car they were not responsible for. For example, in a reachability study, where our experts had to reach an object inside a car, STRIVE stopped their thighs when it collided with the virtual car. We conducted this use case with different cars and noticed that when the experts were responsible for the car, they gave us more feedback. The more insights were because the virtual car's height was identical to the physical prototype's height, with which they had extensive experience. As a result, they could confidently tell us that it felt correct based on their interactions with the real physical prototype. In contrast, when the experts were not responsible for the car and had less experience, they felt less confident in providing precise feedback.

7.1.4 Considerations Integration into a Company

Creating and developing a new haptic feedback device and evaluating its benefits is just the beginning and a prerequisite for integrating it into practice. However, a substantial amount of effort must be invested to integrate it into a company. In this regard, we have compiled several considerations that helped us in this process.

Essential Haptic Feedback: Depending on the specific use case, a full-body haptic feedback system that simulates all forces and torques in every direction may not be necessary, especially considering that such a system is currently beyond our reach technologically. Therefore, it is essential to determine which aspects of haptic stimulation are crucial for each particular use case. During our observations, we noticed that many people feel uncomfortable when someone stands in front of them while using a VR headset, especially if additional equipment is required for haptic feedback. As a result, simplicity and minimalism are often preferable. In the automotive sector, where components are mostly made of metal, the need for simulating varying levels of softness is often unnecessary. In many cases, a passive haptic feedback device proved sufficient for our use cases. Thus, it is valuable to identify common properties among different use cases and focus on specific haptic simulations while maintaining flexibility.

With STRIVE, we prioritized user control and allowed users to decide how much haptic feedback they need and where they need it. Through investigating various automotive use cases, we discovered that forces in only a few degrees of freedom were necessary for many scenarios. This knowledge guided us in identifying the required amount of haptic feedback and allowed us to concentrate on critical feedback simulations to reduce complexity.

Research Push Solution: There are two solutions to connect experts with a new haptic feedback device. First is the “employee-pull” solution, where experts request a new haptic feedback device. Secondly, the “research-push” solution, where researchers advertise the new haptic feedback device to the experts.

During our research, we discovered that the experts were unfamiliar with haptics. Consequently, they could not request new haptic feedback devices as they did not know of their existence. To address this, we introduced the experts to haptic feedback devices and explained how they could benefit from using them.

Furthermore, we observed that gently reminding the experts to use the haptic feedback device resulted in a better integration, as they may have other tasks to attend to and forget about the haptic solution.

Clear Benefits: In the industrial sector, we have observed that engineers often face time pressure and aim to complete their tasks as efficiently as possible. As a result, many of them resort to using 2D desktop solutions to solve their tasks, even though using VR could yield more reliable results. The hesitation to adopt VR is primarily due to the perception that VR requires more effort and setup than a simple 2D screen. Additionally, incorporating a haptic feedback system adds an extra layer of effort, requiring setup and calibration.

To encourage engineers to embrace haptic feedback systems, explaining the substantial benefits they offer is important, which may not be immediately obvious. One effective approach is allowing experts to perform their use cases with and without haptic feedback. By doing so, the benefits of haptic feedback become more apparent.

For instance, in a specific use case where experts had to assemble a car component in VR with limited headspace, we connected STRIVE to the users' heads. After performing the task with haptic feedback, we asked them to repeat it without it. This comparison clearly showed that without haptic feedback, their head position often went inside the virtual car components, making it difficult to assess the use case accurately. In contrast, with haptic feedback, they could navigate the space more effectively and precisely carry out the task. Such hands-on experiences can be helpful in demonstrating the advantages of haptic feedback systems.

Setup and Software Support: When we integrated STRIVE into the expert's workflow, we noticed providing smooth installation and technical support was necessary, especially when experts had little experience with STRIVE. We helped them by offering hardware support to assist them in setting up and running the devices.

Initially, we provided extensive support to help experts use the feedback device with minimal effort and highlight its benefits. This approach motivated them to become interested in using the device independently and more frequently.

Unchanged Workflow: During our research, we identified that maintaining the experts' workflow mostly unchanged was a crucial aspect of seamlessly integrating STRIVE into employees' work routines. Since haptic feedback devices rely on VR software tools for support, we recognized the importance of integrating STRIVE into the existing VR tools that the experts were already familiar with, albeit without haptic feedback.

Introducing new tools can be both time-consuming and costly in the industrial setting. Moreover, employees may be hesitant to adopt new tools due to the need for additional training and mental effort. To overcome this challenge, we strategically integrated STRIVE into their daily tools to allow them to use the haptic extension without the need to learn numerous new steps. Our approach involved creating a single interface tool that connects STRIVE to multiple VR tools seamlessly. This integration ensured that employees could switch between VR software tools without requiring new knowledge or substantial changes to their established workflows.

As a result of this user-friendly integration, STRIVE became the most widely adopted feedback device in our case. Its successful integration into their familiar VR tools made it a practical and efficient choice for the experts, streamlining their tasks and enhancing their overall experience.

7.2 Limitations

During our research, while documenting our insights, we recognized certain limitations in this thesis. One limitation is that only our expert study of STRIVE and the multimodal feedback system focused on real use cases within the automotive industry. In contrast, the user studies for Propeller-Hand and STROE were more centered on a proof of concept with abstract use cases. Although we did not include VR experts from other industries in our studies, we carefully evaluated the usability and applicability of our findings based on our extensive experience and observations. Another limitation is that we conducted only four case studies, which may not be sufficient to generalize our results to all industries. However, it is essential to note that we collected a substantial amount of data, involving over 200 individuals in demonstrations of our feedback devices and observing numerous use cases to draw conclusions and considerations. According to Berg et al. [21], VR tasks share similarities across various industries, including aerospace, construction, energy, and automotive. Therefore, we believe our findings can also be extended to other industry areas. Furthermore, it can be lengthy to evaluate whether a new haptic feedback device is suitable for industry and will be integrated into their daily tasks. Introducing and explaining the new haptic feedback devices to VR experts is just the initial step. We discovered that experts may struggle to abstract the use cases we demonstrated and apply them to their specific scenarios. To address this, we had to demonstrate use cases similar to theirs to illustrate how the haptic device could be effectively utilized for their needs. In summary, determining the practical application and usage of feedback devices in the industry can be a time-consuming process that may require further observation and evaluation in the future.

Chapter 8

Conclusion and Future Work

VR is a rapidly expanding field with diverse applications across various domains. While it successfully supports engineers in different industries, haptic feedback remains an area that lacks adequate development. This thesis aims to bridge the gap between haptic research and practical implementation in the industry, specifically focusing on the automotive sector. Our research comprises four case studies that led to the formulation of the problem, the creation of new haptic feedback devices, and a reflection on the case study design.

In the first case study, we developed the PropellerHand, a force feedback glove with two propeller-cages for simulating forces. Our study demonstrated that participants had a more immersive and realistic VR experience using PropellerHand. However, we encountered issues when integrating it into the daily work of automotive VR engineers, particularly related to its high noise level.

We followed a problem-driven approach to design the STRIVE haptic feedback device in the second case study. After conducting an in-depth requirements analysis and understanding VR engineers' challenges, we developed STRIVE. This string-based haptic feedback device proved suitable for industry use, although engineers expressed a desire for additional weight simulation to enhance its capabilities.

For the third case study, we again adopted a problem-driven approach to address weight simulation in the automotive industry. This approach led to the creation of STROE, a shoe-worn string-based force feedback device that accurately simulates weight with a motor pulling the attached string. Our research confirmed that STROE delivers realistic and immersive weight simulation.

Finally, we developed a multimodal haptic feedback system in the fourth case study by combining existing haptic feedback devices to simulate grabbing, collision, and weight feedback. Evaluating the system with automotive VR experts, we found that the collision and weight simulation combination provided the best results, while participants faced challenges with the grabbing device. These case studies offer valuable insights into improving haptic feedback devices and their integration into real-world industries, enabling more effective and immersive experiences for VR users.

At the end of our research, we have compiled a list of considerations to move haptic research into practice. These considerations are based on insights gathered during more than three years of research, feedback from over 200 users who used our haptic feedback devices, and observations from more than 45 VR use cases involving our haptic feedback devices.

During our four case studies, we came across several ideas that we intend to explore in the future. For PropellerHand, we aim to integrate the device with haptic-feedback gloves, like the Manus Prime X Haptic, to enhance its capabilities. We also plan to increase the degrees of freedom by adding two more propellers or another rotation axis. Additionally, we aspire to conduct a user study involving blind or visually impaired participants to investigate how PropellerHand can impact their emotional and dramatic perception of data. Exploring scientific visualizations, such as flow visualization, where PropellerHand generates forces based on data, is also part of our future work.

Regarding STRIVE, we have several suggestions for future improvements. We aim to conduct a user study focusing on the setup process to identify ways to make it easier and quicker for users to set up STRIVE. We also plan to enhance STRIVE's stability, enabling users to lean against virtual objects with their full body weight. Furthermore, expanding STRIVE to simulate the weight of objects is among our plans.

For STROE, we have received valuable feedback highlighting areas that need improvement, with the most crucial being wearing comfort and ergonomic design. To address this, we plan to redesign STROE, making it smaller, lighter, and better balanced in weight distribution. Additionally, we aim to conduct an expert study within an industrial environment to assess STROE's suitability for industrial use cases, such as buildability tasks in the automotive industry.

In the gaming industry, we recognize specific challenges and requirements. Gamers typically have budget constraints, limited physical space, and engage in longer VR sessions. Therefore, our future plans involve adapting our haptic devices to cater to this sector's needs. We aim to create modifications that align with the gaming community's preferences. Additionally, we will work on integrating kinesthetic feedback devices with tactile feedback gloves to enhance the gaming experience, providing users with a more realistic and immersive haptic sensation.

We also want to explore the combination of VR movement and haptic feedback using devices like the Virtuix Treadmill Omni. We aim to develop haptic feedback devices that seamlessly integrate with VR movement devices, allowing users to have an unrestricted and natural experience while receiving haptic feedback during virtual activities.

Regarding our multimodal haptic feedback system, as introduced in Chapter 6, our future plans include implementing a software tool to assist users in selecting the most suitable multimodal haptic setup. This tool will use collision data recorded during tasks performed without haptic feedback to guide users in identifying the most beneficial feedback modalities. By finding the optimal balance between effort and benefit, users can make informed decisions about their haptic feedback preferences, enhancing their overall VR experience.

Chapter 9

Remarks

The language of the thesis was enhanced using the tools ChatGPT [115] and Grammarly [62]. We employed ChatGPT by providing the following command: *"Improve the following text regarding grammar and readability: [Text]"*. Subsequently, we ensured that the modified text generated by ChatGPT remained unchanged regarding content to ensure that no additional contributions were introduced. Any new or altered content was deleted. ChatGPT was used in Chapters 1,2,6,7, and 8. Additionally, Grammarly was utilized to identify and rectify additional grammar issues.

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