Head-Mounted Display with Mid-Air Tactile Feedback

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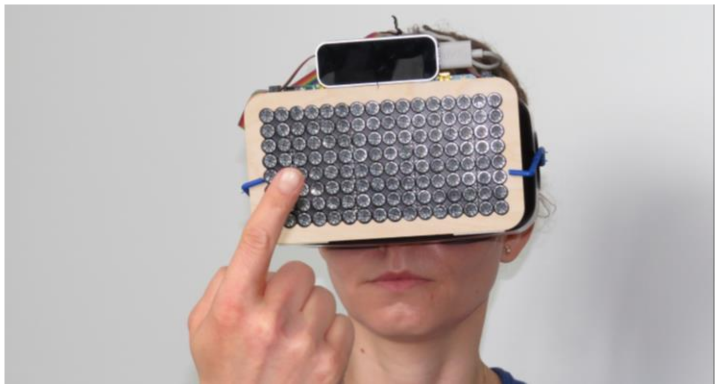

Figure 1: *A modulated ultrasonic phased array integrated to a head-mounted display can provide tactile feedback in mid-air.*

Abstract

Virtual and physical worlds are merging. Currently users of head-mounted displays cannot have unobtrusive tactile feedback while touching virtual objects. We present a mid-air tactile feedback system for head-mounted displays. Our prototype uses the focus of a modulated ultrasonic phased array for unobtrusive mid-air tactile feedback generation. The array and the hand position sensor are mounted on the front surface of a head-mounted virtual reality display. The presented system can enhance 3D user interfaces and virtual reality in a new way.

To evaluate the tactile feedback together with visuals on an Oculus Rift VR headset, we had 13 participants do a simple virtual keypad tapping task with and without tactile feedback. The results indicate that while the measured speed and accuracy differed only a little, the subjects were nearly unanimous in that they preferred to use the tactile feedback. The “raw” NASA TLX questionnaires conducted after use revealed that the participants felt slightly less mental, physical and temporal demand with the tactile feedback. The participants’ self-assessment of their performance was also higher with the tactile feedback.

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1 Introduction

The first head-mounted display (HMD) employing 3D graphics and head tracking was envisioned already 50 years ago [Sutherland 1965] and implemented in 1968 [Sutherland 1968]. Recent HMDs can be categorized to *immersive* HMDs, optical *see-through glasses* and *peripheral displays*. Immersive HMDs (e.g., Oculus Rift) block out reality and replace it with a synthetic one. See-through glasses (e.g., Meta Pro) have a form factor of eyeglasses and they show synthetic objects on top of real ones. *Peripheral* near-to-eye displays cover only a small area of the human visual field at the edges. They are typically monocular and small.

Hand gestures are a natural and intuitive way of pointing or selecting with HMDs [Billinghurst et al. 1998]. Modern gestural sensors such as the Leap Motion Controller[1] or small depth cameras can be mounted on or embedded in HMDs to let users interact through mid-air hand gestures. Mid-air gestures, however, suffer from the lack of tactile feedback that is an important part of the feedback mechanism when interacting with physical objects.

When an HMD is used, often only vision- or audio-based affirmation for the interaction with virtual objects is provided. Data gloves or desktop or wearable haptic hardware can provide tangible sensation [Freeman et al. 2014], but often the devices are

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

tethered, obtrusive or the interaction is indirect. In all fairness, the same can be claimed also about HMDs.

Interaction in virtual reality (VR) without tactile feedback may feel unreal and can lead to uncertainty. The user may wonder: “did the action register”, or “am I pressing a button or just waving my hand in front of it”. Mid-air tactile feedback can make the experience feel more natural and reassure the user that the hand was indeed in contact with the virtual object.

Our contribution in this paper is to demonstrate a mid-air tactile feedback system that can be built into the front surface of an HMD (Figure 1). We also conducted a small experiment to measure the performance and subjective impressions on tactile feedback when using the tacto-visual HMD. We utilized a self-constructed proof-of-concept prototype of an ultrasonic transmitter array with 128 transducers. It enables tactile interaction with virtual objects. In addition to the experiment with the Oculus Rift DK2[2] HMD, we informally tested the prototype with a Homido[3] HMD for smart phones to enhance virtual objects with mid-air tactile feedback. As discussed later in this paper, the system has interesting implications for 3D UIs, VR and other 3D applications.

In this paper we first discuss previous work and then present our mid-air tactile hardware implementation and how it is merged with HMDs such as Oculus and Homido. We describe and discuss the results of user tests and finally give conclusions.

2 Previous Work

Many kinds of 3D user interfaces [Bowman et al. 2004] and devices can benefit from mid-air tactile feedback. Any interface that relies on the user's hand touching objects in VR has potential to benefit from mid-air tactile feedback. Potential usage situation include keyboard use (as in our experiment), sensing of ephemeral elements such as wind or rain, touching objects to feel, move or deform them, feedback from controlling abstract data visualizations, etc.

Prior to the emergence of mid-air haptics, meaningful touch-based interaction was limited to touch detection and tactile sensation through the touched surface. Wider-range tactile feedback required tactile data gloves [e.g., Ku et al. 2003] or other wearable haptics hardware. A comparison of various ways of providing tactile feedback without touching the device has been published recently [Freeman et al. 2014].

Mid-air tactile stimuli mechanisms with air jets or vortex launching [Gupta et al. 2013; Sodhi et al. 2013] can give tactile feedback, but they are coarse and relatively slow for real-time interaction.

Recently several systems of focused acoustic air pressure for providing aerial tactile feedback have been reported [e.g., Carter et al. 2013; Hasegawa and Shinoda 2013; Hoshi et al. 2009; Inoue et al. 2014; Iwamoto et al. 2008; Long et al. 2014; Monnai et al. 2014; Palovuori et al. 2014; Sand et al. 2015; Takahashi and Shinoda 2010; Wilson et al. 2014]. The phased ultrasonic transmitter array focuses the ultrasound signals to one or several focal points. Mid-air tactile feedback is not suitable for large distances of several meters from the transducers, as that would require massive ultrasonic arrays. Mid-air tactile feedback is unobtrusive and maintains the user’s freedom of movement in the target area.

Some mid-air tactile feedback systems [Hoshi et al. 2009; Inoue et al. 2014; Long et al. 2014; Monnai et al. 2014; Sand et al. 2015] have also been merged with display devices such as 3D monitors or mid-air reach-through particle displays. All of them used *stationary* ultrasonic arrays so that the user needed to stay close to the array in order to receive the tactile feedback.

Several works on measuring perception of ultrasonic tactile feedback have been published [Ryu et al. 2010; Wilson et al. 2014; Yoshino et al. 2012]. The human sense of touch in fingers and palms is found to be the most sensitive to vibration of 150 – 250 Hz [Ryu et al. 2010]. A good form of mid-air tactile feedback for a button click has been reported as a single 0.2 s burst of 200 Hz modulated ultrasound [Palovuori et al. 2014], where all test subjects described it to be an 'unmistakable' and confirming response functionally equivalent to a physical button click.

3 Mid-Air Tactile Feedback Array

Head-mounted displays seem to be a natural match with mid-air tactile feedback, as the tactile actuator can be attached to the HMD and thus it can be moved freely with the user. The head mounted ultrasonic array is always pointing to the active field of view of the user.

We created a 2D ultrasonic array, which consists of two infinitely tileable ultrasonic array modules (64 transducers each), thus the whole array has 128 transducers. The system is connected via a USB serial port to a PC, which controls the generation of the tactile feedback effects. Finger or hand is tracked with Leap Motion controller. Figure 2 shows the structure of the transducer array and its control system.

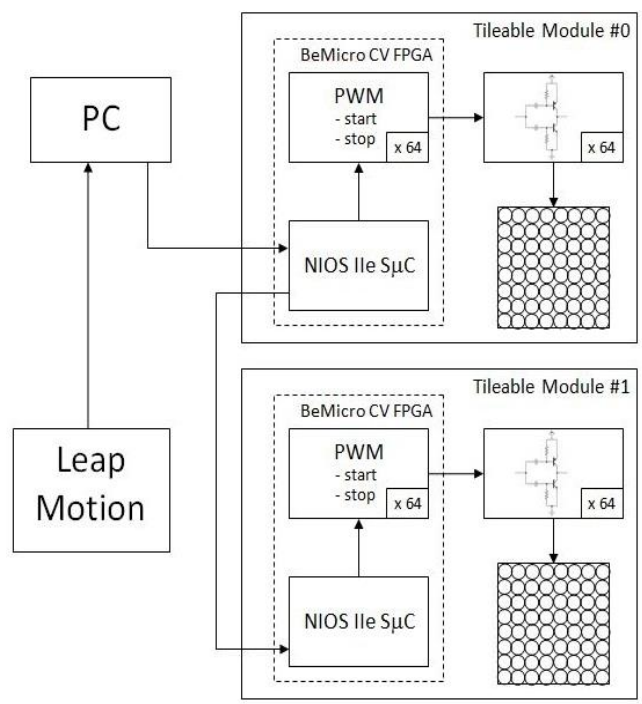

Figure 2: *The ultrasonic transducer array and its control.*

Each ultrasonic array module consists of 64 low-cost 40 kHz transmitters with 64 dedicated, local discrete transistor amplifiers

[2] https://www.oculus.com/

[3] http://www.homido.com/

and a FPGA board with 64 high-resolution pulse-width modulation (PWM) generators marshalled by a NIOS IIe soft processor. We used Multicomp MCUST10P40 B07RO ultrasound transducers.

We integrated a custom voltage amplifier directly below each transducer, being thus able to dispense with the multitude of cables and amplifier boards typical for these kinds of systems. The phase and amplitude of each of the transducers is controlled with 1024 and 512 steps, respectively. The modulation signal is generated directly by the FPGA boards and does not require real-time external control. The modulation frequency can be set freely from 0 Hz to 400 Hz, although at these limits the effect becomes unnoticeable.

We stacked a FPGA board below the transducer board, which makes each module self-contained, requiring only a power supply and high level commands from the application. Figure 3 shows the ultrasonic transducer array for HMD.

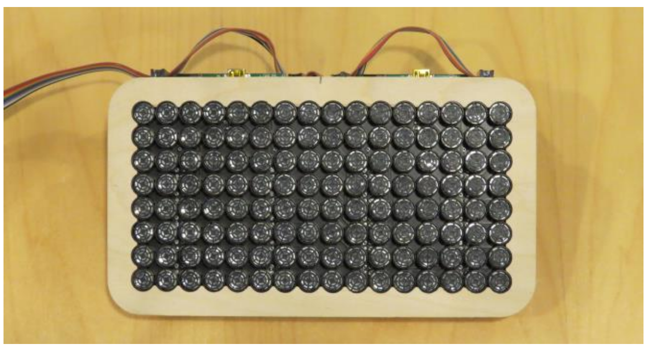

Figure 3: *The 16x8 phased ultrasonic transducer array.*

The 64 ultrasound channels are generated by 64 PWM circuits, which are controlled by individually selectable pulse start and stop times. The timing is relative to a 10-bit counter running at 40.96 MHz resulting in a constant 40 kHz pulse frequency. The amplitude of each ultrasound channel is controlled by its pulse width and the phase by its pulse phase. The amplitude A of the relevant 40 kHz sine component of the harmonic content of a 40 kHz pulse wave depends on the pulse width W non-linearly as

$$A = A_0 \frac{2}{\pi} \sin\left(\pi \frac{W}{T}\right), \quad (1)$$

where A_0 is the pulse wave amplitude and T is the cycle time, i.e., 25 μs. Thus, the amplitude changes from 0 to the maximum of $A_0 \frac{2}{\pi}$ as the pulse duty cycle increases from 0 % to 50 % and similarly returns to 0 as the duty cycle increases to 100 %. Due to this mirroring, there are 9 bits of actual amplitude control while full 10 bits of phase control for each ultrasound channel. Since the steepest slope for the non-linear amplitude response is $\pm\frac{\pi}{2}$ (at 0 % and 100 %), i.e., less than 2, the worst case local resolution of the amplitude is still better than 8 bits. If this worst case is used to quantify the amplitude levels, the result is approximately 326 levels, which coincidentally happens to be very close to the 320 reported in [Hasegawa and Shinoda 2013].

To create a single ultrasonic focal point, it is only necessary to adjust the phases of the channels to coincide at that point. This requires calculating the distance to each transducer and compensating the transmission delay by advancing the phase accordingly.

To create a more complex pattern, e.g. consisting of multiple foci and/or nulls or even an arbitrary force field, the optimal set of phases and amplitudes need to be solved. This was reported to be computationally challenging for real time response [Wilson et al. 2014], but we found a sufficient approximation to be within the reach of the modest NIOS IIe for real-time response. Of course, with a FPGA, the calculations could ultimately be assisted in hardware, too.

Since the human sense of touching fingers and palms is found to be the most sensitive to vibration of 150 – 250 Hz [Ryu et al. 2010], we provided an option to hardware modulate the 40 kHz ultrasound carrier on and off at 200 Hz to create a strong tactile vibrating signal. To avoid generating audible 200 Hz noise as a side-effect, every other channel was turned off by setting it to 0 and every other to 1. In other words, the gross DC signal level of the entire array is kept at 50% at all times. This approach is advisable in normal operation, too, by using the pulse widths of 0 - 50 % for the odd and 50 – 100 % for the even transducers to balance the total array DC component. While the transducers are very resonant, having a Q of about 40, audible frequencies are still easily converted to noticeable sound, due to the high overall signal level. The high Q also limits the modulation rate to 1 kHz, which is not a significant restriction, but results in an additional 1 ms delay to the system response time.

The maximum power requirement is 700 mA / 24 V for the array, and 200 mA / 5V for the FPGA board. Instead of the power cable, a rechargeable battery could be used for the array for light to modest use, especially in case of smartphone-based HMDs such as Homido, which don't have any cables attached (unlike Oculus).

The 10 mm diameter transducers were placed in a 16x8 matrix (160x80 mm, roughly the same as the front plate of Oculus Rift and similar HMDs) to obtain high packing density and a simple and ordered structure for the driving electronics. Maximum depth of the array is 29 mm. The weight of our ultrasound array without cables is 253 g.

The ultrasonic focal point can be created to a desired three-dimensional location in front of the array. The focal point can also be beyond the matrix area, but the further the focus point is projected, the weaker the tactile effect becomes. The system automatically phases each of the transducers in the array to produce a coherent focus of the 40 kHz carrier at the intended point of feedback. The very strong local ultrasound pressure gives rise to radiation pressure pushing the skin slightly. When the ultrasound is modulated (i.e. turned on and off repeatedly), it creates stronger vibration to the skin, and thus the touch becomes much clearer and more noticeable than without modulation.

The phased array is able to generate a clear and tactile focal point with an active spot size of about 10 mm at 100 mm distance. This is close to the Visio-Tactile Threshold reported in [Yoshino et al. 2012]. The typical response time of the system is about 2 ms, dominated by the phased array transducer response time (1 ms) and the sound travel time (~30 cm/ms).

4 HMD with Mid-Air Tactile Feedback

The Leap Motion controller and the ultrasonic transducer array were mounted on the front surface of the Oculus Rift DK2 HMD. The Leap Motion tracked user's finger and hand, and detected when the interactive VR objects and the tip of the index finger of the hand model intersected. The haptic and visual feedback was then given. The feedbacks were played to their full duration of 0.2

seconds regardless of what happened to the intersection during the feedback. The ultrasound was focused onto the center of the pressed key.

As far as we know, there are no earlier implementations of ultrasonic arrays embedded into head-mounted displays. We also made a version for Homido HMD, but that was not used in the user tests.

Figures 1 and 4 show a person wearing our tactile Oculus Rift DK2 prototype. While it is important to be able to dynamically focus the feedback to a point where the fingers are in contact with the virtual model, the volume in which the feedback is needed can be made fairly small in practical implementations. First of all, the comfortable depth range of touching with the hand is limited by the length of the arm. Secondly, working very close to one's own face does not feel comfortable. Furthermore, the HMD limits the shortest possible distance. The needed range can be further reduced by scaling the virtual space so that full arm extensions and interactions very close to the face do not happen.

Figure 4: *Mid-air tactile feedback can focus ultrasound waves to user's finger or palm, which are here tracked with Leap Motion. The system can be used with any HMD, here with Oculus Rift.*

Also, people generally tend to turn their heads so that they face the area where they are looking at [Foulsham et al. 2011]. Thus, the effective volume of our array covers a very large percentage of the interaction situations.

If the point of interaction is known in advance, as is the case for the push buttons in our user study, all the necessary calculations can be computed and tabulated beforehand. For larger or more freeform interaction, these calculations may increase the response time. Still, for a single focal point anywhere within the effective volume, the calculations are easily performed by a low-end microcontroller in real time.

In informal tests with the prototype we found that the user can get a reasonably strong tactile sensation up to 30 cm from the ultrasound array. Adding the thickness of the display and the array, the maximum distance from the face is almost 50 cm. The focus point is best felt if the hand is slightly moving and not stationary. Longer range sensation beyond 30 cm is still perceptible but rather weak. By using more ultrasonic transducers, a tighter focus with much higher intensity can be produced. At some point, however, the size of the array becomes impractical for head-mounted use. We found the 128 transducer array a reasonable compromise between sensation intensity and array size.

The tactile sensitivity of human hand varies widely in different parts of the skin [Pont et al. 1997]. Fingertips and the palmar side of the hand are the most sensitive for vibration caused by ultrasonic pulses. The dorsal side of the hand and most other body parts are significantly less sensitive – in fact the persons that tested it could feel only very weak effect or nothing at all on the dorsal side. Thus hand orientation has an effect for the use of the tactile HMD. Dorsal push gesture (back of the hand pointing towards and moving away from the user and HMD) is ergonomically a little easier to execute, but a pull gesture with the palm facing the array is required for sensing the tactile effect. The user should be guided to orient the hand so that the use the palmar side faces the ultrasonic array in order to gain the maximum tactile effect.

There are several built-in near-infrared LEDs on the front plate (and on all the sides) of the Oculus Rift HMD. Oculus Rift DK2 has an external IR camera which tracks the LEDs and they are used for positional tracking. Our ultrasonic array hides many of the LEDs and thus positional tracking may not be as reliable as normally. This is not an inherent problem in our design. It would be easy to embed both the ultrasonic array and the infrared LEDs to the Oculus front plate. Furthermore, most smart phone-based HMDs such as the Homido do not have IR LEDs, as their tracking is based solely on the sensors embedded in the smartphone.

As the Leap Motion controller and the phased array are attached to the Oculus HMD pointing at the perceived viewing direction, both the hand tracking and tactile feedback occur naturally in front of the eyes no matter which way the user is looking at. As the user can see a representation of the tracked hand in the virtual environment, it is easy to actually point at and feel the virtual UI elements. The tactile effect can cover the field of view of the HMD at the distance of 30 cm.

5 User Tests

In order to evaluate the HMD-based tacto-visual display, we compared it with and without the tactile feedback in an object touching task. The goal of this initial user test was to get insight in performance, usability, and preference.

Participants

We recruited 13 participants (2 female, 11 male; from 23 to 47 years old, with a mean age of 32) from the laboratory staff and students. None of the participants had previous experience with mid-air ultrasonic haptics.

Recruiting "in house" participants may lead to a bias, but recruiting random people might also lead to a bias because the HMD and ultrasonic tactile stimulation are "pretty cool" to a layman. We hoped the technology savvy participants would be more objective and critical. However, we have no data to support this hope and our results should be read with caution given the convenience sampling method we employed for participant recruitment. A key for collecting reliable user experience data would be to do long term studies to get past the initial positive reaction. These were, however, beyond our means at this time.

Apparatus

The test hardware consisted of the mid-air tactile HMD built around the Oculus Rift DK2 as explained above. We also created a semitransparent virtual 3x2 numerical keyboard, which appeared to be about 30 cm away from the user. The keyboard followed head movement, i.e., it was always in the same position in front of the user. This eliminated the problems that covering the frontal LEDs in the Oculus HMD might have caused with motion tracking.

Figure 5 shows the virtual environment with number keys to be touched. Key “2” has become red for 0.2 seconds as it is being touched. The Figure also shows how the task is directed by giving the next numbers to be touched on the upper area of the scene. When a number is entered, the current number is surrounded with angled parentheses (see number “1” in the Figure).

Figure 5: *View of the virtual test environment with numerical keyboard. It shows also the skeletal representation of the user's hand touching a key and the key “2” in the red state that lasted for 0.2 seconds.*

Design
To test the effect of the tactile feedback, we ran a simple keyboard task in two different conditions. The independent variable was the presence of tactile feedback. The visual feedback was identical in both conditions.

The dependent variables were measures of tapping performance (text entry rate (based on the times between pressing 1st and 2nd key and pressing 2nd and 3rd key) and error rate) and subjective ratings of workload. Timing of the first keypress was not comparable to keys 2 and 3 because the starting point of the action could not be clearly determined. For keys 2 and 3 the timing started from the previous key press. At the end of the experiment we also asked whether the participants preferred to have tactile feedback or not and why.

Procedure
Upon entering the laboratory the participants read and signed an informed consent sheet. It was emphasized that they may interrupt the experiment for any reason if they so wish and were told to interrupt immediately if they sensed any signs of simulator sickness, which is a real possibility in experiments with immersive VR. We instructed the participants to use the hand palm towards the array to standardize the experiments, but we had no other strict controls regarding the technique of completing the task.

The users were seated on a chair and fitted with the HMD. In addition to the headset the participants wore over-the-ear hearing protectors. This was to block the slight buzzing sound that the ultrasonic array may create when operating. In this experiment we wanted to measure the effect of tactile feedback only.

A block of number entry consisted of 15 tasks (with or without tactile feedback). Each task consisted of entering 3 random numbers, which were randomized for each task and participant. Each participant first completed training and practice blocks with a tutor in each condition. The results from the actual testing blocks are reported below.

The order of tactile vs. no tactile was balanced between participants. After the training, the next two blocks were completed in the same order as the training blocks. Generally there was clear improvement in performance between the training blocks and the recorded blocks indicating that learning might further improve performance, but this is a topic for further work.

Pressing a key was indicated with a 0.2 second visual flash on the key (see Figure 5). When tactile feedback was active, also a single focal point was projected in front of the key for the same 0.2 s. Whatever part of the hand or fingers was on the location received the feedback. In other words, the feedback was given based on the key locations, not based on the hand location and shape.

For each block the users entered 15 sequences of 3 numbers. The numbers were presented in a virtual environment as shown in Figure 5. The participants were asked to memorize the 3 numbers before they started entering them. Recording started when the first key was pressed. Timing was possible only for the two latter numbers because the starting time of the first key press was unclear. However, all errors, including those made when pressing the first key, were recorded.

All pressed keys were registered but only correct numbers were accepted by the system. Touching wrong numbers caused the same feedback (visual and tactile) as touching correct numbers except for that the task display (the three number sequence) did not change for incorrect presses.

After each non-practice block the participant took off the headset and filled in also a TLX questionnaire on paper. To simplify the participant's task, we used the so called “raw” TLX without the weighting portion [Hart 2006].

After all 4 blocks were completed, the participant answered a question on whether he or she preferred to have the tactile feedback or not. A typical completion time for the experiment was 10 minutes.

6 Results

The system recorded automatically the entered values and their timestamps. From those we calculated the entry speed (in characters per second (CPS)) and error rate. The error bars in Figure 6 and Figure 7 show the standard deviation.

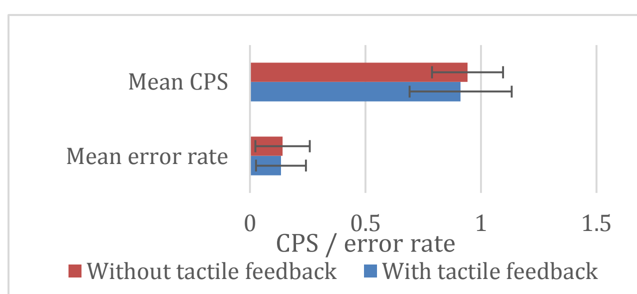

Figure 6: *Characters per second and error rate on both sets with and without the tactile feedback.*

TLX
The TLX had a scale of 0 (very low) to 21 (very high) on mental, physical and temporal demand, perceived performance, perceived effort and frustration. Figure 7 shows the average responses with and without tactile feedback.

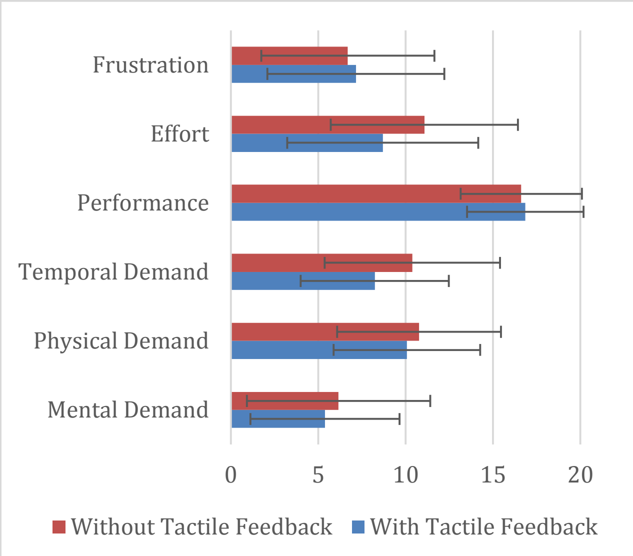

Figure 7: *TLX averages with and without tactile feedback (smaller is better, except in performance, where larger is better).*

Figure 7 illustrates that the perceived demand (temporal, physical and mental) and effort were ranked slightly lower and the perceived performance was ranked higher when using the tactile feedback. Frustration was rated slightly higher with tactile feedback than without it. However, according to t-tests, only the difference in temporal demand was statistically significant (t_{12}=4.38, p=0.0009).

Preference
The responses to the preference question showed a clear preference for the tactile feedback. 11 participants preferred to have it. One participant could not tell because he claimed that he did not feel any tactile stimulation. One participant preferred not to have tactile feedback. She said that this was her preference regarding all vibro-tactile stimulation in all situations.

7 Discussion

From our preliminary results, it appears that the mid-air tactile feedback did not enhance or degrade performance, but was heavily preferred by users. If such results turn out to be replicable, this would suggest that the best use of mid-air haptic feedback is perhaps in situations where user experience is the key issue. Entertainment technology and user interfaces that are used for fun could potentially be even more fun with mid-air haptics, whereas in productivity applications the measurable performance benefits may turn out to be small or non-existent.

The biggest perceived differences were found on the effort and temporal demand. It seems that the users felt that introducing the mid-air tactile feedback made the task feel more relaxed and perhaps require less effort. Based on the feedback from the participants, the tactile feedback made the pace seem lower (while the actual delays didn't change). Perhaps the tactile feedback makes the task cognitively easier. The reduced workload may have made the pace feel more relaxed, although objectively the task completion rate was almost the same for both conditions.

There are several details that can be improved in our implementation. For example, our prototype used a fairly small ultrasonic array, which can easily be integrated into the display. Even with this array size the effect was clearly noticeable up to the distance of around 30 cm. The anatomically possible maximum distance of touching measured from the eyes is about 50 cm for most persons. However, the normal and natural working range is typically about 20-30 cm, and a distance of up to 30-40 cm from the front plate of an HMD would cover all but the most extreme hand positions. The ultrasonic transducers could be packed a little tighter together into a diamond shape, instead of a rectangular array. Another option to stretch the distance would be to add the number of transducers, in which case they would overflow to a wider area than the front plate of the HMDs that we used. We presume that a 256-element array would be fully sufficient for the practical working volume for an HMD.

The fact that one of our participants did not feel the tactile stimulation was to be expected. Sensitivity of the hands varies in a wide range. Because air is soft and gaseous, mid-air tactile feedback can never be as precise and clear as tactile sensation against a rigid object. Whether it is possible to generate stimulation that is sufficient for giving benefits for most users was one of the main reasons for this research. Based on the preliminary results the answer to this question is positive, but more work is needed to confirm this.

A significant limitation of our prototype and ultrasonic mid-air haptics technique in general is that the tactile stimulation was not strong enough to produce sensations in all parts of the hand. The need to construct user interfaces so that objects are touched with the palm facing the ultrasonic array is a major hindrance. Alone this haptic feedback technology will work only in those applications that can adjust to this limitation. Stronger ultrasonic arrays and supplementary arrays in the environment may improve the situation. However, the difference in sensitivity between the fingertips and most other body parts will remain despite improved technology.

There can be different types of tactile signals (e.g., constant, short or long pulses, Morse code, etc.) for different types of actions. Which methods are better and more suitable for various purposes is an open question and invites further research. Gaze tracking, audio and other multimodal techniques could be used e.g., to further extend the user interface possibilities.

Because ultrasound cannot be heard, there is a possibility that unlike with audible sound, dangerous exposure could go unnoticed. Some animals may be sensitive to 40 kHz sounds and the powerful signal in the focal point and its lower harmonics may even be dangerous for human ears. While we have not yet measured the sound field generated by the array in detail, there are several reasons why it can be considered safe. First, as the ultrasound is focused, we estimate that even a dislocation of 10 cm away from the focus would reduce the volume by 20 dB (1/100th of the power). Secondly, user's head is typically 20-50 cm away from the focus area and the sound is always directed away from the user.

According to Lenhardt [2008] "Current exposure standards are based on the concept that detectability and the potential for damage to hearing are related." Apart from the barely audible low-frequency buzz, operation of the array was not detectable by hearing or other human senses outside the focus area. Lenhardt recommended 145dB maximum exposure at 40 kHz, which is extremely loud. Based on other studies (e.g. [Smagowska and Pawlaczyk-Łuszczyńska 2015]) that discuss the safety of ultrasound it seems that even extreme airborne ultrasound noise is well tolerated in industrial settings. In VR headset applications the power is lower and pulse duration is very short.

To block the audible by-product of the ultrasound generation the participants in our experiment wore hearing protection. An added benefit was that even a catastrophic equipment malfunction could not have caused danger to hearing.

Despite all this evidence suggesting that the tactile ultrasonic stimulation is safe, it is better to err on the side of caution and test possible products utilizing this technology fully to ensure that they conform to ultrasound exposure safety guidelines.

8 Conclusions

We have presented a mid-air tactile feedback system for head-mounted displays. As far as we know, our prototype is the first mid-air tactile headset. Ultrasonic tactile feedback suits well for HMDs, as it enables the user to touch virtual objects in an unobtrusive way, and the tactile feedback is always directed to the working visual area of the user.

User tests affirm that our system provides a means of interacting in an intuitive and easy-to-use manner. According to our tests, it seems that the users prefer it very much over no tactile feedback, even though its measured added effectiveness is small. The presented concept seems to be useful and easy to use.

Mid-air tactile feedback for HMDs can enhance the user experience and it may have implications also for 3D UIs and VR. While dwelling over an UI element (such as a button), tactile feedback can enhance the otherwise non-tangible button and affirm the user that a selection has been made when making a gesture. It can also deliver an enhanced tactile warning over the air to the user. The tactile effect cannot simulate a fully natural and realistic touching of an object, but nevertheless it gives some tactile feedback for the user.

The benefits of embedding ultrasonic actuators to HMD instead of embedding them to the environment include mobility, economy (small actuator panel is needed, instead of the walls and ceiling of a room to be covered), better tolerance for obstructions in the space, and safety (signal is directed away from the user). The shortcomings include limited possible size (and power) of the ultrasonic array, the added weight, the ability to stimulate only the palm facing towards it, and the fact that interaction with objects outside of the user's field-of-view isn't possible. Combining head-mounted panels with external panels would enable full coverage from all angles. Naturally also alternative methods of haptic and multimodal interaction can be merged with the system.

We conclude that mid-air tactile feedback is a viable and intriguing option for HMDs if the hand is oriented suitably. We will continue developing the ultrasonic transducer hardware system and gestural user interaction with it to test these issues further.

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