STRIVE: String-Based Force Feedback for Automotive Engineering

Alexander Achberger
Mercedes-Benz AG
Stuttgart, Germany
alexander.achberger@daimler.com

Fabian Aust
Mercedes-Benz AG
Stuttgart, Germany
fabian.aust@daimler.com

Daniel Pohlandt
Mercedes-Benz AG
Stuttgart, Germany
daniel.pohlandt@daimler.com

Kresimir Vidackovic
Hochschule der Medien — University of Applied Sciences
Stuttgart, Germany
vidackovic@hdm-stuttgart.de

Michael Sedlmair
University of Stuttgart
Stuttgart, Germany
Michael.Sedlmair@visus.uni-stuttgart.de

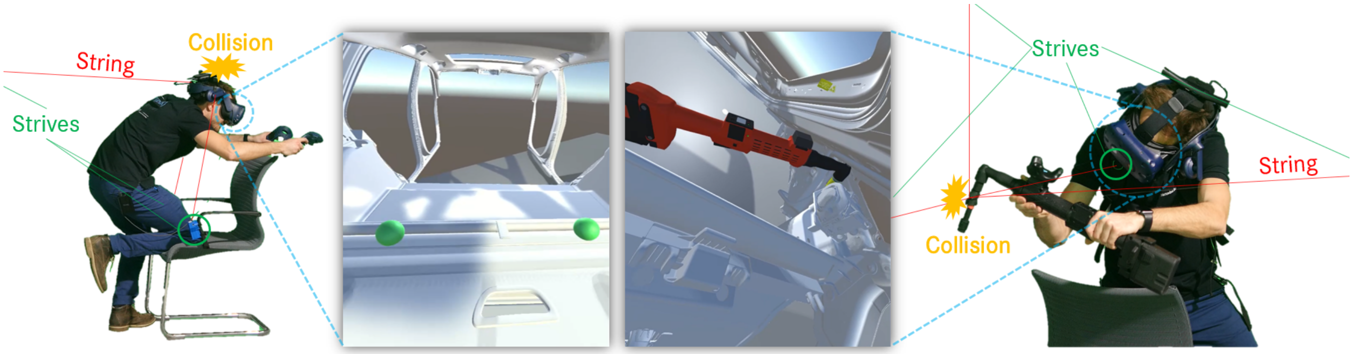

Figure 1: The use of STRIVEs in two automotive use cases. On the left, an assembly task in a trunk in which STRIVEs provide a force feedback on the user's head. On the right, a screwdriver task in which the user feels forces acting on the screwdriver. Most of the STRIVEs boxes are not visible in this figure because they were mounted outside the picture.

ABSTRACT

The large potential of force feedback devices for interacting in Virtual Reality (VR) has been illustrated in a plethora of research prototypes. Yet, these devices are still rarely used in practice and it remains an open challenge how to move this research into practice. To that end, we contribute a participatory design study on the use of haptic feedback devices in the automotive industry. Based on a 10-month observing process with 13 engineers, we developed *STRIVE*, a string-based haptic feedback device. In addition to the design of STRIVE, this process led to a set of requirements for introducing haptic devices into industrial settings, which center around a need for flexibility regarding forces, comfort, and mobility. We evaluated STRIVE with 16 engineers in five different day-to-day automotive VR use cases. The main results show an increased level of trust and perceived safety as well as further challenges towards moving haptics research into practice.

CCS CONCEPTS

• **Human-centered computing → Participatory design**; *Haptic devices.*

KEYWORDS

participatory design, force feedback, haptic device, automotive

ACM Reference Format:
Alexander Achberger, Fabian Aust, Daniel Pohlandt, Kresimir Vidackovic, and Michael Sedlmair. 2021. STRIVE: String-Based Force Feedback for Automotive Engineering. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21), October 10–14, 2021, Virtual Event, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3472749.3474790

1 INTRODUCTION

Virtual reality (VR) is a fast-growing field of research that is applied in various domains such as gaming, medicine, training, or engineering. It provides useful visual and audible feedback, but often lacks force feedback [9]. There are many research prototypes that emphasize the potential of force feedback in different domains, such as ElastiLinks [54], Thor's Hammer [22], or Spidar [30]. However,

---

UIST '21, October 10–14, 2021, Virtual Event, USA

ACM ISBN 978-1-4503-8635-7/21/10…$15.00
https://doi.org/10.1145/3472749.3474790

the number of force feedback devices that are used privately or integrated into the daily work of industrial employees is low [5]. In fact, it largely remains unclear how we can move this stream of work from research into practice. There are different requirements depending on the domain application, 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 [47]. For haptics, this process is investigated rarely, especially in industrial settings [5].

In this work, we focus specifically on the automotive industry. There is research on the use of haptics for in-car interaction [12, 20, 21], 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 finding issues in the digital version of the cars and fixing them before the expensive physical prototype phase. VR use cases include assembly validation or accessibility inspections [56]. Some research demonstrates that the integration of force feedback devices can help engineers complete their tasks more efficiently [7, 44]. 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 expensive and complex to set up.

Towards filling this gap, we conducted a participatory design study on the use of haptic feedback devices in the automotive industry. The goal of our design study was 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 10 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 [41] and Wireality [15]. STRIVE is designed in such a way that it can be used flexibly in order to cover as many of the engineers' use cases as possible. It can be attached to the user's body, to static objects, or both, depending on the use case, can stimulate multiple body parts, and allows the engineers to find their own trade-off 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 that it supports the experts. It helps users to orientate 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

2 RELATED WORK

This section discusses work related to haptics and their application in practice. Nowadays, haptics research has become part of many fields, but the movement of haptics into practice is still rare in some domains [5]. We can find haptics research in arts [3, 50], education [31, 38], and the entertainment area such as Windblaster [27] or ElastiLinks [54], 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 [45], robot-assisted surgery for minimal invasive surgical procedures [10], or for training an eye cataract surgery [14]. Most works' focus is technique-driven, to give readers an inspiration for developing 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 field of data visualization, haptics have become important to support users to understand their data more accurately and quickly [13]. Here, participatory design has shown that haptics were successfully integrated for visual impairments [18, 29, 34, 35, 51, 52] by involving them in their design process.

In the automotive area, there are two different domains where haptics research exists. On the one hand, there is the in-car interaction haptics, that offer the driver and co-driver haptic feedback to better interact with the car. There is haptics research on a shape-changing car seat [20], mid-air ultrasonic feedback for automotive user interfaces [21], tactile feedback for virtual automotive steering wheel switches [12], or haptic feedback for the transfer of control in autonomous vehicles [11]. Besides these haptic car interfaces, there have also been conducted participatory design studies to involve drivers in the design process. Brown et al. [6] conducted an exercise to design and validate an ultrasound-haptic mid-air interface. Pitts et al. [42] 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, there is the car engineering process that benefits from haptic feedback, such as in assembly, ergonomic tasks, or reachability studies, where our focus lies. There are some technique-driven applications that introduce a string-based haptic feedback workbench that gives users haptic stimuli in assembly tasks [39, 46]. However, they do not conduct user studies and do not involve automotive experts. Richard et al. [44] 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 the requirements of automotive experts and do not investigate how to move the haptic feedback into their daily work. Chamaret et al. [7] 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 compared to just the visual stimuli. However, they did not conduct the study with automotive experts and did not evaluate whether the experts would use such a device. More efficiency does not necessarily imply that automotive experts would use the technique, there are more requirements that have to be met. As opposed to this, we involved the automotive engineers in the design process to understand their problems and requirements for using a haptic device in their daily work.

3 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.

3.1 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.

3.2 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 [22], Wind-blaster [27], Drone-based [2]), one electrical muscle stimulation (EMS) [32], two string-based devices (Wireality [15], INCA 6D [41]), one arm exoskeleton [16], one Glove [53], and the feedback arm Virtuose 6D [17]. 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.

		Usability Requirements							Technical Requirements					
Main Approach	Device	Flexible	Mobile	Setup	Simple	Quiet	Hygiene	Comfort	Grab	DoFF	Accuracy	Price	Body	Impact
Exoskeleton	Gloves [19, 25, 40]	✗	✓	✗	✗	✓	✗	✓	✓	✗	✓	✓	✗	✓
	Active (VI-Bot) [16]	✓	✓	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓
Propeller-Based	Thor's Hammer [22]	✗	✓	✓	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗
	Aero-Plane [26]	✗	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗
	Wind-Blaster [27]	✗	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✗	✗
Drone-Based	Drones [1, 2, 24, 55]	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓	✗
EMS	EMS [32]	✓	✓	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	✗
Feedback Arm	Phantom [33]	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓
	Virtuose 6D [17]	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗	✓
String-Based	Spidar [23]	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓
	Spidar G [30]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
	Spidar G&G [36]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
	Spidar-W [37]	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓
	INCA 6D [41]	✗	✗	✗	✗	✓	✓	✓	✗	✓	✓	✗	✗	✓
	Wireality [15]	✗	✓	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓
Elastic Strings	ElastiLinks [54]	✗	✓	✓	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
	ElasticVR [48, 49]	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗

Table 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.

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.

3.3 Requirements Fulfillment of Current Devices

Table 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 breaks 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.

4 STRIVE

STRIVE is a string-based haptic feedback device that consists of a small wireless box (see Figure 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

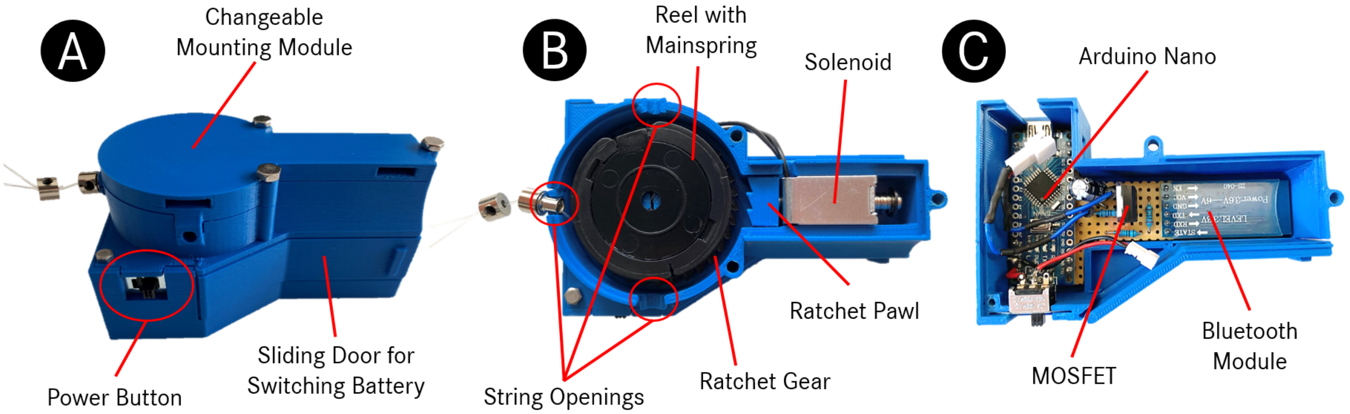

Figure 2: (A) One entire STRIVE. (B) The solenoid box, when the solenoid is activated, pushes the ratchet pawl inside the ratchet gear and blocks the reel, stopping the string extraction. (C) The communication receives commands from the VR application.

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. 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 fast and simple and added a switch to turn the device on and off (RU-Simple). We modeled three string outputs in STRIVE (see Figure 2) in order to switch the position where the string leaves the case to get a higher flexible usage (RU-Flexible). For reproducibility, we added a full step-by-step manual to the supplemental materials.

4.1 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 [15], which demonstrated strong arresting forces (180 N) with low latency (30ms) 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 2), but can power also up a STRIVE over 1 hour. A HC-05 Bluetooth module provides wireless communication. A circuit diagram and a detailed list of all electric components are attached to the manual in the supplemental material.

4.2 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.

4.2.1 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.

4.2.2 Results. Wireality [15] 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

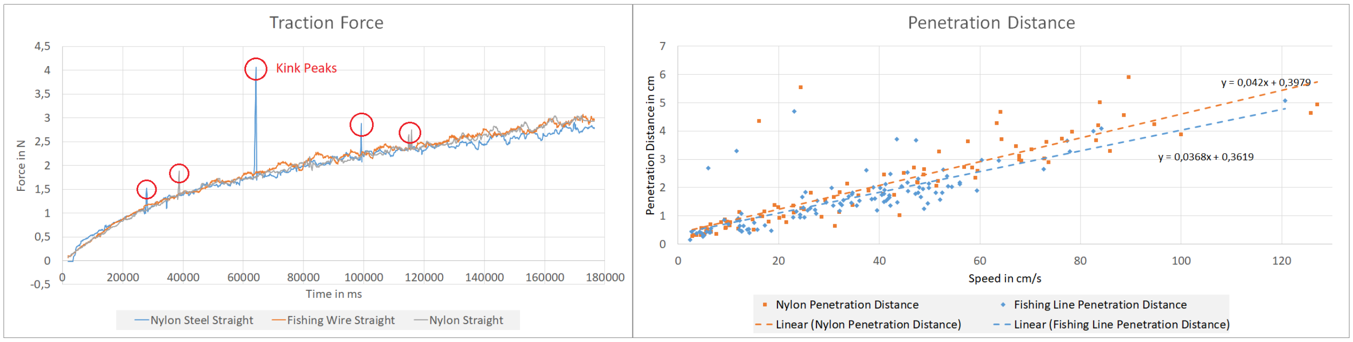

Figure 3: The left chart shows the traction force measurements. The force peaks in the nylon and nylon steel material are highlighted with red circles. The right chart shows the penetration distance with the nylon string and fishing wire. The distance increases linearly, therefore we added the linear trend lines.

during unwinding [43]. 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 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 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 [15], we recommend fishing wires, because they cannot have kinks.

The penetration distances show a linear increase depending on the speed (see Figure 3). 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.

Table 2: The measured time that is needed to set up the use cases that are described in Section 5

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

4.3 Modules and Mounting Locations

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). 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 A), 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 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 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 D).

4.4 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 5. 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.

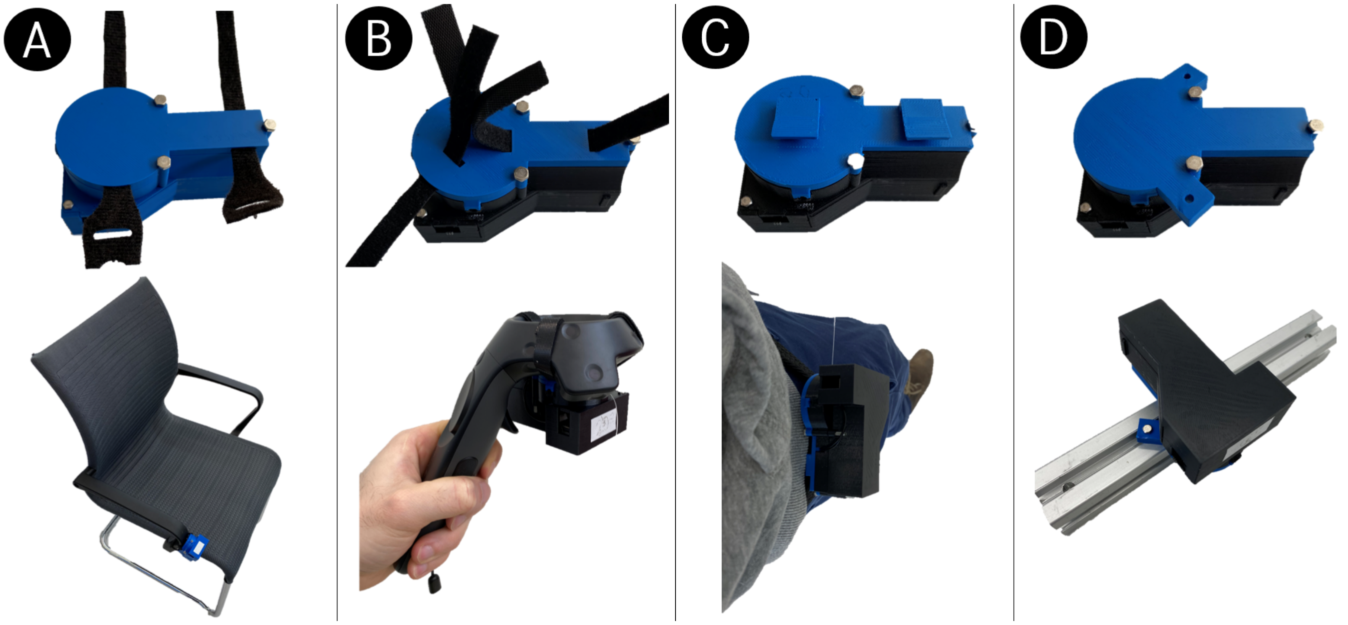

Figure 4: The different mounting modules for STRIVE: (A) The Velcro Strip Module, (B) the Controller Module, (C) the Pants Module, and (D) the Screw Module.

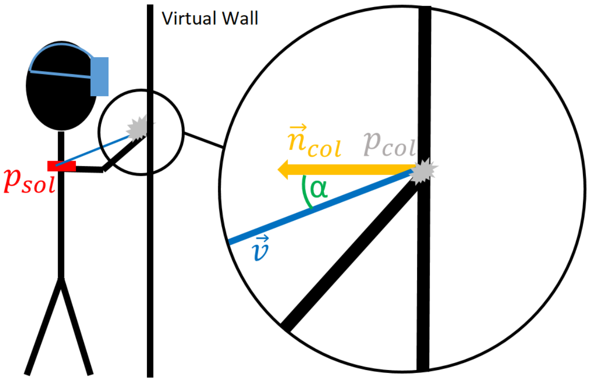

Figure 5: Illustration of parameters that need to be calculated for a solenoid activation.

- **Mounting Step (S-Mount):** Mounting the STRIVEs on the objects such as chairs, tables, HMD, or backpack.
- **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 2. Overall, the average setup took 237 s. We can see, however, that the measured time of course differs substantially between the use cases.

4.5 Software Implementation

The software and the use cases from Section 5 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 $\vec{n}_{col}$ (see Figure 5). We calculate the angle α between $\vec{n}_{col}$ and the vector $\vec{v} = p_{sol} - p_{col}$ through the points p_{col} and p_{sol}:

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

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.

5 AUTOMOTIVE USE CASES

In Section 3, 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

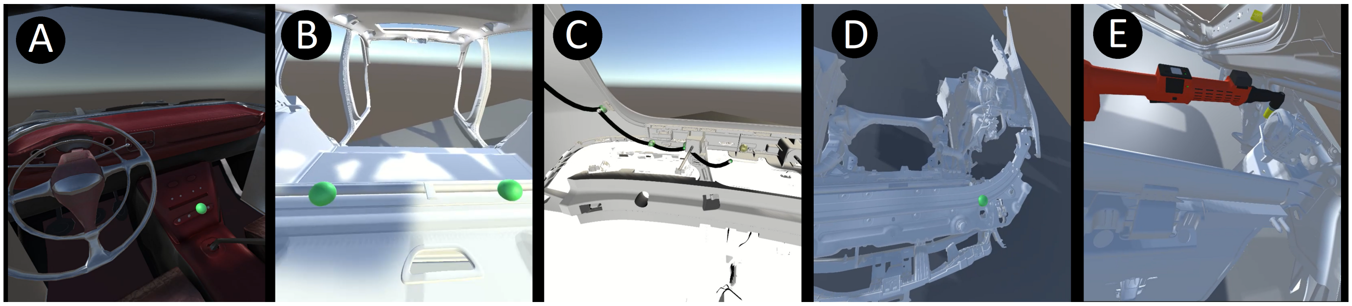

Figure 6: Screenshots of the automotive VR use cases, where the green spheres represent the user's hand positions. (A) The reachability use case, (B) the head collision use case, (C) the cable routing use case, (D) the bi-manual assembly use case, and (E) the screwdriver use case.

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.

5.1 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 6 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.

5.2 Head Collision (UC2)

In this use case, the users have to assemble a pole on the end of a trunk (see Figure 6 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.

5.3 Cable Routing (UC3)

In this use case, the engineers have to route cables on a car component (see Figure 6 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.

5.4 Bi-manual Assembly (UC4)

In this use case, the users have to place a front module onto the front of a car (see Figure 6 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.

5.5 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 6 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.

6 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.

6.1 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, (see supplemental material for more details). The experts were from different teams. Combined, they cover all VR tasks that were described in Section 3. 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 [17], diverse haptic gloves, or used tables to simulate collisions with car components.

6.2 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* [28], 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.

6.3 Results

In total, we recorded over 11 hours of audio during the study, which we transcribed and coded. Figure 7 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.

6.3.1 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 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*".

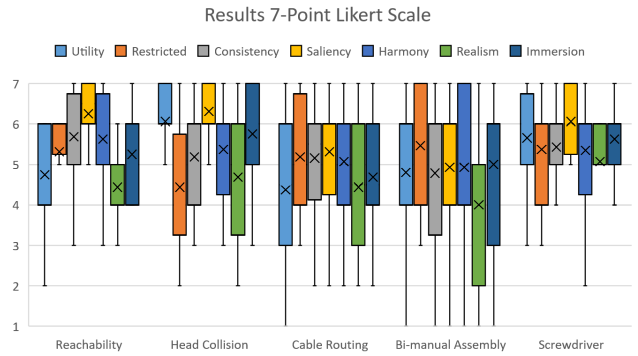

Figure 7: The results of the 7-point Likert scale of the 16 automotive experts (7: strongly agree - 1: strongly disagree). The boxes indicate the first and third quartile, the lines the minimum and maximum values, and the X-symbols the mean value.

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.

6.3.2 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.

7 DISCUSSION AND LIMITATIONS

In the following, we discuss in how far STRIVE met the initial requirements from Section 3, as well as potential alternative approaches, further application areas, and its limitations.

7.1 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-Mobil) 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.

7.2 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 abject, 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 4.2.2) 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).

7.3 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 [8]. 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 [4]. 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.

7.4 Other Applications

We hypothesize that STRIVE is also of interest to other application areas, specifically due to its price and flexibility. We especially see potential in the entertainment area, where gamers could simply use furniture to mount the STRIVEs, such as tables, chairs, or cupboards. For the field of haptic communication, we believe STRIVE could have problems because it is a passive haptic feedback device.

7.5 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.

8 CONCLUSION AND FUTURE WORK

In this paper, 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.

Based on these limitations, we have collected several suggestions for future work. For instance, we would like to conduct a user study with a focus on setup. With the experts mentioning that quick and easy setup is one of the most important requirements, we would like to explore the setup process further to understand how we can bring STRIVE into their daily work. Another technical future work is to make STRIVE more stable so that users can lean against virtual objects with their entire body weight. In addition, we would like to expand STRIVE so that it can also simulate the weight of objects.

ACKNOWLEDGMENTS

Partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germanys Excellence Strategy – EXC 2120/1 – 390831618.

REFERENCES

[1] Muhammad Abdullah, Minji Kim, Waseem Hassan, Yoshihiro Kuroda, and Seokhee Jeon. 2017. HapticDrone: An encountered-type kinesthetic haptic interface with controllable force feedback: Initial example for 1D haptic feedback. In *ACM Symposium on User Interface Software and Technology (UIST)*. 115–117.

[2] Parastoo Abtahi, Benoit Landry, Jackie Yang, Marco Pavone, Sean Follmer, and James A Landay. 2019. Beyond the force: Using quadcopters to appropriate objects and the environment for haptics in virtual reality. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 1–13.

[3] Bill Baxter, Vincent Scheib, Ming C Lin, and Dinesh Manocha. 2001. DAB: Interactive haptic painting with 3D virtual brushes. In *Conference on Computer graphics and interactive techniques (SIGGRAPH)*. 461–468.

[4] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *ACM Symposium on User Interface Software and Technology (UIST)*. 717–728.

[5] Leif P Berg and Judy M Vance. 2017. Industry use of virtual reality in product design and manufacturing: A survey. *Virtual Reality (VR)* (2017), 1–17.

[6] Eddie Brown, David R. Large, Hannah Limerick, and Gary Burnett. 2020. Ultrahapticons:"Haptifying" drivers' mental models to transform automotive mid-air haptic gesture infotainment interfaces. In *ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)*. 54–57.

[7] Damien Chamaret, Sehat Ullah, Paul Richard, and Mickael Naud. 2010. Integration and evaluation of haptic feedbacks: From CAD models to virtual prototyping. *International Journal on Interactive Design and Manufacturing (IJIDeM)* 4, 2 (2010), 87–94.

[8] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D Wilson. 2017. Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 3718–3728.

[9] Wang Dangxiao, Guo Yuan, Liu Shiyi, Yuru Zhang, Xu Weiliang, and Xiao Jing. 2019. Haptic display for virtual reality: progress and challenges. *Virtual Reality & Intelligent Hardware (VRIH)* (2019), 136–162.

[10] Jaydev P Desai, Gregory Tholey, and Christopher W Kennedy. 2007. Haptic feedback system for robot-assisted surgery. In *ACM Proceedings of the Workshop on Performance Metrics for Intelligent Systems (PerMIS)*. 188–195.

[11] Patrizia Di Campli San Vito, Edward Brown, Stephen Brewster, Frank Pollick, Simon Thompson, Lee Skrypchuk, and Alexandros Mouzakitis. 2020. Haptic feedback for the transfer of control in autonomous vehicles. In *ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)*. 34–37.

[12] Lisa Diwischek and Jason Lisseman. 2015. Tactile feedback for virtual automotive steering wheel switches. In *ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)*. 31–38.

[13] Lisa JK Durbeck, Nicholas J Macias, David M Weinstein, Chris R Johnson, and John M Hollerbach. 1998. SCIRun haptic display for scientific visualization. In *Phantom Users Group Meetings (PUG)*.

[14] NR El-Far, Saeid Nourian, Jilin Zhou, Abdelwahab Hamam, Xiaojun Shen, and ND Georganas. 2005. A cataract tele-surgery training application in a hapto-visual collaborative environment running over the canarie photonic network. In *IEEE International Workshop on Haptic Audio Visual Environments and their Applications*. 4.

[15] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 1–10.

[16] German Research Center for Artificial Intelligence GmbH. 2021. Exoskeleton Active (VI-Bot). https://robotik.dfki-bremen.de/en/research/robot-systems/exoskelett-aktiv-vi/. Online; accessed 7 April 2021.

[17] Philippe Garrec, Jean-Pierre Friconneau, and François Louveau. 2004. Virtuose 6D: A new force-control master arm using innovative ball-screw actuators. In *Proceedings of Symposium on Robotics (OSR)*.

[18] Uttara Ghodke, Lena Yusim, Sowmya Somanath, and Peter Coppin. 2019. The cross-sensory globe: Participatory design of a 3D audio-tactile globe prototype for blind and low-vision users to learn geography. In *ACM Conference on Designing Interactive Systems (DIS)*. 399–412.

[19] Timo Götzelmann. 2017. A 3D printable hand exoskeleton for the haptic exploration of virtual 3D scenes. In *ACM Conference on PErvasive Technologies Related to Assistive Environments (PETRA)*. 63–66.

[20] Thomas Grah, Felix Epp, Martin Wuchse, Alexander Meschtscherjakov, Frank Gabler, Arnd Steinmetz, and Manfred Tscheligi. 2015. Dorsal haptic display: A shape-changing car seat for sensory augmentation of rear obstacles. In *ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)*. 305–312.

[21] Kyle Harrington, David R Large, Gary Burnett, and Orestis Georgiou. 2018. Exploring the use of mid-air ultrasonic feedback to enhance automotive user interfaces. In *ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)*. 11–20.

[22] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's hammer: An ungrounded force feedback device utilizing propeller-induced propulsive force. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 1–11.

[23] Yukihiro Hirata and Makoto Sato. 1992. 3-dimensional interface device for virtual work space. In *IEEE/RSJ Conference on Intelligent Robots and Systems (IROS)*. 889–896.

[24] Matthias Hoppe, Pascal Knierim, Thomas Kosch, Markus Funk, Lauren Futami, Stefan Schneegass, Niels Henze, Albrecht Schmidt, and Tonja Machulla. 2018. VRHapticDrones: Providing haptics in virtual reality through quadcopters. In *ACM Conference on Mobile and Ubiquitous Multimedia (MUM)*. 7–18.

[25] Mohssen Hosseini, Ali Sengül, Yudha Pane, Joris De Schutter, and Herman Bruyninck. 2018. ExoTen-Glove: A force-feedback haptic glove based on twisted string actuation system. In *IEEE Symposium on Robot and Human Interactive Communication (RO-MAN)*. 320–327.

[26] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2D plane. In *ACM Symposium on User Interface Software and Technology (UIST)*. 763–775.

[27] Seungwoo Je, Hyelip Lee, Myung Jin Kim, and Andrea Bianchi. 2018. Wind-blaster: A wearable propeller-based prototype that provides ungrounded force-feedback. In *ACM SIGGRAPH Emerging Technologies*. 1–2.

[28] Erin Kim and Oliver Schneider. 2020. Defining haptic experience: Foundations for understanding, communicating, and evaluating HX. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 1–13.

[29] Hyung Nam Kim. 2009. Haptic user interface design for students with visual impairments. In *ACM SIGACCESS Conference on Computers and Accessibility (ASSETS)*. 267–268.

[30] Seahak Kim, JJ Berkley, and M Sato. 2003. A novel seven degree of freedom haptic device for engineering design. *Virtual Reality (VR)* (2003), 217–228.

[31] Adjan Kretz, Remo Huber, and Morten Fjeld. 2005. Force feedback slider (FFS): Interactive device for learning system dynamics. In *IEEE International Conference on Advanced Learning Technologies (ICALT)*. IEEE, 457–458.

[32] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 1471–1482.

[33] Thomas H Massie, J Kenneth Salisbury, et al. 1994. The phantom haptic interface: A device for probing virtual objects. In *IEEE conference on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS)*. 295–300.

[34] Oussama Metatla, Nick Bryan-Kinns, Tony Stockman, and Fiore Martin. 2015. Designing with and for people living with visual impairments: Audio-tactile mock-ups, audio diaries and participatory prototyping. *CoDesign* (2015), 35–48.

[35] Oussama Metatla, Fiore Martin, Adam Parkinson, Nick Bryan-Kinns, Tony Stockman, and Atau Tanaka. 2016. Audio-haptic interfaces for digital audio workstations. *Journal on Multimodal User Interfaces* 10, 3 (2016), 247–258.

[36] Jun Murayama, Laroussi Bougrila, YanLin Luo, Katsuhito Akahane, Shoichi Hasegawa, Béat Hirsbrunner, and Makoto Sato. 2004. SPIDAR G&G: A two-handed haptic interface for bimanual VR interaction. In *EuroHaptics*. 138–146.

[37] Kazuki Nagai, Soma Tanoue, Katsuhito Akahane, and Makoto Sato. 2015. Wearable 6-DoF wrist haptic device" SPIDAR-W". In *SIGGRAPH Asia Haptic Media And Contents Design*. 1–2.

[38] Trond Nilsen, Steven Linton, and Julian Looser. 2004. Motivations for augmented reality gaming. *New Zealand Game Developers Conference (FUSE)* (2004), 86–93.

[39] Michael Ortega and Sabine Coquillart. 2005. Prop-based haptic interaction with co-location and immersion: An automotive application. In *IEEE International Workshop on Haptic Audio Visual Environments and their Applications*. 6.

[40] Yeongyu Park, Inseong Jo, and Joonbum Bae. 2016. Development of a dual-cable hand exoskeleton system for virtual reality. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 1019–1024.

[41] J Perret and L Dominjon. 2009. The inca 6d: A commercial stringed haptic system suitable for industrial applications. In *Joint Virtual Reality Conference, Springer Tracts in Advanced Robotics*.

[42] Matthew J Pitts, Mark A Williams, Tom Wellings, and Alex Attridge. 2009. Assessing subjective response to haptic feedback in automotive touchscreens. In *ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)*. 11–18.

[43] Les Pook. 2011. An introduction to coiled springs (mainsprings) as a power source. *International Journal of Fatigue* 33, 8 (2011), 1017–1024.

[44] Paul Richard, Damien Chamaret, François-Xavier Inglese, Philippe Lucidarme, and Jean-Louis Ferrier. 2006. Human-scale virtual environment for product design: Effect of sensory substitution. *The International Journal of Virtual Reality (VR)* 2, 5 (2006), 37–44.

[45] Ismail Shakra, Mauricio Orozco, Abdulmotaled El Saddik, Shervin Shirmohammadi, and Edward Lemaire. 2006. VR-based hand rehabilitation using a haptic-based framework. In *IEEE Instrumentation and Measurement Technology Conference Proceedings*. 1178–1181.

[46] Nicolas Tarrin, Sabine Coquillart, Shoichi Hasegawa, Laroussi Bouguila, and Makoto Sato. 2003. The stringed haptic workbench: A new haptic workbench solution. In *Computer Graphics Forum (CGF)*. 583–589.

[47] J Thomas and K Cook. 2005. Illuminating the path: Research and development agenda for visual analytics. IEEE National Visualization and Analytics Center.

[48] Hsin-Ruey Tsai and Jun Rekimoto. 2018. ElasticVR: Providing multi-level active and passive force feedback in virtual reality using elasticity. In *ACM Conference on Human Factors in Computing Systems (CHI), Extended Abstracts*. 1–4.

[49] Hsin-Ruey Tsai, Jun Rekimoto, and Bing-Yu Chen. 2019. Elasticvr: Providing multilevel continuously-changing resistive force and instant impact using elasticity for vr. In *ACM Conference on Human Factors in Computing Systems (CHI)*. 1–10.

[50] Luca Turchet and Mathieu Barthet. 2018. Co-design of musical haptic wearables for electronic music performer's communication. *IEEE Transactions on Human-Machine Systems* (2018), 183–193.

[51] Ella Tuson, Samantha Hughson, Christina Zymaris, and Ryan King. 2017. Participatory design using sensory substitution devices with tactile and audio feedback. In *ACM SIGACCESS Conference on Computers and Accessibility (ASSETS)*. 415–416.

[52] Frances L Van Scoy, Vic Baker, Chaim Gingold, Eric Martino, and Darren Burton. 1999. Mobility training using a haptic interface: Initial plans. *Phantom Users Group Meetings (PUG)* (1999).

[53] LLC VRGluv. 2021. VRGluv. https://www.vrgluv.com/enterprise. Online; accessed 7 April 2021.

[54] Tzu-Yun Wei, Hsin-Ruey Tsai, Yu-So Liao, Chieh Tsai, Yi-Shan Chen, Chi Wang, and Bing-Yu Chen. 2020. ElastiLinks: Force feedback between VR controllers with dynamic points of application of force. In *ACM Symposium on User Interface Software and Technology (UIST)*. 1023–1034.

[55] Kotaro Yamaguchi, Ginga Kato, Yoshihiro Kuroda, Kiyoshi Kiyokawa, and Haruo Takemura. 2016. A non-grounded and encountered-type haptic display using a drone. In *ACM Symposium on Spatial User Interaction (SUI)*. 43–46.

[56] Peter Zimmermann. 2008. Virtual reality aided design. A survey of the use of VR in automotive industry. In *Product Engineering*. Springer, 277–296.