Towards a VR Evaluation Suite for Tactile Displays in Telerobotic Space Missions

Premankur Banerjee[1,4], Evelyn Muschter[2,3], Harsimran Singh[1,3], Bernhard Weber[1], and Thomas Hulin[1,3]

[1]**Institute of Robotics and Mechatronics**
German Aerospace Center (DLR)
82234 Wessling, Germany
premankur.banerjee@outlook.de
<firstname.lastname>@dlr.de

[2]**Lifespan Developmental Neuroscience**
Technische Universität Dresden
01062 Dresden, Germany
<firstname.lastname>@tu-dresden.de

[3]**Centre for Tactile Internet with Human-in-the-Loop (CeTI), Cluster of Excellence at TU Dresden**
01062 Dresden, Germany

[4]**Sorbonne Université, CNRS**
Institut des Systémes Intelligents et de Robotique, ISIR
Paris, France

Abstract— **Research and development of telerobotic systems supplemented by haptic feedback for future planetary exploration missions has gained significant importance in the past decade. Major space agencies endeavor to deploy such systems before sending humans to the surface of unknown or unexplored celestial bodies. Astronauts control these telerobotic systems from remote locations, such as an orbital space station. Haptic feedback for teleoperating the robots in outer space is extremely important, not only to improve user immersion and task performance, but also to improve our understanding of surface properties. At the same time, for spaceflight, making use of compact, light-weight and robust devices are preferred for precise tactile feedback from telemanipulation tasks. In this paper, we introduce "ViESTac", a first attempt to develop a generic VR suite to be able to evaluate and compare fingertip-wearable tactile devices. Applications of such a suite include, but are not limited to allowing teleoperators to judiciously choose suitable tactile devices for a particular task. To account for the wide variety of existing fingertip-wearable tactile devices and their display capabilities, the suite contains a set of virtual scenarios to investigate different tactile properties of virtual objects. It also dedicates a virtual scenario to evaluate how tactile feedback may govern the accuracy of human positioning in standard tasks. This proposed suite is advocated by a pilot study with 13 participants and two distinct state-of-the-art tactile devices. Results of the study clearly indicate that the virtual suite can successfully cater to the need of evaluating and comparing fingertip-wearable tactile devices.**

TABLE OF CONTENTS

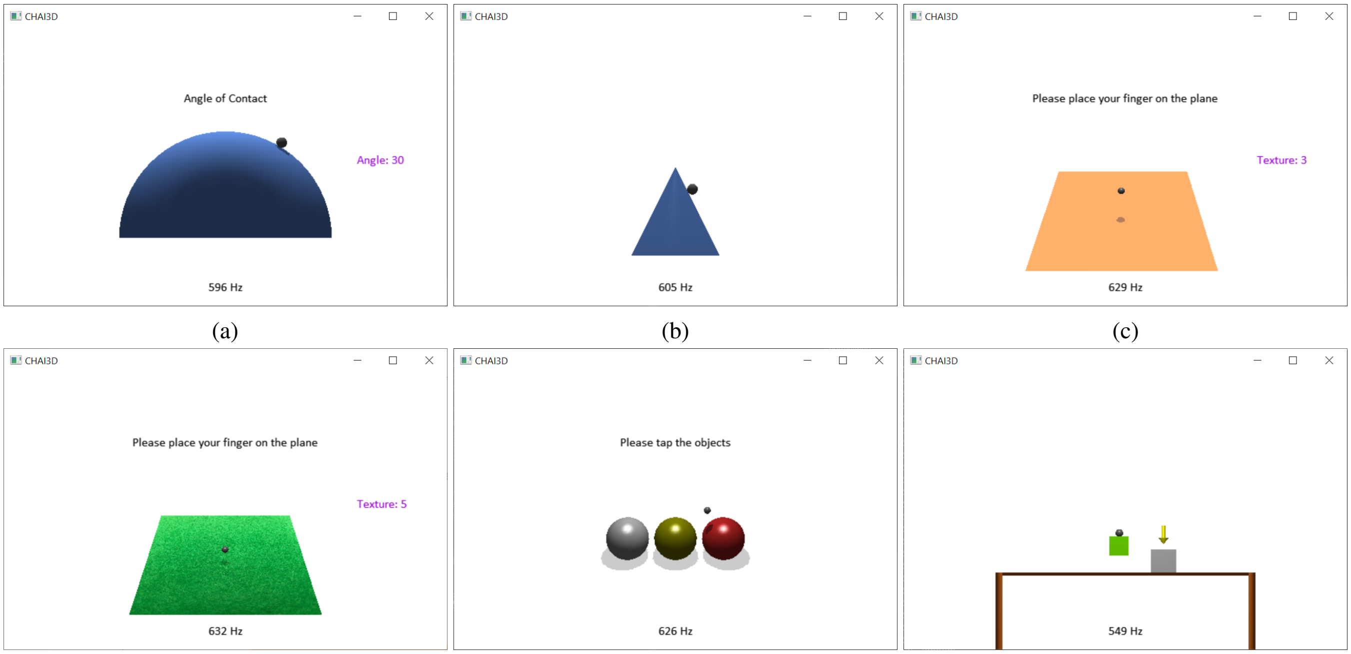
1. INTRODUCTION

The international space agencies are already planning planetary exploration missions for the next few years that will take man back to the moon and, as the next big step, to mars. Habitats are to be established on these celestial bodies. To achieve this, telerobotic systems will be used in a first phase. Humans will then be able to control robotic systems on the planetary surface from the safety of an orbital spacecraft. The effectiveness and usability of telerobotic systems, however, depends decisively on the quality and bandwidth of the sensory information that the human receives from the robotic system. In addition to visual information, haptic feedback plays a significant role in the extent to which humans can immerse themselves in the remote environment. In recent years, force feedback systems have been primarily developed for telerobotic application scenarios and first evaluation campaigns on the International Space Station (ISS) have been successfully conducted [1], [2], [3], [4].

In addition to such force feedback systems, however, there is also a need for tactile feedback systems that can support fine manipulative telerobotic tasks or substitute force feedback. The great advantage of tactile feedback devices, especially in the context of space missions, is that they are small, lightweight, modularly configurable and hence versatile. The present work is dedicated to the question of how to design an evaluation tool for such tactile feedback systems. Such an evaluation suite also opens the possibility to investigate the use of tactile feedback under weightlessness conditions in future space missions, as it was done for force feedback devices in previous missions, e.g. [5].

Providing a realistic sense of touch through haptic interfaces in Virtual Reality (VR) still remains a challenge. Over the past decade, different tactile devices based on different actuation techniques and capabilities to display one or more tactile properties have been developed [6]. VR provides compelling environments to investigate the capabilities of such tactile devices and evaluate them through human user studies. Typically, these studies are limited either by focusing only on a given haptic device with a specific VR environment, or contain only a few very specific experimental tasks [7]. Different hardware and software settings are additional aggravating factors to ascertain the overall effectiveness and comparability across different tactile devices. For instance, the virtual environments used for evaluating the finger-feedback device *hRing* [8] and an asymmetric 3-RSR wearable device [9], both consist of a simple pick-and-place task. The

*Funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of Technische Universität Dresden.
978-1-6654-9032-0/23/$31.00 ©2023 IEEE



(a) (b) (c)

(d) (e) (f)

Figure 1: ViESTac scenarios for (a)&(b) Orientation and shape detection, (c)&(d) Texture, (e) Stiffness and (f) Object positioning. Frequencies indicated in each figure are the respective update rates of the simulation in CHAI3D.

virtual environment designed for the ferrofluid based haptic device [10] was used to discriminate the curvature and vibrational feedback. However, factors such as dimensions of virtual objects, distance between source and target, tracking mechanism, and simulation software used, to name a few, are completely different. Moreover, the information and parameters acquired from simulation vary widely, making evaluation of the two devices under similar conditions, or a comparison between the two, challenging.

Fingertip wearable tactile devices such as *Altered Touch* [11], a vibrotactile haptic device developed for stiffness discrimination [12], and a thermal module integrated haptic wearable [13], were each validated in virtual environments tailored specifically to their display properties capable of rendering augmented haptic interactions, stiffness encoded as vibrations, temperature and surface interaction respectively. On the other hand, these scenarios were highly disparate from the VR applications developed for the *Haptic Revolver* [14] for detection of surface edges and a wide range of textures, thereby making a uniform appraisal of such tactile devices using a single virtual environment implausible. This calls for designing a new application-specific virtual environment every time a novel tactile device for virtual object interactions needs to be tested through user studies.

As a result, it becomes difficult to compare multiple such devices (e.g., to determine the most appropriate one for a given use-case) due to the absence of a standardized virtual environment. There have been frameworks which benchmark haptic systems [15], force quality in haptic rendering [16], grounded force-feedback devices [17], haptic data reduction [18] and discovering haptic devices [19], but to the best of the authors' knowledge, no such previous framework exists for assessing tactile devices by their ability to display different tactile properties of virtual objects [20].

In this paper we propose ViESTac, a first approach to design a tactile device-agnostic multimodal VR[2] Our VR suite aims to serve as a benchmark for evaluating and comparing fingertip-wearable tactile devices primarily. In the following we present the design of the virtual suite, a pilot study with two tactile devices, the FingerTac [21] and a ferrofluid based tactile device [10], and suggest some directions for future research. Please note that for the remainder of the paper, the ferrofluid based tactile device shall be addressed as FerroVibe.

2. DESIGN OF THE VR SUITE

ViESTac consists of a number of Virtual Scenarios (VS) as shown in Fig. 1. The goal is to encompass the various display capabilities of fingertip-wearable tactile devices predominantly, with respect to the multitude of tactile properties of virtual objects. Broadly classified into two main categories, the first comprises of scenarios targeting the human discrimination capability for various tactile properties of virtual objects displayed via tactile devices [20]. The second category focuses on providing positioning guidance and is inspired by standard tasks in teleoperation and VR applications [22], [23]. Together, the implemented VS form the basis of the VR suite for evaluating the rendering quality and performance of any fingertip-wearable or handheld tactile device in telerobotic space applications, aggregating multiple standard methods or tasks. The design of this suite is such that it sends application specific signals from each virtual scenario to the respective hardware. This in turn, allows to generate the respective haptic stimuli adapted to the capabilities of the tactile device at hand.

---

[2] For the sake of clarity, we refer to the term VR in its original meaning, i.e., virtual objects and interactions in a virtual environment, without placing the focus on any particular immersive visual hardware or VR goggles. Instead we use a standard laptop for visualizing virtual scenes.

Discriminating Tactile Properties

This section discusses the VR scenarios (Fig. 1a–e) that aim to determine the discrimination performance of humans, while receiving haptic stimulation from a tactile device. The scenarios are designed to be universally applicable to integrate and evaluate various tactile devices that can render one or more tactile properties of virtual objects.

Contact orientation and Shape detection—Contact orientation enables tactile devices to convey the overall shape of a virtual object or how it is positioned in 3D space. Previous research has investigated the discrimination threshold of force stimuli applied to the finger and have found that humans can distinguish force directions from angles of 33° [24] up to angles as small as 7° [25] and 4° [26] for real objects, depending on the experimental conditions. These diverging findings suggest that the direction discrimination ability might be influenced by to-be-integrated multimodal information such as the amount of force applied for direction discrimination [27], kinesthetic information of the finger movement itself or visual information [25]. The suite has two dedicated VS – one for providing surface orientation information of virtual objects, and the other for detecting different shapes of objects in VR by touching. The first scenario (Fig. 1a) comprises of a semi-disc shaped virtual object with a radius of 6 cm^3, located on a ground plane, whose contour can be explored using a suitable tactile device, while the tactile device provides the user with stimuli about the angle. The bottom left and bottom right positions on the circumference of the object correspond to angles of $-90°$ and $+90°$, respectively, as shown in Fig. 2. The VS sends the angle value over to the respective tactile device to output a desired feedback to users. A second VS (Fig. 1b) for detecting object shapes consists of three virtual objects, a cube, a sphere and a cone (Fig. 3). Each side of the cube is made to be 10 cm in length, the radius of the sphere is set to 5 cm, and the cone has a base radius of 5 cm and a height of 10 cm. All other physical properties are set to a constant value. Surface information (e.g. flat or curvy) along with inclination angle (slopes of edges) are communicated from the VS to the respective hardware. Furthermore, information about the texture of respective objects (e.g., how smooth or rough, or even real material texture) can be conjoined and displayed via suitable tactile devices, such as the FerroVibe, Haptic Thimble [12], or Touch&Fold [28], using this VS. In the above scenarios, it is assumed that the orientation of a user's finger remains constant, so that the fingernail always points upwards as shown in Fig. 3, thus allowing both directions to be felt, i.e. left/right and front/rear.

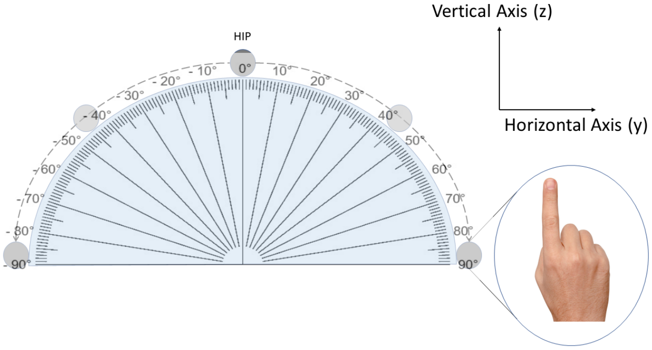


Figure 2: Trajectories for surface orientation.

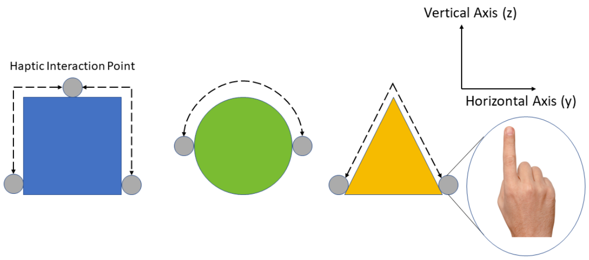


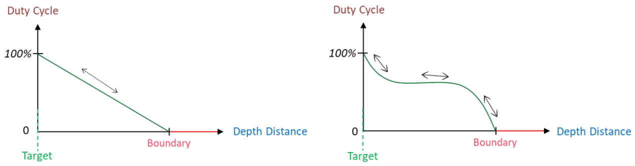
Figure 3: Trajectories for shape detection.

Texture—One of the main features of tactile devices is their ability to display high frequency vibrations, giving users an augmented sense of the texture percept along the rough–smooth dimension for virtual objects [29], [30]. The VS to evaluate this property consists only of a virtual plane of the dimensions 30×30 cm^2 (Fig. 1c). Except for the virtual textures, presented as high frequency sinusoidal vibrations, all other physical properties of the virtual plane are kept unchanged. Psychophysical studies [31], [32], [33] have shown that users exploring a plane with the same texture at different exploration velocities may perceive the texture differently. Thus, the actuator vibration frequency output of virtual textures implemented in the scene varies linearly with finger exploration velocity tracked using a Leap Motion controller. As the goal of the present paper was to determine whether users could discriminate between a series of high frequencies displayed via tactile devices, the interaction speed was set to a constant velocity of 1 cm/s. Based on the perceptual sensitivity curves of [34], [35], [36], which reveal high sensitivity in the range approximately between 150 and 500 Hz in humans, the texture signals to focus on in this dedicated task should be within this range, i.e., frequencies of 500 Hz, 333.33 Hz, 250 Hz, 200 Hz, and 166.67 Hz corresponding to vibration time periods of 2, 3, 4, 5 and 6 milliseconds respectively. The VS can, however, be easily programmed to cover a wider spectrum of frequencies within the range of human tactile perception. This VS can also be used to reproduce pre-recorded textures from publicly available datasets as shown in Fig. 1d, where textures have been loaded and assigned to the ground plane from the LMT texture database [37].

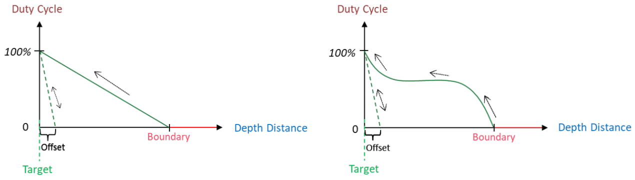
Stiffness—Stiffness of an object is defined as the resistance of the object to deformation by an applied force. Existing studies show that perceptual discrimination of stiffness is significantly better by tapping an object than with squeezing or pressing it [38], [39]. The VS for stiffness discrimination is therefore based on the assumption that object stiffness is determined by tapping. This does not require velocity or acceleration measurements on the object surface, and the relevant information can be conveyed via devices only worn on one finger. Parameters such as relative differences in stiffness due to stiffness of the human finger, along with various stiffness exploration principles for soft objects taking into consideration the surface area of contact [40], is out of the scope of this paper, which focuses on providing a preliminary benchmark suite for each tactile property observed in virtual objects. The chosen design for the VS consists of three static virtual spheres situated on a plane, each having a radius of 4 cm (Fig. 1e). The leftmost grey and rightmost

---

[3] All dimensions of virtual objects indicated henceforth commensurate with real physical objects used in similar experiments.



(a) Linear time-invariant (b) Non-linear time-invariant



(c) Linear time-variant (d) Non-linear time-variant

Figure 4: Vibration patterns investigated.

red spheres represent reference spheres with the lowest and highest stiffnesses of 1 N/m and 100 N/m, respectively. The green sphere in the middle has stiffness values between 1 to 100 N/m, which can be adjusted as multiples of 10 including 1, using the up and down arrow keys on the keyboard. Apart from the colors and stiffness, all other physical properties of each sphere are invariable. The VS transmits the stiffness coefficient values of each virtual sphere, when tapped, to be displayed through any tactile device. If a tactile device is not able to stimulate stiffness by deforming or by applying a normal force to the fingerpad [21], [10], then the stiffness information from this scenario is encoded as vibrations and rendered on the respective devices. Stiffness encoding depends on the tactile capabilities of the respective device, and can be realized e.g., by changing the temporal interval between two subsequent vibration stimuli.

Friction and Temperature—Among the VS discussed so far, these two attributes can also be incorporated within them. The spheres used for stiffness discrimination (cf. Fig. 1e) could be assigned different temperatures to be sensed through a tactile device capable of providing thermal feedback. For displaying friction, the scenario for texture discrimination (cf. Fig. 1c) may be modified by assigning different values of static or dynamic friction to the virtual plane. Frictional effects such as dryness or moistness, and stickiness or slipperiness may as well be implemented depending on the display potential of the tactile device under consideration.

Object Positioning

Any standard interaction or manipulation task in VR or teleoperation (such as pick-and-place or peg-in-hole), which is supported by a haptic device, involves some form of positioning. Authors in [41] use color coding to indicate object positioning in a peg-in-hole task, whereas [42] has investigated vibrotactile cues for target acquisition in 2D images. Experiments in [9] also involved positioning an object at a certain height threshold for a certain time interval, before dropping it. The VS in Fig. 1f is designed with the aim to support such positioning accuracy in a 3D environment using a 2D display, by providing visual depth information through tactile cues. Since the 2D visualization does not provide any depth information, the user has to rely solely on tactile feedback for movements along the depth direction.

The VS consists of two cubic objects with side lengths of 3 cm, and one spherical object of radius 1.5 cm. The hole corresponding to the cube has an inner length and breadth of 3 cm, and an outer length and breadth of 4 cm each, with a height of 5 cm, respectively. The spherical object fits into a cylindrical hole with an inner radius of 1.5 cm and an outer radius of 2 cm, with a height of 4 cm. The mass of each object is set to 50 g, and is made easily variable according to the type of experiments performed and devices used. In a sequence of pick-and-place and peg-in-hole tasks, the difficulty level can be altered by slightly adjusting the size of the hole – with a larger hole, the task becomes easier as the play between the objects increases [41]. The initial distance between objects and holes is set to 13 cm. At the onset, the front view of orthographic projection of the VS is enabled (Fig. 1f), which makes the depth perception impossible. An arrow appears in the VS that marks the target (corresponding hole) as soon as the user picks up the object. The depth distance of the picked-up object from the target is sent over from the VS to a tactile device, when the object is within a boundary of radius 20 cm from the target. For vibrotactile devices, depth distance is translated into Pulse Width Modulation (PWM) vibrations.

Vibration Modes—Two types of vibration modes are investigated during this positioning task, whenever the object is within a 20 cm boundary. (i) Increasing vibration pulse rates, which serve as an indication of target approach, and continuous vibrations at the target. (ii) The second vibration mode is the converse of the former, with vibrations ceasing completely at the target.

Vibration Patterns— Existing vibrotactile devices usually play PWM vibrations, which change linearly with time or with distance to a target [42], [43]. The vibrational patterns inspected in this paper (Fig. 4) have never been tested with tactile devices before, to the best of the authors' knowledge. For each pattern, the intensity of vibrations is kept constant in order for users to better perceive the difference in stimuli.
Linear Time-Invariant (LTI): At the boundary, the duty cycle is 0%, whereas at the target position it is 100%. In between, the duty cycle changes linearly with the distance to the target.
Non-linear Time-Invariant: There is an initial spike in the duty cycle when the object is picked up and moved. Following the spike, there is a slower, gradual increase in duty cycle up until a certain distance to the target, beyond which there is again a steep increase in pulse rate.
Time-Variant: Once the object is picked up from its initial position, depth dependent vibrations are cued. The duty cycle may change linearly or non-linearly, as discussed in the earlier sub-sections, depending on the chosen initial pattern. Once the object reaches the target position, the goal is to assist the users to hold that position without overshooting. To achieve this, there is a sudden drop in PWM within a very short distance from the target, beyond this distance, the vibrations stop entirely.

3-DoF Tactile Guidance— In order to evaluate tactile devices with more than 1 degree-of-freedom (DoF), additional feedback may be provided through this particular VS. In this scenario, the suite communicates the 3-dimensional position of the picked up object to the tactile device. The horizontal, vertical and depth distance between the object and the target is sent over to the tactile device from the simulation in every update rate. These values are then translated into corresponding tactile cues based on the device display capabilities in consideration.

3. METHODS

System Description

The experimental setup (Fig. 5) consists of a Leap Motion controller for tracking hand positions in free space, and a screen for rendering the virtual suite designed in CHAI3D [44]. Two different fingertip-wearable tactile devices are employed for the study, namely the FingerTac [21] and a prototype of the FerroVibe [10]. These two particular devices were selected because they were the only devices available for the study at that time. The FerroVibe contains a neodymium magnet suspended in ferrofluid that can be rotated in 2-DoF to provide directional and vibrational feedback to the fingertip. On the other hand, the FingerTac generates vibrational feedback at the centre of the fingerpad, keeping it unobstructed so as to allow simultaneous interactions with real objects. A serial communication for data exchange between CHAI3D and the device microcontrollers is established through a USB serial link or via Bluetooth running at a baud rate of 115200.

Participants

Thirteen right-handed participants (2 females, 11 males M_{Age} = 23.5 ± 2.9 years) were recruited from the student and staff population at DLR. All participants had normal or corrected-to-normal vision and gave informed consent. They wore earmuffs during all the experiments to not incur any bias due to auditory cues. The entire study took about 75 min for each participant.

Experimental Procedure

The tasks of the virtual suite, described in the present work, were adapted to the two DLR fingertip-wearable tactile devices and were presented to the participants in a predefined order. In the following subsections each utilized task is described in detail.

Task 1: Contact orientation discrimination— In this task, conducted using a FerroVibe, participants had to distinguish between different contact angles across a hemispherical surface. This device conveys information about orientation and other tactile cues by tilting a magnet suspended in ferrofluid at different angles, and pressing against the user's fingertip. As the finger moves the haptic interaction point (HIP) along the circumference of the virtual object, all the way from left-to-right, the magnet gradually rotates under the finger from right-to-front-to-left, while always maintaining the same magnitude of tilt and a force of 1.7 N, and vice versa, similar to the exploration patterns shown in Fig. 3. During the practice phase, which lasted for 2 min for each user, participants were shown the virtual objects and how the angles changed with different HIP position across the surface. With their arm placed on the table, they were asked to position their finger on top of the FerroVibe device which was anchored on the table such that there was no wiggle room in the orientation of their finger. The participants were then blindfolded and asked to estimate the angles based on tactile information only, provided for 30 sec or till the participants answered, whichever was earlier. This task consisted of ten predefined angles, five positive and five negative with 20° intervals between them, that were presented to the participants in a pseudo-random order.

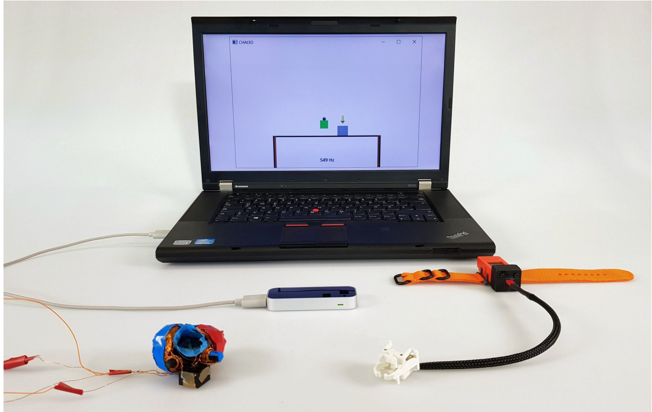


Figure 5: Experimental Setup. A laptop, connected to a Leap Motion controller and the evaluated fingertip-wearable devices (here shown with the FerroVibe on the lower left and the FingerTac in the lower right corner), rendered the ViESTac virtual scenarios (here shown object positioning).

Task 2: Vibrotactile texture perception— In the first sub-task, participants rated the texture dimension roughness on a continuum of rough to smooth in comparison to the 250 Hz reference frequency. Prior to the experiment participants were also familiarized with the two most extreme texture frequencies corresponding to 166.67 Hz (roughest) and 500 Hz (smoothest). After every trial, participants were asked to rate the perceived roughness of the test texture compared to the reference on a 7-point Likert-type scale, with "1" being *much smoother*, 4 being *same* and "7" being *much rougher*. In the second sub-task, participants had to identify the frequency of the texture being displayed out of the five pre-defined frequencies (i.e., 166.67, 200, 250, 333.33, and 500 Hz). In a training phase, participants had up to 3 min to familiarize themselves with all the frequencies. For the main task, five trials were conducted where each texture was presented for a duration of 5 sec to each participant twice, varied systematically. Both sub-tasks were carried out using the FerroVibe only. The generation of high frequency signals was achieved by tilting the magnet for half of the designated time period, and keeping it flat for the other half.

The contact velocity was held constant by having the virtual plane start moving horizontally at a predefined speed of 1 cm/s as soon as the HIP comes into contact with it. Thus, only the vertical movement of the user's finger was considered and the movement of the plane was correspondingly activated or stopped.

Task 3: Stiffness magnitude estimation and production— Wearing a FingerTac, participants were instructed to explore the spheres (see Fig. 1e) by tapping on them and to rate the stiffness of the green sphere on a scale from 1 to 10 (where 10 means the highest stiffness). In this *Magnitude Estimation* task, each participant underwent a short training phase, during which they could freely explore the VS. After this, stiffness values from 1 to 10 (corresponding to values from 1 to 100 N/m with a step size of 10) were tested in ten trials, without repetition and in a pseudo-random order. In an additional *Magnitude Production* task, participants were asked to adjust the stiffness of the rightmost reference red sphere using the up and down arrow keys until it matched the stiffness of the green sphere. Changes in stiffness and completion time were recorded.

Task 4: Object positioning—Here, participants had to pick up a virtual object, position it at a specified target for 2 sec, and then insert the object into its corresponding hole.

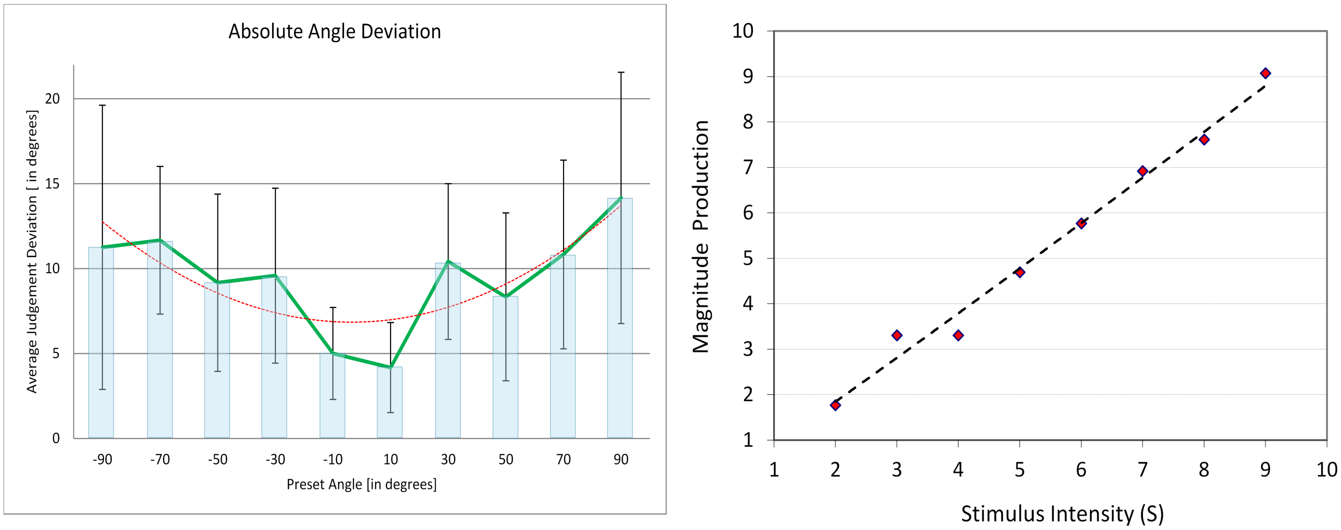


Figure 6: Evaluation Results for contact orientation discrimination (left) and stiffness magnitude production (right)

Participants were asked to take the shortest route to the target and finish the task as fast as possible. Counterbalanced across participants, the vibration modes and three of the four vibration patterns as discussed in Section 2 were tested using the FingerTac. After a training phase of practising the task three times, a total of nine trials were conducted to investigate each vibration pattern for the three target positions. The simulation recorded the completion times and trajectories for each participant internally. Afterwards, they were asked to indicate which vibration pattern aided them the most in reaching the target. Using the FerroVibe, the same procedure was carried out, but using a 3-DoF tactile guidance instead. The horizontal and depth positions were indicated by tilting the magnet under the user's fingerpad, whereas the vertical distance to the target was encoded as vibration pulses. The duty cycle increased as the object was moved closer to the target in the vertical dimension, and vice versa.

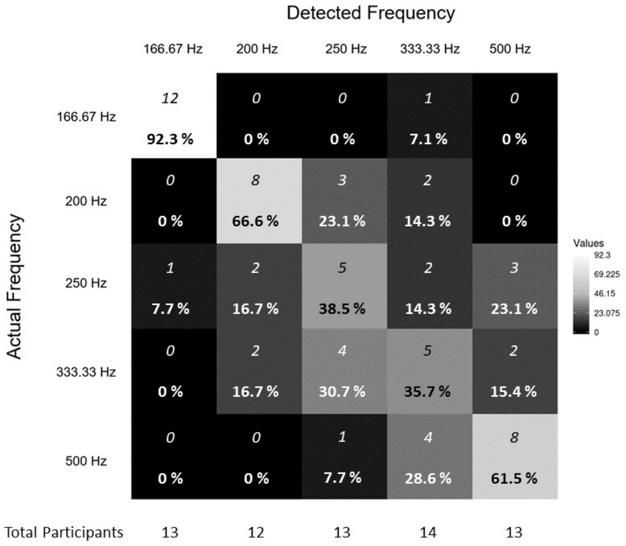
4. RESULTS AND DISCUSSION

Task 1: Contact orientation discrimination

Mean absolute deviations of angles with a 95% Confidence Interval (CI) exhibit a fan-out effect. A repeated measures ANOVA (rmANOVA) on absolute deviations was carried out (with Greenhouse-Geisser [GG.] correction) and results showed no significant effect of angles [$F(3.4; 38.9) = 1.57$]. A quadratic relationship between preset angles and deviation was established in curve-fitting regression analysis [$F(1, 126) = 4.0$; $p < .05$], illustrated by the red curve in Fig. 6 (left panel). In conclusion, deviations and variances increased for larger angles. These results are in line with previous findings on contact force direction discrimination [24], [25]. A possible reason behind the fan-out effect could be the placement of the participants' fingertips on the device, leading to the pressure at the sides of the fingertips being correspondingly lower. Alternatively, it could also be due to the fingertip sensitivity, which might not be uniformly distributed all across the fingerpad.

Task 2: Vibrotactile texture perception

A rmANOVA performed on the subjective ratings (first sub-task) revealed a significant main effect of comparison categories [$F(2.24; 26.84) = 25.29$; $p <.001$; GG. corrected]. Post-hoc comparisons with Bonferroni correction revealed significant mean differences between 166.67 Hz vs 250 Hz ($p < 0.001$) as well as 500 vs 250 Hz ($p < 0.01$). On the other hand, participants were not able to clearly distinguish between 200 Hz as well as 333.33 Hz when compared to 250 Hz in terms of perceived roughness or smoothness. A statistical relationship between the actual and detected frequencies (second sub-task) was evaluated using Kendall's τ. A significant positive correlation was found ($r_\tau = 0.67$; $p < 0.001$). However, detection rates for 250 Hz and 333.33 Hz were below 40%, that is, these values were frequently confused, see right panel of Fig. 7. The present results suggest that indeed different frequencies could be utilized



	166.67 Hz	200 Hz	250 Hz	333.33 Hz	500 Hz
166.67 Hz	12 92.3 %	0 0 %	0 0 %	1 7.1 %	0 0 %
200 Hz	0 0 %	8 66.6 %	3 23.1 %	2 14.3 %	0 0 %
250 Hz	1 7.7 %	2 16.7 %	5 38.5 %	2 14.3 %	3 23.1 %
333.33 Hz	0 0 %	2 16.7 %	4 30.7 %	5 35.7 %	2 15.4 %
500 Hz	0 0 %	0 0 %	1 7.7 %	4 28.6 %	8 61.5 %
Total Participants	13	12	13	14	13

Figure 7: Texture detection results

to augment the texture perception of virtual objects in such simplified scenario. However, because human roughness perception is also affected by stimulus intensity, scanning speed, force amplitude [32], [45] etc., further research is warranted.

Task 3: Stiffness magnitude estimation & production

For the analysis of the stiffness discrimination and production results, values between 2-9 were considered, since 1 and 10 were identical with the reference stimuli provided. By means of magnitude estimation and production the relationship between physical stimulus intensities and perceived magnitude of sensation is investigated. This empirical relationship is described by Steven's power law [46]. For magnitude estimation, a psychometric power function was derived to be: $p = 1.164 \times S^{0.85}$. The psychometric curve reveals an almost linear trend. There was, however, a tendency for response repression of participants. Resulting power function for magnitude production was derived to be: $p = 0.897 \times S^{1.04}$, which revealed a clear linear trend as shown in the right panel of Fig. 6. The observed tendency for response repression is perfectly in compliance with previous experiments, which reveal that a drawback of magnitude estimation tasks is subjects being hesitant to choose extreme values [47]. The linear trend of the magnitude production tasks suggest that participants could successfully perceive the stimulus provided by the tactile device as desired. In summary, clear evidence for a linear relationship between physical stimulation and perception of stiffness was found.

Task 4: Object positioning

Outlier analysis led to the exclusion of one participant. The mean trajectory lengths (in simulation environment) for experiments conducted with the FingerTac were $M_{pattern1}$ = 4.34 m (SD = 2.01), $M_{pattern2}$ = 4.70 m (SD = 2.45), $M_{pattern3}$ = 4.60 m (SD = 2.43). The mean completion times were $M_{pattern1}$ = 13.85 s (SD = 7.84), $M_{pattern2}$ = 14.96 s (SD = 7.43), $M_{pattern3}$ = 13.68 s (SD = 7.69). Subjective ratings indicated highest preference for the non-linear time-invariant pattern, followed by the linear time-invariant pattern, and finally the linear time-variant pattern. No significant main effects were found for both measures in rmANOVA with target position and vibration patterns as within factors.

The mean trajectory lengths and completion times for 3-DoF tactile guidance using FerroVibe, after excluding one participant based on outlier analysis, were $M_{target1}$ = 5.78 m (SD = 3.71), $M_{target2}$ = 8.16 m (SD = 8.23), $M_{target3}$ = 7.12 m (SD = 5.13), and $M_{target1}$ = 18.45 s (SD = 8.01), $M_{target2}$ = 19.1 s (SD = 7.93), $M_{target3}$ = 21.26 s (SD = 7.8), respectively. No significant main effects were observed for both measures in rmANOVA with target position as within factor. A majority of 84.6% of the subjects indicated a preference of continuous vibrations at the target position to no vibrations. Out of 13 participants, 5 preferred the linear time invariant vibration pattern (38.5%), 6 preferred the non-linear time invariant pattern (46.2%), and 1 chose the linear time variant pattern (7.7%). One participant remarked that all patterns felt the same. Overall, the results of this task reveal no significant differences in task performance with respect to target position and vibration pattern for each tested device individually. Although participants indicated a preference for vibration pattern to augment depth cues, the current results suggest that neither pattern provided statistically significant better depth information. Interestingly, even though the FerroVibe provides more DoF—and hence presumably more detailed sensory information—the overall performance in this task was inferior to the task performance with the FingerTac. The subsequent section will investigate both devices on a comparative level in more detail.

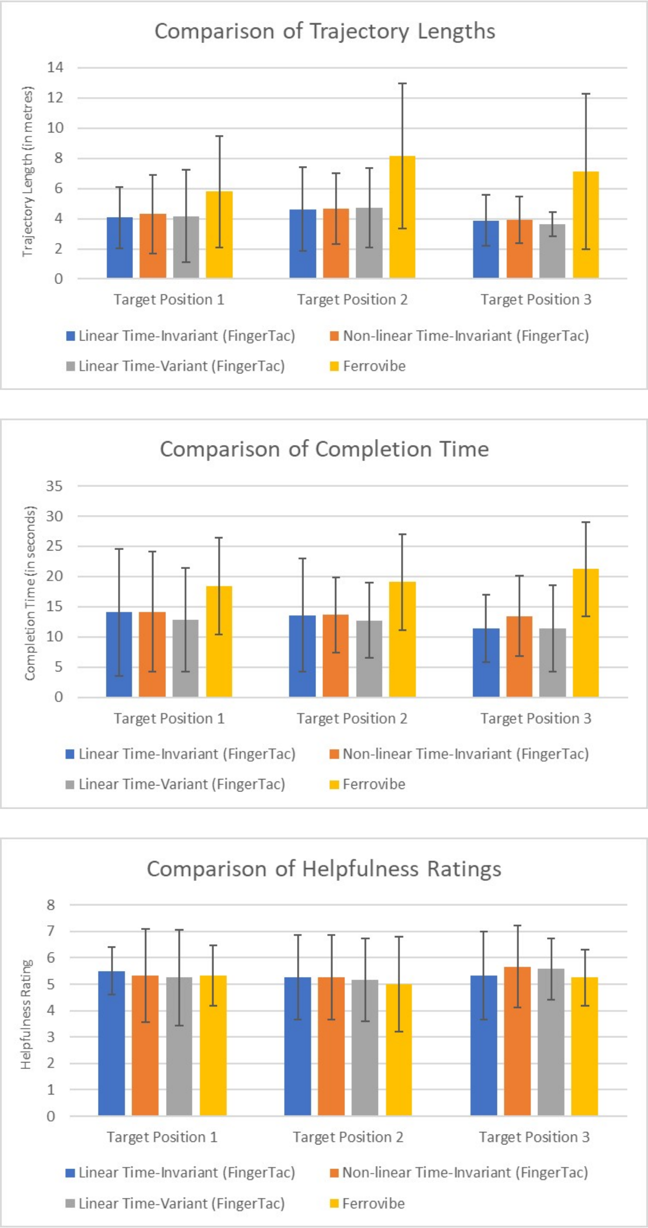


Figure 8: Comparison charts of FingerTac and FerroVibe

Comparison of used devices

Tasks 1, 2 and 4, and the respective VS were utilized to evaluate the FerroVibe, whereas the evaluation of the FingerTac was performed using tasks 3 and 4 along with their corresponding VS. The tasks assigned to the devices were chosen depending on their respective display capabilities. Task 4 was deemed to be most suitable for comparing the two devices, as we could record and compare outcomes such as such as completion time, trajectories, and subjective helpfulness ratings for each device. Both the devices exhibited a similar

Table 1: Performance measures: Mean completion times and trajectory lengths (standard deviation in parentheses) for the different vibration patterns and Target Positions (TP) tested with the FingerTac and FerroVibe.

Device Used	Mean (Standard deviations)					
	Trajectory Length			Completion Time		
	TP1	TP2	TP3	TP1	TP2	TP3
FingerTac (Linear Time-Invariant)	4.08 (2.04)	4.63 (2.78)	3.88 (1.68)	14.05 (10.51)	13.62 (9.41)	11.47 (5.58)
FingerTac (Non-linear Time-Invariant)	4.29 (2.61)	4.65 (2.35)	3.91 (1.53)	14.18 (9.97)	13.65 (6.19)	13.43 (6.67)
FingerTac (Linear Time-Variant)	4.17 (3.04)	4.72 (2.61)	3.63 (0.82)	12.83 (8.56)	12.73 (6.19)	11.4 (7.14)
FerroVibe	5.78 (3.71)	8.16 (4.78)	7.12 (5.13)	18.45 (8.01)	19.1 (7.93)	21.26 (7.8)

level of approval, but subjects evidently performed better in terms of the other two factors wearing the FingerTac than the FerroVibe, as shown in Fig 8 and described in Table 1. This can be attributed to the difference in tactile feedback from the two devices, and with regard to applications analogous to the one in task 4, it can be concluded that the FingerTac might be a more suitable device to use. Although suitable, the other tasks did not provide the same degree of impartiality (on the basis of device display capabilities) to compare the two devices. Moreover, we did not want the experiments to be prolonged to such an extent that users incurred fatigue towards the end. Overall, the present results show how our VR suite can be used to successfully evaluate or compare fingertip-wearable tactile devices.

Evaluation and Implications for ViESTac

All the quantitative and subjective results discussed show that ViESTac can indeed be used to successfully evaluate or compare fingertip wearable tactile devices. On completion of the experiments, participants remarked that the tasks in the VS were intuitive, and the devices and ViESTac were well understandable and easy to use. No participant indicated any signs of fatigue or discomfort incurred during the experiments using our virtual suite, except one participant, who faced difficulty completing the object positioning tasks.

The tasks performed, the procedure, the parameters recorded and the results evaluated were designed to be as generic as possible, in addition to being easily adaptable and transferable to other devices. However, they could only be evaluated using the two tactile devices available at DLR, as explained in Section 3.

Given the nature of the suite developed and ease-of-use of open-source CHAI3D applications along with plug-and-play integration of hardware devices (both kinesthetic as well as tactile) in these applications, it allows a straightforward addition of more scenarios that can contribute to strengthen ViESTac further. While the software was not the main focus of this evaluation, but rather the design of the VS and its interactive tasks, a suite similar to ViESTac may be also realized with other underlying software packages including game engines. We plan on releasing an open-source version of ViESTac for research purposes soon.

5. CONCLUSION

Motivated by telerobotic applications in space, with this paper we introduced ViESTac, a first approach to designing a generic VR suite for assessing and comparing fingertip wearable tactile devices. Its VR scenarios were chosen in an attempt to minimize bias towards specific tactile display capabilities, and are well defined for reproducibility, while also being easily extendable to a wide array of tactile devices. Furthermore, we presented a first pilot study with two wearable tactile devices, namely, the FingerTac, and the FerroVibe. The VR scenarios address tactile object properties as well as position guidance through device dependent actuation cues. This study not only served as a proof-of-concept for the ViESTac suite itself, but also validated the respective device display capabilities. Results revealed that users could successfully discriminate tactile object properties, and that tactile cues from both devices were successful in substituting depth information in a 3D scene.

The present work focused on evaluating and comparing two available tactile devices of the DLR. Different sets of tasks, questionnaires and recorded parameter may be utilized for a selection of other tactile devices, while using the ViESTac suite. In order to extend the sense of touch in VR and for telerobotics by facilitating a wider array of tactile devices, adding further scenarios dedicated to rendering thermal properties or interacting with fluids, might be necessary. Furthermore, future suite and tactile device evaluations could include object shape detection (see VS in Fig. 1b and Fig. 3). Researchers can use our suite as a base and if needed, easily develop, modify or extend existing scenarios to suit the functioning of their device in-use. In addition, this suite has the potential to also be used for the evaluation of kinesthetic devices due to the generic design of its scenarios. The addition of consumer-grade head-mounted VR displays as well as the extension to multi-point interactions could furthermore cater to the experience of a more compelling, immersive, multisensory virtual environment.

Our ViESTac suite is a first step towards an evaluation tool to investigate tactile perception and the suitability of devices under microgravity conditions in future telerobotic space missions. Such a suite would also be important to evaluate novel telerobotic approaches and methods that aim to integrate local and remote models to facilitate task performance, as described in [48].

REFERENCES

[1] A. Schiele, M. Aiple, T. Krueger, F. v. d. Hulst, S. Kimmer, J. Smisek, and E. d. Exter, "Haptics-1: Preliminary results from the first stiffness jnd identification experiment in space," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2016, pp. 13–22.

[2] J. Artigas, R. Balachandran, C. Riecke, M. Stelzer, B. Weber, J.-H. Ryu, and A. Albu-Schaeffer, "Kontur-2: force-feedback teleoperation from the international space station," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2016, pp. 1166–1173.

[3] C. Riecke, J. Artigas, R. Balachandran, R. Bayer, A. Beyer, B. Brunner, J. Buchner, T. Gumpert, R. Gruber, F. Hacker *et al.*, "Kontur-2 mission: the dlr force feedback joystick for space telemanipulation from the iss," 2016.

[4] M. Panzirsch, A. Pereira, H. Singh, B. Weber, E. Ferreira, A. Gherghescu, L. Hann, E. den Exter, F. van der Hulst, L. Gerdes *et al.*, "Exploring planet geology through force-feedback telemanipulation from orbit," *Science Robotics*, vol. 7, no. 65, p. eabl6307, 2022.

[5] B. M. Weber, S. Schätzle, and M. Stelzer, "Aiming performance during spaceflight: Individual adaptation to microgravity and the benefits of haptic support," *Applied Ergonomics*, vol. 103, p. 103791, 2022.

[6] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Transactions on Haptics*, vol. 10, no. 4, pp. 580–600, 2017.

[7] V. Nitsch and B. Färber, "A meta-analysis of the effects of haptic interfaces on task performance with teleoperation systems," *IEEE Transactions on Haptics*, vol. 6, no. 4, pp. 387–398, 2013.

[8] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hRing: A wearable haptic device to avoid occlusions in hand tracking," in *IEEE Haptics Symp.* IEEE, 2016, pp. 134–139.

[9] D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli, "A 3-rsr haptic wearable device for rendering fingertip contact forces," *IEEE Trans. on Haptics*, vol. 10, no. 3, pp. 305–316, 2016.

[10] H. Singh, B. Suthar, S. Z. Mehdi, and J.-H. Ryu, "Ferro-fluid based portable fingertip haptic display and its preliminary experimental evaluation," in *IEEE Haptics Symp.*, 2018, pp. 14–19.

[11] T. Murakami, T. Person, C. L. Fernando, and K. Minamizawa, "Altered touch: Miniature haptic display with force, thermal and tactile feedback for augmented haptics," ser. SIGGRAPH '17. New York, NY, USA: Association for Computing Machinery, 2017. [Online]. Available: https://doi.org/10.1145/3084822.3084836

[12] A. T. Maereg, A. Nagar, D. Reid, and E. L. Secco, "Wearable vibrotactile haptic device for stiffness discrimination during virtual interactions," *Frontiers in Robotics and AI*, vol. 4, p. 42, 2017.

[13] M. Gabardi, D. D. Leonardis, M. Solazzi, and A. Frisoli, "Development of a miniaturized thermal module designed for integration in a wearable haptic device," *2018 IEEE Haptics Symposium (HAPTICS)*, pp. 100–105, 2018.

[14] E. Whitmire, H. Benko, C. Holz, E. Ofek, and M. Sinclair, *Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller*. New York, NY, USA: Association for Computing Machinery, 2018, p. 1–12. [Online]. Available: https://doi.org/10.1145/3173574.3173660

[15] X. R. Cao, "A framework for benchmarking haptic systems," 2006.

[16] M. Sagardia, T. Hulin, C. Preusche, and G. Hirzinger, "A benchmark of force quality in haptic rendering," 07 2009.

[17] F. Fazlollahi and K. J. Kuchenbecker, "Haptify: A comprehensive benchmarking system for grounded force-feedback haptic devices," Work-in-progress poster presented at EuroHaptics, Leiden, The Netherlands, Sep. 2020.

[18] R. Chaudhari and E. Steinbach, "Towards an objective quality evaluation framework for haptic data reduction," 07 2011, pp. 539 – 544.

[19] H. Seifi, F. Fazlollahi, M. Oppermann, J. A. Sastrillo, J. Ip, A. Agrawal, G. Park, K. J. Kuchenbecker, and K. E. MacLean, "Haptipedia: Accelerating haptic device discovery to support interaction amp; engineering design," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, ser. CHI '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 1–12. [Online]. Available: https://doi.org/10.1145/3290605.3300788

[20] S. Okamoto, H. Nagano, and Y. Yamada, "Psychophysical dimensions of tactile perception of textures," *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 81–93, 2013.

[21] T. Hulin, M. Rothammer, I. Tannert, S. S. Giri, B. Pleintinger, H. Singh, B. Weber, and C. Ott, "FingerTac – a wearable tactile thimble for mobile haptic augmented reality applications," in *Proceedings of the International Conference on Human-Computer Interaction (HCI International)*, 2020.

[22] F. Abi-Farrajl, B. Henze, A. Werner, M. Panzirsch, C. Ott, and M. A. Roa, "Humanoid teleoperation using task-relevant haptic feedback," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 5010–5017.

[23] P. Feys, I. Lamers, G. Francis, R. Benedict, G. Phillips, N. LaRocca, L. D. Hudson, R. Rudick, and M. S. O. A. Consortium, "The nine-hole peg test as a manual dexterity performance measure for multiple sclerosis," *Multiple Sclerosis Journal*, vol. 23, no. 5, pp. 711–720, 2017.

[24] H. Z. Tan, F. Barbagli, J. Salisbury, C. Ho, and C. Spence, "Force-direction discrimination is not influenced by reference force direction (short paper)," 2006. [Online]. Available: http://hdl.handle.net/1773/34894

[25] A. Panarese and B. B. Edin, "Human ability to discriminate direction of three-dimensional force stimuli applied to the finger pad," *Journal of neurophysiology*, vol. 105, no. 2, pp. 541–547, 2011.

[26] M. Lévy, S. Bourgeon, and C. E. Chapman, "Haptic discrimination of two-dimensional angles: influence of exploratory strategy," *Experimental Brain Research*, vol. 178, pp. 240–251, 2006.

[27] X.-D. Yang, W. F. Bischof, and P. Boulanger, "Percep-

tion of haptic force magnitude during hand movements," in *2008 IEEE International Conference on Robotics and Automation*, 2008, pp. 2061–2066.

[28] S.-Y. Teng, P. Li, R. Nith, J. Fonseca, and P. Lopes, *Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality*. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3411764.3445099

[29] S. J. Lederman, R. L. Klatzky, C. L. Hamilton, and G. I. Ramsay, "Perceiving surface roughness via a rigid probe: Effects of exploration speed and mode of touch," 1999.

[30] M. Hollins, F. Lorenz, A. Seeger, and R. Taylor, "Factors contributing to the integration of textural qualities: Evidence from virtual surfaces," *Somatosensory & motor research*, vol. 22, no. 3, pp. 193–206, 2005.

[31] C. M. Greenspon, K. R. McLellan, J. D. Lieber, and S. J. Bensmaia, "Effect of scanning speed on texture-elicited vibrations," *Journal of the Royal Society Interface*, vol. 17, 2020.

[32] C. J. Dallmann, M. O. Ernst, and A. Moscatelli, "The role of vibration in tactile speed perception," *Journal of neurophysiology*, vol. 114, no. 6, pp. 3131–3139, 2015.

[33] E. Muschter, A. Noll, J. Zhao, R. Hassen, M. Strese, B. Gülecyüz, S.-C. Li, and E. Steinbach, "Perceptual quality assessment of compressed vibrotactile signals through comparative judgment," *IEEE Transactions on Haptics*, vol. 14, no. 2, pp. 291–296, 2021.

[34] M. Prsa, D. Kilicel, A. Nourizonoz, K.-S. Lee, and D. Huber, "A common computational principle for vibrotactile pitch perception in mouse and human," *Nature communications*, vol. 12, no. 1, pp. 1–8, Sep. 2021.

[35] M. Rothenberg, R. T. Verrillo, S. A. Zahorian, M. L. Brachman, and S. J. Bolanowski Jr, "Vibrotactile frequency for encoding a speech parameter," *The Journal of the Acoustical Society of America*, vol. 62, no. 4, pp. 1003–1012, 1977.

[36] C. E. Sherrick, "A scale for rate of tactual vibration," *The Journal of the Acoustical Society of America*, vol. 78, no. 1, pp. 78–83, 1985.

[37] M. Strese, C. Schuwerk, A. Iepure, and E. Steinbach, "Multimodal feature-based surface material classification," *IEEE Transactions on Haptics*, vol. 10, no. 2, pp. 226–239, 2017.

[38] F. Freyberger and B. Faerber, "Compliance discrimination of deformable objects by squeezing with one and two fingers," *Proc. EuroHaptics*, 01 2006.

[39] G. Paggetti, B. Cizmeci, C. Dillioglugil, and E. Steinbach, "On the discrimination of stiffness during pressing and pinching of virtual springs," in *2014 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE) Proceedings*, 2014, pp. 94–99.

[40] I. Kao and F. Yang, "Stiffness and contact mechanics for soft fingers in grasping and manipulation," *IEEE Transactions on Robotics and Automation*, vol. 20, no. 1, pp. 132–135, 2004.

[41] J. Aleotti, S. Caselli, and M. Reggiani, "Evaluation of virtual fixtures for a robot programming by demonstration interface," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 35, no. 4, pp. 536–545, 2005.

[42] T. Oron-Gilad, J. L. Downs, R. D. Gilson, and P. A. Hancock, "Vibrotactile guidance cues for target acquisition," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 37, no. 5, pp. 993–1004, 2007.

[43] S. Schätzle and B. Weber, "Towards vibrotactile direction and distance information for virtual reality and workstations for blind people," 08 2015.

[44] F. Conti, F. Barbagli, D. Morris, and C. Sewell, "CHAI: An open-source library for the rapid development of haptic scenes," in *IEEE World Haptics Conference (WHC)*, vol. 38, no. 1, 2005.

[45] A. M. Smith, G. Basile, J. Theriault-Groom, P. Fortier-Poisson, G. Campion, and V. Hayward, "Roughness of simulated surfaces examined with a haptic tool: effects of spatial period, friction, and resistance amplitude," *Experimental brain research*, vol. 202, no. 1, pp. 33–43, 2010.

[46] S. Stevens, "On the physiological law," *Psychol. Rev*, vol. 64, pp. 153–181, 1957.

[47] G. A. Gescheider, *Psychophysics: The Fundamentals*, ser. International series of monographs on physics. Lawrence Erlbaum Associates, Mahwah, New Jersey, 1997.

[48] T. Hulin, M. Panzirsch, H. Singh, A. Coelho, R. Balachandran, A. Pereira, B. M. Weber, N. Bechtel, C. Riecke, B. Brunner, N. Y. Lii, J. Klodmann, A. Hellings, K. Hagmann, G. Quere, A. S. Bauer, M. Sierotowicz, R. Lampariello, J. Vogel, A. Dietrich, D. Leidner, C. Ott, G. Hirzinger, and A. Albu-Schäffer, "Model-augmented haptic telemanipulation: Concept, retrospective overview, and current use cases," *Frontiers in Robotics and AI*, vol. 8, p. 76, 2021.

BIOGRAPHY

Premankur Banerjee *received his M.Sc. in Communications Engineering from the Technical University of Munich (TUM), Germany, in 2021. His thesis focused on the development of a generic multi-modal evaluation suite for novel tactile devices. He is currently a research engineer at the human-computer interaction group at Institut des systemes intelligents et robotique (ISIR) lab, working on room-scale haptic interactions for VR.*

Evelyn Muschter *received her B.A. in psychology from Cleveland State University (USA), and her M.Sc. and Ph.D. in cognitive and brain sciences from CiMeC/ Univeristà di Trento (Italy). She is currently a PostDoc at the Technische Universität Dresden (Germany). Her research interests include multisensory perception, brain oscillations and human-machine interaction.*

Harsimran Singh *received his B.Tech. degree in electrical and electronics engineering from Sikkim Manipal Institute of Technology, India, in 2009, his M.Sc. degree in robotics from the University of the West of England, U.K., in 2012, and his Ph.D. degree in mechanical engineering from Korea University of Technology and Education, South Korea, in 2017. Since 2017, he is a research scientist with the Institute of Robotics and Mechatronics at the Germany Aerospace Center (DLR). His research interests include haptics, teleoperation, human-machine interface, and nonlinear control.*

Bernhard Weber *received his diploma in psychology from University of Wuerzburg, Germany, in 2004 and his Ph.D. in 2008. Since 2011 he is the Human Factors Expert of the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR). His research focuses on human-centered development and evaluation of telerobotic systems (e.g., in the field of surgery, nursing, and space robotics) and haptic interaction technologies.*

Thomas Hulin *Thomas Hulin received his Dipl.-Ing. degree in electrical engineering from the Technical University of Munich (TUM) in 2003, and the Dr.-Ing. degree in mechanical engineering from the Leibniz University of Hannover (LUH) in 2017. He joined the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR) in 2003 as a research associate and heads the Telemanipulation Research Group since 2020. He is co-author of more than 60 peer-reviewed scientific articles in international journals, books and conferences. His research interests include haptics (control, devices, and algorithms), telerobotics, physical human-robot interaction, robot visualization, augmented reality, and skill transfer.*