Enhancing Multimodal Interaction for Virtual Reality Using Haptic Mediation Technology

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Abstract. As our interaction in virtual space expands from 2D to 3D, the absence of meaningful touch output restricts our ability to explore new virtual frontiers. The core limitation of not being able to reach out and feel or interpolate an object or sense its texture and form, within a virtual environment, hinders the intuitiveness of the interaction experience. Although, in recent years, tactile feedback has been introduced, as a necessary component of multimodal interaction, the resolution and type of output is still very primitive compared to visual and auditory modalities. For this reason we have developed a radical new approach called 'Haptic Mediation' through which it is not only possible to actively monitor signal integrity and skin sensitivity but also the applied actuation signal, dynamically adjusting the actuation to ensure reliable perception of intended information. In this research, we have extended this technique to develop a self-sensing and actuation haptic glove prototype.

Keywords: Human-Systems Integration · Multimodal Interaction, Haptics, Wearables.

1 Introduction

Human beings interact with external objects or systems using a combination of their core senses. Utilizing these senses, it is possible to interpolate the components of a given system and develop the most efficient method of communicating with it. This ability to learn and adapt, creates the basis of interaction that can be extended to similar environments and systems. When an external system utilizes commonly used interaction techniques (i.e. door knob being rotated clockwise or anticlockwise to open a door), the user of the system is easily able to transition into the particular interaction paradigm, even if the environment or its surroundings vary considerably. This interaction metaphor was first put to the test in the designing and development of 2D virtual environments. In fact, most 2D virtual environments (operating systems such as Windows, MAC or Linux etc.) and the objects within them (i.e. files, folders, menus, etc.) were created to extend the user's understanding of similar interaction, in the physical

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world. This is still the case today and it essentially means that, simple input tools, such as a pointer (mouse) and a text entry device (keyboard), can be sufficient for interacting with complex virtual environments. It was not until the introduction of direct touch based input, that more sophisticated and multichannel interaction tools were needed for effective system interaction.

Furthermore, before the advent of touchscreen based devices, most computing systems, and their virtual environments, primarily engaged the users' visual and auditory senses [1]. This meant that in any environment system usability heavily depended on the user's ability to extrapolate methods of interaction, using only these two modalities. These days, direct touch input complemented with tactile output have become necessary components to support interaction that is more natural. In the last decades, multimodal interaction was extended to include touch output (haptic feedback), however, the resolution and type of output is still very rudimentary. In fact, haptic interaction is used as a form of "confirmation feedback" in most multimodal interaction systems, rather than an active medium of interaction. This may be due to the power and computational requirements of providing a comprehensive haptic-information-channel. For this reason, most touchscreen devices use basic vibrational signals to create rudimentary low-resolution event based feedback, which can only be useful in the presence of other modalities (visual and auditory).

With virtual and augmented reality becoming a more popular approach in system interaction, as well as social interaction, there is a need to redevelop the role of haptics in virtual environments [2]. It may no longer be possible to focus solely on visual and auditory interaction, ignoring the role of haptics. Complex virtual environments such as Virtual Reality (VR) and Augmented Reality (AR) require more comprehensive tactile input and output. For this reason, primitive tactile signals, used in previous systems, need to give way to more precisely calibrated actuation, which is specifically designed for various parts of the body. Furthermore, haptic feedback needs to be redeveloped to create natural tactile actuation as compared to encoded haptic signals, for complex multimodal VR environments. And most importantly, to ensure immersive interaction in VR and AR system, there is a need to develop new interaction devices that can continuously input and output real-time haptic information along with visual and auditory information between the user and the VR system, with similar efficiency, as was done by the mouse and keyboard for 2D virtual environments.

2 Using the Haptic Mediation Concept in VR / AR Environments

In our previous work, we have tried to overcome some of the limitations in creating and providing effective haptic feedback, by introducing a new concept known as "Haptic Mediation". Haptic mediation is a process of effectively relaying the actuation signal from the source (actuator) to the necessary point of contact (receptive fields of the skin), mitigating environmental noise and other internal and external inefficiencies within the system [2]. This is done by actively monitoring signal integrity and skin sensitivity to the applied actuation signal, dynamically adjusting the actuation source to ensure reliable perception of intended signal. Using this approach, we have illustrated [3, 4] that it is possible to actively monitor user interaction, and relay sensible haptic information, to the point of contact in the most efficient manner. Therefore, it is possible to deliver precisely calibrated actuation signals (i.e. vibration, electrical, pneumatic or temperature based) with the help of (an active or passive) medium, which is calibrated for such an information exchange. ln our research we have implemented this concept into a number of 2D interaction devices to gauge the effectiveness of the concept and the results have been quite positive [5, 6]. It is also possible and desirably to incorporate this new technology of "haptic mediation" into VR/AR systems, enhancing user interaction into a more natural and fluid experience.

Conventional techniques of tactile simulation provide direct or indirect actuation signals to the skin, which may not always generate the immersive experience in VR/AR environments. Contrary to how visual and auditory modalities are presented, haptic feedback needs to be precisely calibrated and channeled to provide specific actuation for specific points on the skin (points of contact with virtual objects / environments), to induce the necessary sensory illusions. Haptic Mediation (HM) may be an ideal mechanism to facilitate the exchange of actuation signals from an electro-mechanical source to the bio-mechanical receptors in the skin. In fact, an active haptic medium can calibrate the haptic signal with reference to environmental noise and skin sensitivity requirements by creating a real-time feedback loop between the generated signal and the signal received at the point of contact.

In our previous research [2], we demonstrated that not only can this approach be used to generate tactile illusions [7], but also through haptic mediation it may be possible to stimulate mechanical proprioceptive [8] feedback to the skin. By applying actuation to the muscle tendons (e.g. elbow and shoulder) through haptic mediation, we can induce illusory sensations of complex movements far more accurately than previously possible [9]. As demonstrated by Thyrion and Rolls, strategically applied actuation to various joints and tendons can induce spatial and kinematic perception. Furthermore, research by Rolls et al., [10], shows that it may even be possible to induce virtual two-dimensional movement simulating the sense of straight lines, letters, numbers, and geometrical figures in the horizontal plane. Moreover the authors using direct vibrotactile actuation, through user testing, also achieved 3D figures resembling spirals. We think that with precise and more calibrated actuation signals using haptic mediation, these techniques and their application can be dramatically improved.

Similarly, other actuation techniques, such as funneling and saltation (or hopping effect) [11] can also be improved considerable. By enhancing the simultaneous tactile stimuli presented in two locations on the touch-surface or directly onto the human skin, through haptic mediation, the funneling effect can be made more pronounced. Moreover, because the virtual location of the illusory tactile sensation (phantom object), is somewhere between the pairs of actuators, it can easily be controlled by changing the parameters (such as intensity, phase and duration) of actuation. Thus, dynamically altering the virtually simulated object, which can be ideal for VR and AR interaction. We postulate that by utilizing haptic mediation and existing techniques of generating tactile illusions, it is possible to develop tools that can augment a wide range of haptic illusion for VR / AR environments. In this research, we specifically focus on enhancing funneling and saltation effects through a pair of customized prototype haptic gloves.

3 Advance Haptic Glove: System Design

To enhance funneling and saltation effects we developed a pair of custom haptic gloves with embedded actuation components. The gloves were used to provide localized actuation as well simulated phase shifts and funneling effects between the fingers and the thumb. One of the gloved was layered with a liquid medium to mediate the signals provided by the actuation components while the other provided direct action to the skin. This section elaborates the design and interaction with each of the gloves (Fig.1).

Fig. 1. Various implementations of the Haptic Mediation Glove (HMG) and the Haptic Glove (HG).

3.1 Glove Design

Both gloves had five Tectonic voice coil actuators (TEAX09C005-8) attached to each fingertip and thumb as well as one actuator on the inside of the palm (between the index finger and the thumb). The actuation components were fixed at the tip of each finger of the glove in such a way that when worn the user would have some contact directly with the actuators or indirectly through the liquid medium (as seen from Fig 1). The glove with liquid medium was a custom sown multi-layered glove that had a thin latex glove embedded within it. The latex glove was sealed and filled with inert low viscosity transparent oil (as seen from Fig 1 bottom right). The actuators were attached on the top of the latex glove and the entire assembly was sown into a stretchable cloth in the shape of a glove.

The second glove was similarly designed to the first one. Small pockets were sown inside the glove at the fingertips and the palm area for each actuator. Each actuator was kept in position using these tightly sown thread pockets to ensure the placement and actuation remained constant. As with the first glove, the wiring of the actuators was internally covered using a cloth lining, to ensure the user did not accidentally pull them and sever the connections (Fig.2). All the actuator wiring was channeled down towards the wrist band of the glove and extended outward. A single extra-flexible shielded twisted pair LAN cable was used to connect each actuator separately to a four channel D-class amplified and signal generator This meant that each actuator could be used independently from the others, with a maximum four actuators running at the same time.

Fig. 2. Internal design of the Liquid Mediation layer, Actuator placement and signal attenuation for the two gloves.

3.2 Glove based Interaction

To maximize the quad-channel configuration both gloves were connected to the signal generator and amplified one at a time. Each channel corresponded to one of the actuators positioned on one of the fingers. We then applied actuation pulses with duration of 1, 2 and 3 seconds each within the frequency range of 10-250Hz. The intention was to define specific signals that can generate funneling or saltation effects. We also adjusted to amplitude of the signal between 3-12V at fixed 1A. During the internal testing, we observed that actuator attachment and proximity to the fingertips yielded clear and sharp signals to the skin at even lower voltages. However, frequency, delay and placement (traveling path of the signal) yielded the maximum perceptual variations. Therefore, we decided to use these three parameters as the key variable in the user study.

To test the effectiveness of ‘Haptic Mediation’ technique for virtual reality interaction, we developed two gloves with identical actuation components (Fig. 3). One of the gloves utilized an embedded liquid mediation layer while the other provided actuation directly to the skin contact (fingertip). Actuation components operated at the same signals to generate similar actuation effects across the different experiment conditions, the only difference was how the feedback signals were delivered to the skin contact.

4 User Study

4.1 Testing Methodology

In our internal pilot testing, we observed that some signal parameters affected the tactile illusion of funneling and saltation more than others. These included frequency, delay and the placement (traveling path of the signal) of actuation components. We narrowed down out actuation path to the index finger, the palm and the thumb. This was required due to two key reasons. Firstly, the limitation of having only a quad-channel amplifier and signal generator made it quite challenging to accommodate all five-fingers and the palm accurately at the same time. Secondly, if all five fingers were used in the study alongside the three conditions of each of the three signal parameters (Freq, delay & placement), the user test would become extremely long and difficult to complete. Therefore, for the sake of collecting focused data we limited the user testing to the index finger, the webbing between the thumb and the index finger (inside of the palm) and the thumb itself (as seem in Fig. 3). This approach ensured we had three segments or discrete points of the signal between the tip of the index finger and the tip of the thumb (A, B & C).

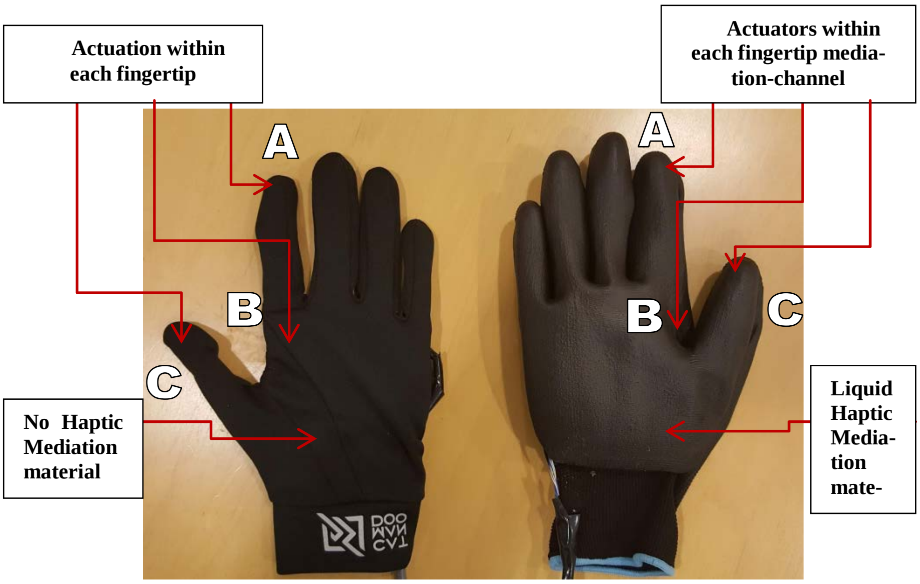

Fig. 3. (*Left*) Glove without Liquid Mediation (HM-Glove), (*Right*) Glove with Liquid Mediation (H-Glove).

For each of the signal parameters, we selected three subsequent values. With frequency, we choose to have 50, 150 and 250Hz signals as it represented low, mid and high tactile signal thresholds most commonly applied to the fingertips. To vary the delay between the different actuator signals we first ensured that the duration of one segment (either A, B or C) of the signal remained close to 250ms, irrespective of the frequency of the signal (50, 150, 250Hz). This meant that each actuator was switchedon for ~250-260ms. We then added delays of -50, 50 and 150ms, where -50ms meant that the second segment (second actuator) was triggered 50ms before the end of the first actuation segment. Delays of 50ms and 150ms were when the second segment (second actuator) was turned-on after the 250ms actuation created by the first actuator. Additionally, the last parameter that was varied was the placement or sequence of the segments being turned on. This meant that participants felt the signal sequence as A-B-C (Index-Palm-Thumb), C-B-A (Thumb-Palm-Index) or B-C-A (Palm-Thumb-Index).

The user study was conducted with 20 participants (17 male and 3 female) and they were provided each feedback signal three (redundant) times after which they were asked to rate the signal and its type in a questionnaire. The participants rated nature (type) of the signal (discrete / continuous) between the three segments (A, B & C). They also evaluated the perceived signal strength as well as the pleasantness of the feedback signal. In total 27 different (unique) feedback signals were provided to each participant for each glove. This was done in such a way that every parameter (Freq., Delay, Sequence of combination) and its sub-value was presented to the user for each glove. This meant that the participants were provided with different frequencies as a sub-parameter (i.e. 50Hz) within which they were provided the three delay sub-parameters (i.e. -50, 50 & 150) and the further three sequence combinations (i.e. A-B-C, C-B-A, B-C-A), with a total of 9 sub-conditions for each parameter value of Frequency. For all three parameter values of Frequency, the total conditions were 27 (each repeated 3 times for redundancy making 81 feedback signals per glove). This approach was used as it provided the most comprehensive method of delivering actuation signals within related signal parameters (Freq., Delay, and Sequence).

4.2 Results of the User Study

Participants rated the provided signal in three categories: nature, sequence or direction and pleasantness. Data for the nature of the signal provided information on how the users perceived the signal (discrete vs continuous). The sequence of the signal was collected by having the users identify which segment the signal traveled through and in what order. While the pleasantness rating was collected to analyze how users perceived the signal variation over the frequency spectrum. The nature of the signal and pleasantness data was collected using 5-point likert scale, whereas sequence was entered in Start-Finish order (i.e. A->B->C). The likert scale data from both gloves was analyzed using a Pearson Chi-Square test, while the sequence data was first broken down into number of errors (1, 2 or 3) using each glove and then analyzed using Fisher’s Exact test. Finally, the experimenter also conducted a freeform interview to review the participants reasoning for each section, focusing on sub-values of the three parameters.

If we look at user rating of nature of signal we saw that the although there were variance between the HM-Glove (HMG) and the H-Glove (HG) there were no statistical differences at 50Hz either for -50ms, 50ms, or 100ms. This meant that the participants were able to identify each signal as a unique (discrete) feedback signal irrespective of the glove technology (Liquid Haptic Medium). The results were similar for 100Hz feedback signal as well, but there was a trend for -50 and 50ms of delay signal that approached statistically significant difference.

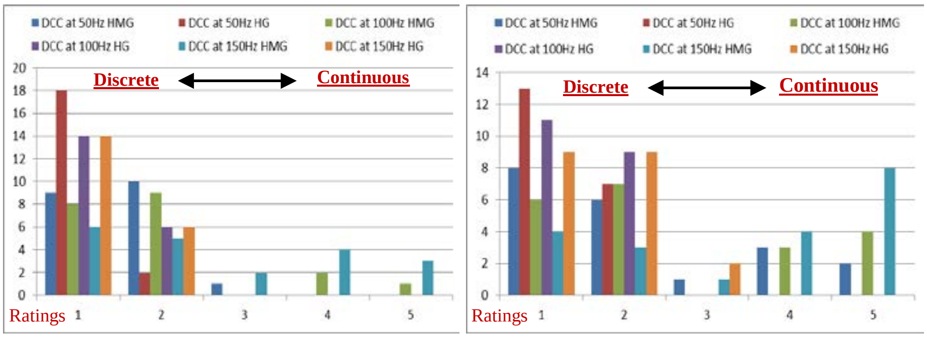

Fig. 4. Subjective ratings of the applied signals averaged over 20 participants (Discrete VS Continuous) over the three frequencies (50Hz, 100Hz, 150Hz) with 100ms (left) and 50ms (right) delay between each signal for both gloves.

A larger sample size would be able to validate this further. Essentially, at a frequency of 100Hz, the difference between the three signals became less distinct for participants using the HM-Glove (HMG), as they started to perceive the discrete feedback signals as one large signal, which was especially visible from the results for signal applied at 100Hz, at -50ms (Fig.4).

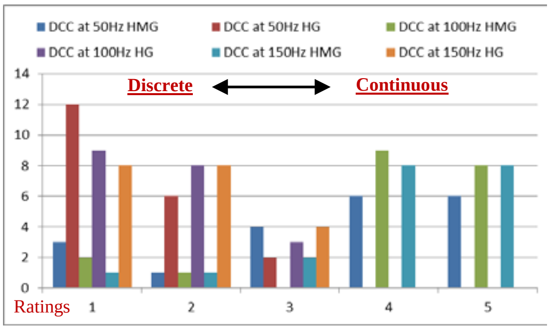

Fig. 5. Subjective ratings of the applied signals averaged over 20 participants (Discrete VS Continuous) over the three frequencies (50Hz, 100Hz, 150Hz) with -50ms delay between each signal for both gloves.

However, once the signal was provided at 150Hz the results show (Fig.5), participants using the HMG perceived the three signals as one continuous signal. However, this was not the case for the HG, where participants could identify the three signals independently with reasonable accuracy. Using Pearson Chi-Square test, we identified that there was a statistically significant difference between the results for the two gloves (HMG and HG) for both -50ms and 50ms of delay at 150Hz. Results were not very clear for the 100ms delay; however, we think this is because of the smaller sample size (Fig.5). Interestingly enough, during the interview, the participants pointed out that the HMG felt more sensible throughout the entire hand as compared to the HG, which created a perception of higher intensity and a non-locality of the signal source.

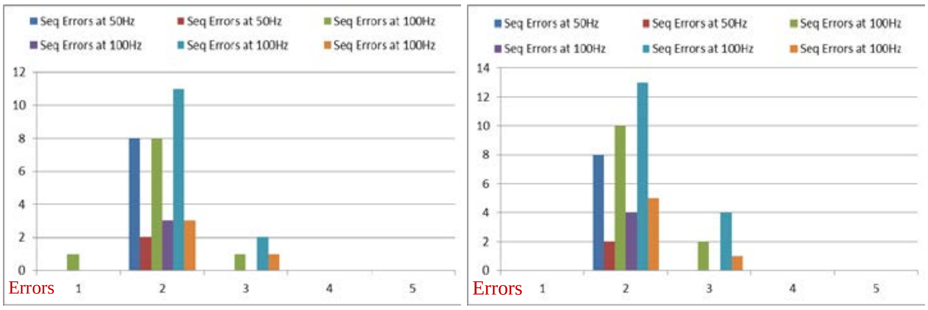

Fig. 6. Error rates for the perceived Sequence of applied signals (number of errors) averaged over 20 participants over the three frequencies (50Hz, 100Hz, 150Hz) with 100ms (left) and 50ms (right) delay between each signal for both gloves.

Looking at the number of errors in identifying the correct sequence of feedback signals on either glove, we see a similar trend (Fig.6). When the signal was provided at 100ms delay, the users were able to identify the sequence quite accurately for both HMG and HG. However, the error rate rose when the delay was reduced to 50ms. Although there was no statistically significant difference between the two gloves for 100ms or 50ms for all three frequencies, we did see a specific trend that HMG increased the error rate enforcing the hypothesis that participants observed the applied signals as one large distributed signals, compared to individual localized signals. This result was more prominent at -50ms of delay for all frequencies (Fig.7), especially at 150Hz, where there was a statistically significant difference between HMG and HG. When questioning the participants regarding their selection, the overwhelming response was that due to actuation signal in the HMG covering most of the hand; it was difficult to isolate one signal from the other. Participant also mentioned that they perceived the same lower frequency signal (especially 50Hz) as a higher intensity signal on the HMG as compared to the HG, while this was completely opposite for the higher intensity signal (150Hz) especially when the delay was -50ms.

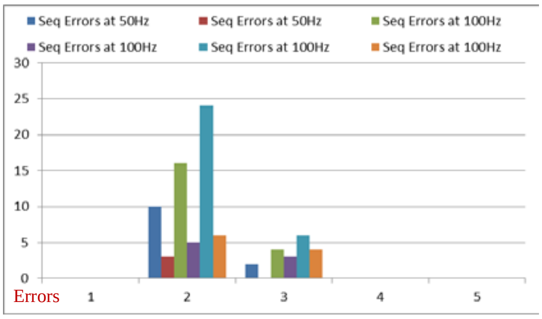

Fig. 7. Error rates of the perceived Sequence of the applied signals (number of errors) averaged over 20 participants over the three frequencies (50Hz, 100Hz, 150Hz) with -50ms delay between each signal for both gloves.

Looking at how users rated the overall pleasantness of the various signals applied to the two gloves (Fig.8), we also see an interesting trend. As expected, no clear variations were seen between the different delay values; however, there were difference with reference to the three frequency values. For signal 100Hz and below, there were only minor differences as participants rated the HMG higher than the HG. However, for 150Hz frequency there was a clear deference between the two gloves, as users rated HG to be less pleasant. This was over all the three-delay parameter (Fig.8), which meant that due to the higher frequency and its unpleasant application directly to the skin, the users perceived this type of feedback as too strong and somewhat disconcerting. Furthermore, the participant added in the interview that the acoustic noise of the actuators, which was higher in the HG added to the unpleasantness during interaction.

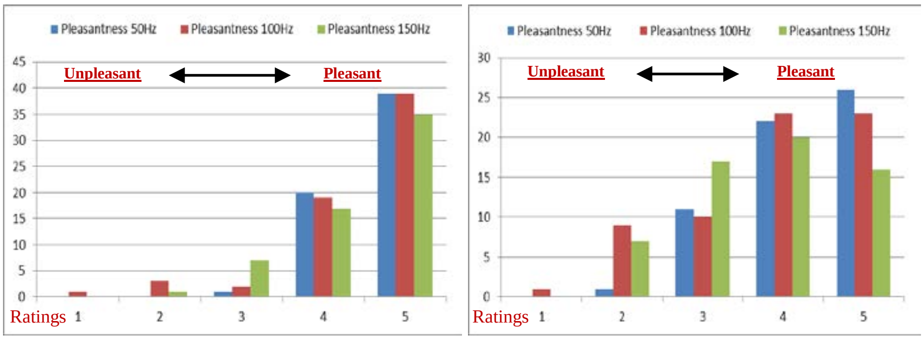

Fig. 8. Subjective ratings of pleasantness for the applied signals averaged over 20 participants over the three frequencies and delay parameters for HM-Glove (left) and Haptic Glove (right).

However, in the HMG where the actuators were not connected to the skin directly, the medium acted as a filter to the 150Hz applied signal, integrating the signal to remove the unpleasantness of the feedback. During the interview, most participants were asked about the overall strength of the signal between the two gloves, and their perception variations between them were quite low. Retrospectively, perceptual strength of the signal could also have been measured (rated) in the main questionnaire as higher frequency feedback signals could have been perceived at higher intensity signals. Measuring the acoustic noise could have been another useful metric to distinguish the two gloves and their actuation signals, as in the post-test interview all the participants mentioned the lack of acoustic noise on the HMG was one of the key reasons for the higher pleasantness rating.

5 Discussion and Conclusions

In this paper, we presented a comparison of two types of haptic gloves for VR interaction: A conventional glove (H-Glove with embedded actuators that directly contact the skin) and a glove layered with tactile mediation mechanism (HM-Glove with a liquid mediation layer between the embedded actuators and the skin). Both the gloves were embedded with identical actuation components and were provided similar electrical signals to general compatible tactile feedback. As with previous results [2, 3, 4, 5, 6], the use of haptic mediation enhanced the actuation signal over a larger area while dampening the acoustic noise of the actuation components. This research also showed that an efficient mediation mechanism can improve the overall haptic feedback experience.

The HM-Glove used in the research, provided increase area of actuation as compared to H-Glove using identical actuation components. The glove also integrated multiple actuation sources, creating complex tactile signals, which were perceived as far more pleasant. Moreover, as the application of a haptic medium is able to integrate specific actuation signals and frequencies, it is possible to create a far richer and more natural feedback mechanism as compared to conventional direct skin actuation methods. This opens up tactile simulation in a way that is not possible conventional techniques. This is because an ideal medium cannot only amplify and localize certain actuation (lower frequency) signals but also integrate other (higher frequency) signals to simulate complex textures and object tactility without introducing unpleasant actuation frequencies.

Although further evaluation may be needed to ascertain an improved configuration and technology (i.e. structure and chemical properties of the mediation material or gel-structure), the results clearly, indicate the effectiveness of the proposed approach utilizing haptic mediation in glove-based VR interaction. Furthermore, it may also be possible to combine a number of actuation signals to provide a complex tactile feedback without limiting individual signal parameters due to inefficiency of transfer or intensity variations within similar frequency bandwidths. In our future research, we plan to explore how it may be possible to combine two or more signals within a complex haptic stimuli yet keeping the signal perceptual integrity, thereby achieving true form of complex haptification

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References

1. Nukarinen T., Kangas J. Kangas, Rantala J., Pakkanen T., and Raisamo R. (2018). Hands-free vibrotactile feedback for object selection tasks in virtual reality. Presented at the 24th ACM Symposium on Virtual Reality Software and Technology. DOI: 10.1145/3281505.3283375
2. Farooq, A. (2017). Developing technologies to provide haptic feedback for surface based interaction in mobile devices, PhD Thesis, University of Tampere, Faculty of Communication Sciences. http://tampub.uta.fi/handle/10024/102318.
3. Farooq, A., Evreinov, G., Raisamo, R., Takahata, D. (2015). Evaluating Transparent Liquid Screen Overlay as a Haptic Conductor. In Proceedings of IEEE SENSORS Conference. DOI: 10.1109/ICSENS.2015.7370186

4. Farooq, A., Evreinov, G., Raisamo, R. (2016). Evaluating Different Types of Actuators for Liquid Screen Overlays (LSO). In Proceeding of IEEE Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS, DTIP'16, 97-102. DOI: 10.1109/DTIP.2016.7514847.
5. Evreinov, G., Farooq, A., Raisamo, R., Hippula, A., Takahata, D. (2017) Tactile imaging system, United States Patent 9672701 B2 · Filed: 07/08/2015 · Published: 06/06/2017. Assignee: TAMPEREEN YLIOPISTO (Tampereen yliopisto, FI) and FUKOKU CO., LTD. (Ageo-shi, Saitama, JP)
6. Evreinov, G., Farooq, A., Raisamo, R., Hippula, A., Takahata, D. (2017) Haptic device, United States Patent 9789896 B2 · Filed: 07/08/2015 · Published: 10/17/2017. Assignee: TAMPEREEN YLIOPISTO (Tampereen yliopisto, FI) and FUKOKU CO., LTD. (Ageo-shi, Saitama, JP)
7. Lederman. S.J., & Jones L.A. (2011) Tactile and Haptic Illusions. IEEE Trans. on Haptics, 4(2): 273-294.
8. Albert, F., Bergenheim, M., Ribot-Ciscar, E., Roll, J.-P. (2006) The Ia afferent feedback of a given movement evokes the illusion of the same movement when returned to the subject via muscle tendon vibration. Exp Brain Res 172: 163-174.
9. Roll, J.-P., Albert, F., Thyrion, C., et al. (2009) Inducing Any Virtual Two-Dimensional Movement in Humans by Applying Muscle Tendon Vibration. J. of Neurophysiology 101(2): 816-823.
10. Thyrion, C., and Roll, J.-P. (2010) Predicting Any Arm Movement Feedback to Induce Three-Dimensional Illusory Movements in Humans. J. Neurophysiol 104:949-959; doi:10.1152/jn.00025.2010.
11. Leonardis, D., Frisoli, A., et al. (2012) Illusory perception of arm movement induced by visuo-proprioceptive sensory stimulation and controlled by motor imagery. IEEE Haptics Symp., pp. 421-424.