Generating Localized Haptic Feedback over a Spherical Surface

Patrick Coe[1][a], Grigori Evreinov[1][b], Mounia Ziat[2][c] and Roope Raisamo[1][d]
[1]*The Faculty of Information Technology and Communication Sciences, Tampere University, Tampere, Finland*
[2]*Dept. of Information Design and Corporate Communication, Bentley University, MA, U.S.A.*

Keywords: High Definition Haptics, Tangible Mental Images, Virtual Tactile Exciter, Interference Maximum, Actuation Plate.

Abstract: The ability to control and manipulate haptic imagery (aka imagining haptic sensations in the mind) makes use of and extends human vision, allowing "seeing by touch", exploring, and understanding multidimensional information. In the purpose of exploring potential tools that can support visuo-haptic imagery, we performed testing on a spherical surface to investigate whether the placement of actuators at key locations and their activation at different time offsets can be used to generate dynamic movements of peak vibrations at a given point and across the curved surface. Through our testing of the spherical structure prototypes, we have found that offset actuations can be used to magnify vibrations at specific locations on a spherical surface. The gathered data show that increased amplitude can be created at a given point across the surface by using the actuation plate instead of multiple actuators affixed to the curved surface. Our plan is to use these results to induce dynamic haptic images in a vector format across any surfaces in the future.

1 INTRODUCTION

When interacting with graphical objects through a tactile surface, people combine visual information with a tangible surface such as physical buttons on a keyboard, a mouse, or a haptic device. The force feedback coming from the surface is used to confirm visual input or present general information instead of sound (Fish, 2002). Still, force feedback parameters can vary within only a limited range of the magnitude gradient and time (length of tactile stimuli). Moreover, in most haptic interfaces which are based on direct finger touch, force feedback is referred to as shared forces (those tangential to the skin). When skin moves laterally over a sensitive surface, the weight generated based on the pressure applied (65-100g) produces a contact force that leads to orthogonal skin deformation (normal to the surface). However, human sense of touch is a more sophisticated analyzer of processing dynamic arrays of force vectors (e.g., when distinguishing the concave and convex components of surfaces). That is obvious, when haptic textures and objects are simulated with 3D haptic instruments (Culbertson et al., 2018), but not yet widely applicable to surface haptics on touchscreens (Kim et al., 2019) when regular haptic exciters are used. Therefore, in order to display more complex vector graphic haptic images than primitive down sampling based reliefs (Loomis and Lederman, 1986; Krufka et al., 2007), dynamically actuated virtual vibration sources of vector force traveling across the display surface can be used to convey a higher bandwidth of information to the user (Evreinova et al., 2014; Evreinova et al., 2012; Loomis, 1981; Loomis and Lederman, 1986; Kim et al., 2017; Oakley et al., 2001; Shin and Choi, 2018).

By providing kinesthetic, proprioceptive, and cutaneous information, contact surfaces that are actively explored by fingers deliver a rich haptic experience to users. The method generally used for tactile simulation of objects and their surfaces has been to control each "tactile pixel" (or taxel) laid out in a two-dimensional array (Vechev et al., 2019). Taxels cannot be used for high-definition tactile simulation of objects, instead they have been used for sparse low-resolution approximation of interactive surfaces and virtual stages (Culbertson et al., 2018; Loomis and Lederman, 1986; Krufka et al., 2007). Yet proceeding from visual principles of perception (Sofia and Jones, 2013; Shin and Choi, 2018), to mimic a most advanced tactile display technology (Xie et al., 2017),

[a] https://orcid.org/0000-0003-3822-1696
[b] https://orcid.org/0000-0001-7132-8378
[c] https://orcid.org/0000-0003-4620-7886
[d] https://orcid.org/0000-0003-3276-7866

Coe, P., Evreinov, G., Ziat, M. and Raisamo, R.
Generating Localized Haptic Feedback over a Spherical Surface.
DOI: 10.5220/0010189800150024
In *Proceedings of the 16th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2021) - Volume 2: HUCAPP*, pages 15-24
ISBN: 978-989-758-488-6

might not work for haptic visualization because a surface can be characterized by different physical properties. These need to be perceived, recognized, and interpreted through haptic imagination as static, dynamic, or virtual (cross-section) array of identical elements. A variety of technological approaches have been explored for surface simulation and control of properties (mechanical and acoustic) when exploring and interacting directly or indirectly with virtual surfaces (Evreinova et al., 2012; Evreinova et al., 2013), simulating shapes (Evreinova et al., 2014; Evreinova et al., 2013; Follmer et al., 2013), texture (Shin and Choi, 2018) properties such as stiffness, curvedness (Follmer et al., 2013; Jang et al., 2016), friction (Müller-Rakow et al., 2020), and compliance/elasticity (Mansour et al., 2015).

In this work, we considered properties of the seismic wave propagation and interference, to investigate the possibility of creating feelable precise high definition tactile points that could travel across a curved surface and lead to the perception of an apparent tactile motion (Burtt, 1917; Oakley et al., 2001; Park et al., 2016; Raisamo et al., 2013). Based on this premise, fewer actuators would be needed to create a high definition vibrotactile display. This could be achieved by precisely offsetting any number of given actuations. Our hypothesis is that the resulting point of constructive wave interference would significantly amplify the level of vibration signal above the ambient noise at the specific point of contact. If we are able to know the necessary actuation offsets which are required to create a point of maximum constructive wave interference dynamically at every given point across the surface, then a matrix of values can be stored and used to stimulate apparent tactile motion by inducing haptic imagination. An example of haptic imagination is a music teacher asking a pupil to play the piano on their desk. The student can imagine and feel the music piece to be played without using the piano keys. We can enhance this imagination, for example, with virtual movable haptic vibrations that can be felt moving across the surface and enabled by sequentially triggering the respective offsets that create a feelable moving point of maximum interference. This position of vibration interference could be dynamically positioned in order to display information to a user in a unique way. Tactile information could move around a user's hand, or a user could be instructed to focus on or follow a moving virtual actuator.

Past work in this area of haptic research has shown a similar approach of inducing points of virtual actuation across a given surface by taking advantage of wave properties. For example, Enferad and others (Enferad et al., 2019) worked on generating a controlled localized point of stimulation using voltage modulated signals to actuate piezoelectric patches across an aluminum beam. They successfully achieved superposition primarily using voltage phase modulation. Charles Hudin and his team approached a similar problem by using time-reversal wave focusing (Hudin et al., 2015). A vibrometer calibrated the time-reversal wave during a focusing stage, followed by an actuation signal by an array of 32 actuators bonded to the underside periphery of a glass plate. This was successful at creating a precise, localized, point of haptic stimulation. However, the use of a closed loop control system raises significant difficulties as it limits its practical implementation when a contact point is hidden or suppressed by a finger in consumer devices.

Although our current research focuses on localized haptics over the surface of a hemisphere, we believe that the data and results gathered will be helpful for designing haptics over a multitude of different shapes. More innovative and interesting device form factors are continuously revealed. From curved edges to flexible displays (Huitema, 2012). As interfaces and displays arrive in increasingly complex and nonstandard form factors, adaptable tactile output will be necessary for the continued advancements in haptics in consumer devices. Tactile click buttons that could once be felt began to rapidly phase out in favor of relying only on the capacitive touchscreens found on the present devices. We can see continuing investment in the tech industry from companies such as Apple (Parisi and Farman, 2018) focused on the improvement of haptic feedback. It is clear there is demand for improved tactile feedback. As form factors evolve and we move away from the traditional flat display, understanding how advanced haptic signals can be used to introduce high fidelity haptics will continue to increase in relevance.

From the aspect of technical novelty, we take a simplified approach over existing research to achieve localized points of actuation. Although the use of a multitude of actuators is effective, it is not practical as it introduces complexity and cost. Furthermore, any system that needs consistent monitoring of a surface may be difficult to implement outside of a laboratory setting. We aim to eliminate the aforementioned issues by both reducing the quantity of actuators needed to produce a localized point of vibration and calculating the required offsets for a given material. In addition, the understanding of wave propagation over a spherical surface opens the techniques that will be presented in this paper to the multitude of curved and molded devices continuously being introduced on the market.

2 CONCEPT & DESIGN OF THE SPHERICAL HAPTIC DISPLAY

To test the design concept (Figure 1) explained earlier, we have developed a mockup of a spherical haptic display (Figures 2-6). This preliminary design is used to test the feasibility of the virtual force actuation, as well as possible ways of optimizing the configuration of actuators assembly with respect to these forces. Optimization can be adjusted by changing the layout and the number of actuators, the parameters of the virtual sources of vector force and the configuration of elementary haptic signals. The prototype will also be used to measure the resulting constructive wave interference propagation across the curved display surface. Measurements from related research have demonstrated that it is possible to achieve accurate localization of increased vibration at a desired point of contact through controlled offset of multiple signals (Coe et al., 2019b; Coe et al., 2019a).

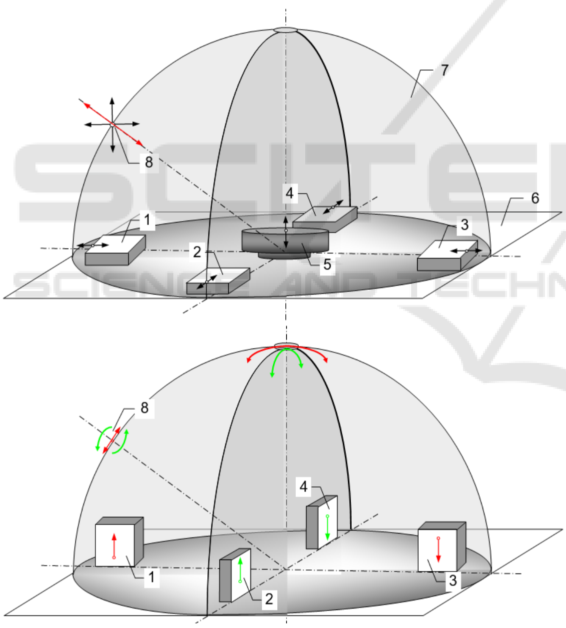

Figure 1: The variants of haptic actuators assembly affixed to the actuation plane. 1-5 - Lofelt L5 (1-4) actuators and Tectonic exciter TEAX25C10-8HS (5). Red arrows indicate linear motion, while green arrows indicate angular motion. Black arrows indicate actuator movement. 8 - Represents a targeted point of increased magnitude or vibration; 6 - an actuation plate; 7 - a spherical haptic surface.

To generate a virtual vibration source at a point on the curved contact display surface, we used a specific configuration of powerful unidirectional voice coil actuators (Tectonics and Lofelt). The concept is defined as the Volumetric Tactile Display (VTD) and presented in Figure 1. It consists of constructive wave interference propagating sequentially to the specific points of contact with the skin. The resulting point of localized vibration is able to properly mediate haptic signals by integrating spatially and temporally discrete sensory inputs.

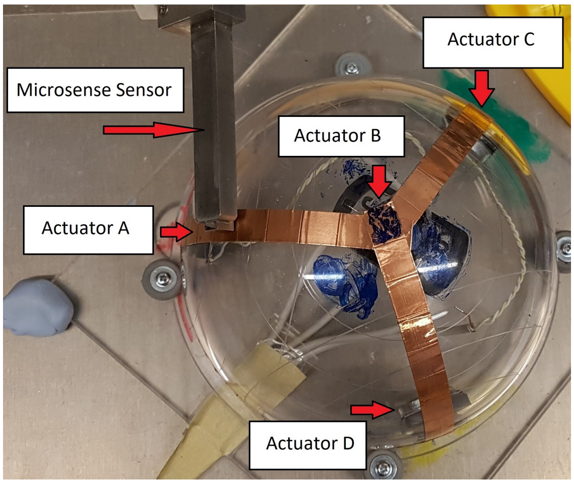

Figure 2: Top view of the first spherical prototype with centimeter marks across copper tape used for sensor measurement placement.

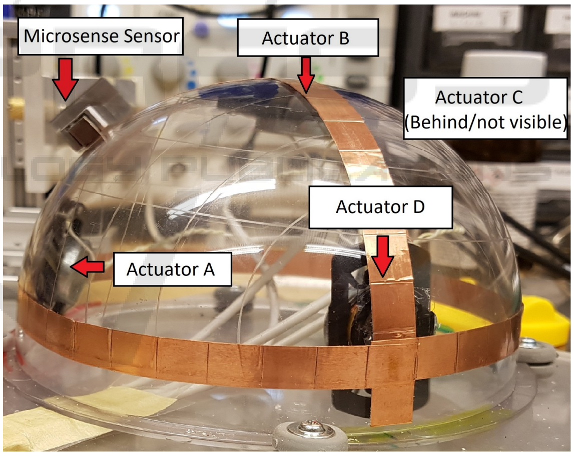

Figure 3: Side view of the first spherical prototype with centimeter marks across copper tape used for sensor measurement placement.

To gather preliminary data, we built two dome shaped prototypes. The purpose of each prototype was to investigate multiple methods of localization that aim to achieve the same goal. One sphere focused on wave interference, the other was based on principles of vector forces. Successfully testing each prototype individually was done before attempting to combine both principles in the future. The design of both prototypes was built within a 116mm diameter polycarbonate dome. In both domes wires were run from the inside out to an external motor controller (L298).

The motor controller used an Arduino DUE chosen for its high speed of 84Mhz, allowing high precision outputs and the collection of data at intervals of 5.3μm. A copper strip had been used for a precise calibration of vector forces (when micro-displacements over touch surface are measured with the MicroSense sensor) traveling over the Spherical Haptic Surface (SHS) from the layout of unidirectional actuators.

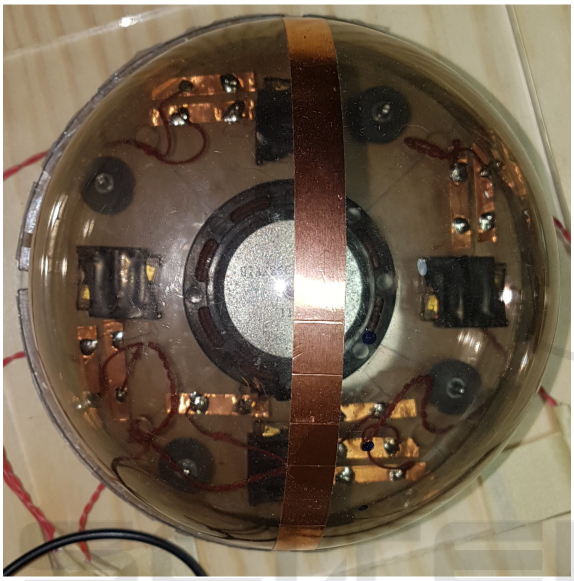

Figure 4: Top view of the second spherical prototype with centimeter marks used for sensor measurement placement. This construction consists of four Lofelt L5 actuators and a single Tectonic exciter TEAX25C10-8HS at its base.

The first dome was used to test the possible wave interference of seismic signals generated by actuators affixed directly to a spherical haptic surface. It consisted of four Tectonic actuators (TEAX1402-8) attached from the inside and placed in vertices of the tetrahedron (Figure 3 and 2). Localization of the vector force at the desired point of contact over SHS was to be achieved through the controlled offset of multiple actuation signals. The controlled offset actuation aimed to shift the point where constructive wave interference occurred over the surface of the hemisphere.

In the second dome (Figure 5 and 4) we focused on testing the principles of a shifting magnitude. We implemented these effects by varying magnitudes of lateral and vertical movements. The installed more powerful next-generation Lofelt technology L5 actuators were affixed to the actuation plate along the X and Y axis, while a powerful Tectonic exciter was used to actuate vertically in the direction of the Z-axis. Using this configuration, we planned to rise up the resulting force of seismic signals initially interfered in orthogonal directions across from an actuation plate by applying different magnitudes of actuation in the vertical and horizontal axis. Nevertheless, as displayed in Figure 1, unidirectional haptic actuators could be assembled in a different way to generate both linear (red) and angular (green) momentum of forces (torques).

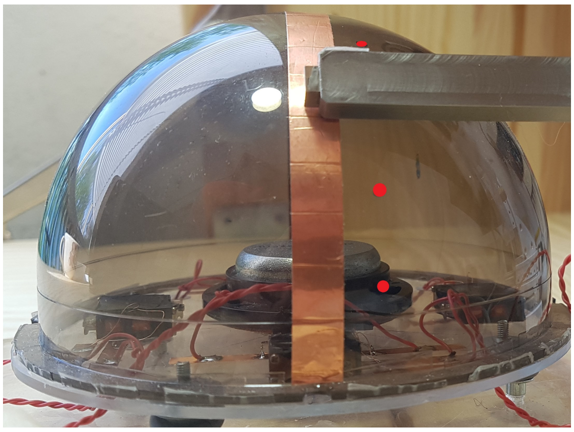

Figure 5: Side view of the second spherical prototype with red markers every two centimeters used for measurement placement.

During development of the actuation plate, it was found that the hydrophobic material (such as the Gorilla-glass, Teflon, and silicone) can affect the sense of convexity vs. concavity at the point of finger's contact. Modifying the thickness of a material such as glass also has an impact on the vibration that is to be felt (Xu et al., 2019). The result is promising for future verification through a user study. This opens new ways of simulating volumetric shapes in virtual and augmented reality. Thus, the combination of new material properties and actuation technology can allow us to induce complex haptic sensations which are necessary for developing haptic imagination in both healthy people and those with perceptual disabilities.

Besides physical parameters, personal exploration behavioral features will impact on perceiving multiple tactile information gathered when interacting with SHS during the perception of mental images of the objects presented. Therefore, user-centered approach will be used to further clarify the problems and limitations of the proposed interaction techniques (Figure 6). The spherical surface as shown complements the shape of the hand. This allows tactile feedback to propagate across the palm and fingers.

In the design of the second dome, we focused on the effects of varying magnitudes of lateral and vertical movements. Due to its shape, wave interference not only existed and occurred traveling over the surface, but the entire object was moved by the vertical and horizontal movement generated by attached actu-

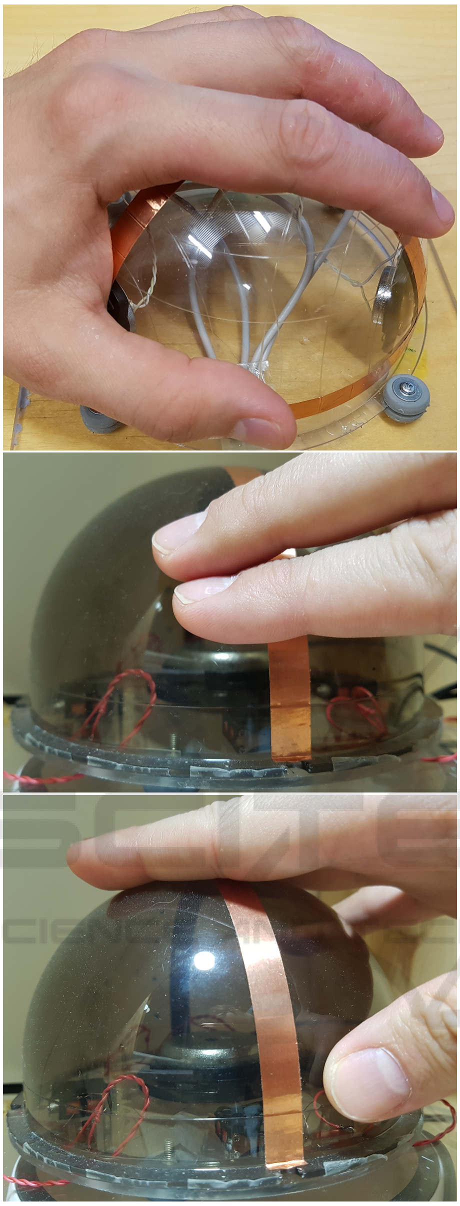

Figure 6: Top: Hand at rest placed over spherical prototype demonstrating a comfortable position Middle: Exploratory behavior demonstrated by touching with the finger pads only. Bottom: Four fingers elongated straight forward, as if trying to feel the flat edge of a surface.

ators. Therefore, it was possible to magnify a point of maximum vibration by applying different magnitudes of actuation in the vertical and horizontal axis. These magnitude points of maximum could also be used in combination with wave interference maximums to amplify tactile signals and focus given vibration detected on the surface.

3 METHODS

We explored two methods to determine the optimal offset in creating a point of peak magnitude vibration at around five centimeters from the base of the hemisphere. This was measured by traveling vertically along the surface of the sphere from the first actuator (A, Figure 2 and 3). The first method consisted of testing a range of offset vibrations on the sphere between an initial pair of actuators (AB). After finding the offset required to reach a point of maximum vibration interference between these two actuators, we tested an additional actuator, offsetting this third actuator against the existing offset pulse of the first two actuators (ABC). This process was repeated for the fourth actuator, offsetting the fourth actuator against the existing offset pulse of the previous three actuators (ABCD).

Measurements were taken with a MicroSense sensor (Model 5622-LR Probe, with 0.5 mm x 2.5 mm sensor). As it is a capacitive sensor, a copper strip was required to be placed over the surface of the sphere for measurements to take place. The sensor has an accuracy of 0-200um with noise of 3.44 um-rms @5kHz amplified with Gauging Electronics until 10V and attenuated to a range of 0 to 5V to make it compatible with the Arduino's analogous input. The sensor placement was adjusted to follow the curvature of the sphere.

4 RESULTS

4.1 Constructive Wave Interference

Figure 7 shows that the addition of the third actuator (C) increased displacement significantly while the addition of the fourth actuator (D) introduced a very small increase. Specifically, a possible constructive wave interference happened between the first two actuators A and B, with actuator A, triggered 2ms before actuator B, creating a displacement of 183μm. Triggering the third actuator 3ms after actuator B increased this vibration to 257μm. However, triggering the fourth actuator provided very little increase to the peak vibration. The fourth actuator (D) activated 24ms before actuator A increased the vibration to 276μm. That said, actuator (D) can still positively influence the overall vibration. A deconstructive pulse provided by actuating actuator (D) 19ms before actuator A, reduced the vibration to 203μm.

Because we were unsure whether the actuators in a spherical setup would interact with each other in the

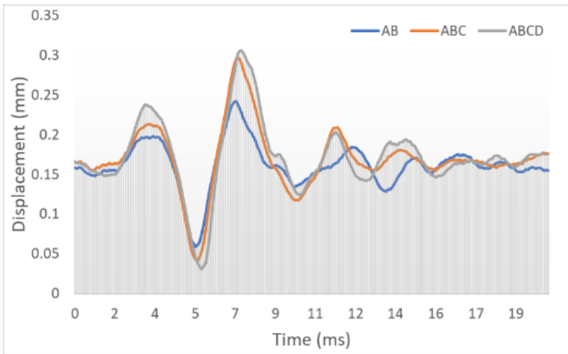

Figure 7: Measured maximum displacement using offsets for two (AB), three (ABC) and four (ABCD) actuators.

same way as that of a flat actuation plane, we proceeded with more thorough testing by trying out every possible combination of offsets between each of the four actuators for 15ms before and after each other. The optimal offset found by this process resulted in a maximum displacement of 276μm which is identical to the previous result when all four actuators were activated.

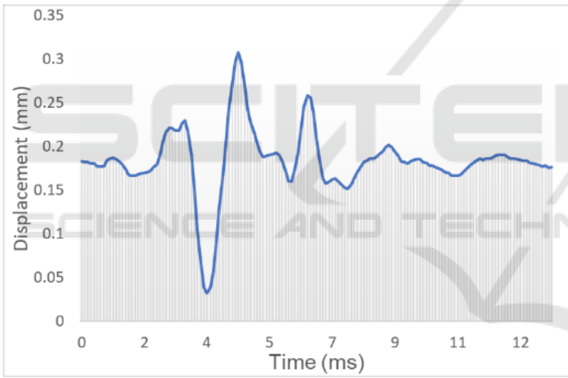

Figure 8: Measured maximum displacement using offsets when scanning through all four actuators simultaneously.

Figure 8 shows the maximum displacement when using the full range offset sweep test to determine offsets required to reach a maximum displacement. The found offsets differ, indicating that there are multiple possible variances of reaching a peak vibration maximum. We also found the offset is the result of actuators (B) and (C) actuated 5ms after actuator (A) and actuator (D) actuated 9ms after actuator (C). Although we believe the data gathered using the method of cycling through every possible combination provides very accurate offsets, the method is hindered by the length of time required to measure all combinations along with the amount of data that is required to be collected.

Based on this data, we believe that while some waves likely travel across the surface, the semi flexible attachment to the base entails that actuators are likely pulling the entire object. We cannot only consider wave propagation delay; we need to consider the movement of the entire dome. Besides calculating the required offset delays, we must test the ideal magnitudes and phase of each signal applied to each actuator.

4.2 Combination of Peak Displacement Magnitudes

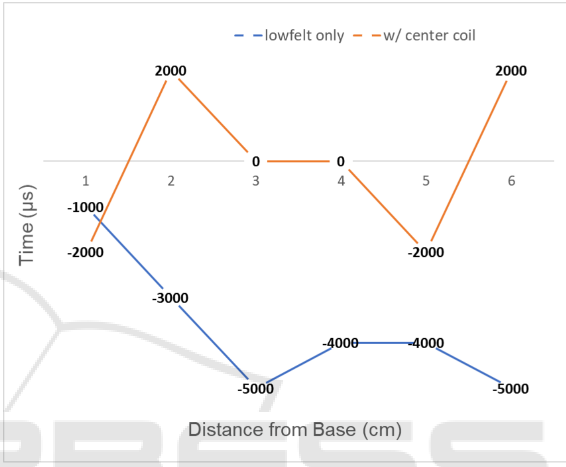

Figure 9: Offset required for maximum peak vibrations for Lofelt L5 actuators with and without Tectonic actuator (center coil).

To address the previous issue related to wave propagation, we performed additional testing by combining different magnitudes of actuation with offset triggering. For this test we used the second prototype (Figure 4 and 5) with Lofelt L5 actuators for X and Y vibrations, and a central Tectonic actuator for movement along the Z axis. More specifically, we actuated the Lofelt L5 actuators across the X-axis for 10ms along with the central actuator for 1ms. This configuration should reduce the magnitude by which the central actuator is actuated in relation to the Lofelt L5 actuators. We tested different offsets to find the peak vibration offset (Figure 10). The data displayed in Figure 9 shows a trend until about the third point when the angle of the sphere begins to be more horizontal. The implication of this trend is that we are not only experiencing forces attributed by wave interference vertically placed actuators, but also vertical displacement of the entire hemisphere produced by the horizontally placed actuator. In the future, we would need to measure different magnitudes for a set offset rather than a shifting offset. Magnitude can be adjusted by changing the size of the pulse or adjusting the voltage provided to a given actuator. Further testing should measure the range of these adjustments and their effects on the resulting vibration.

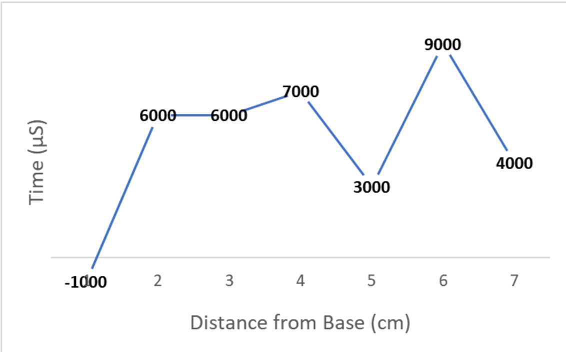

Figure 10: Time offset required for maximum peak vibrations while activating Lofelt L5 actuator (1) for 10ms and tectonic actuator (5) for 1ms.

5 DISCUSSION AND FUTURE WORK

The high-fidelity spherical display opens a new form of interactivity to a wide range of users. The sphere encompasses a natural form where a user can rest their hands on for extended periods of time. As we continue to see increased access to a multitude of interactive technologies, we will need to begin to explore new intuitive methods of feedback and interaction.

Our visual culture has a strong impact on human intellectual and creative potential as well as the development of perceptual and motor abilities (Kantner et al., 1968). Despite the importance of haptics in development of human perception, once spatial visual representations of distance, size, shape, and motion have been developed, visual information tends to dominate over haptic perception (Burtt, 1917) (Klevberg and Anderson, 2002). Blind and visually impaired users often lack access to much of the content available in visual form (Jones et al., 2006). Coincidentally learning is often shown to improve with the aid visual feedback, often leaving those with visual impairment struggling in classrooms. Fortunately, it has been shown that with the introduction of haptic feedback this gap between visual learning can begin to be bridged.

The use of haptics in education can be expanded to aid all students compelled and connected with a subject, building a bridge between for example the sciences and physical reality. A subject that has been studied with success by David Grow and his study of educational robotics (Grow et al., 2007) and more generally by Michael Pantelios (Pantelios et al., 2004) with input gloves and force-feedback devices. Much research available (Hamza Lup and Stefan, 2018; Fernández et al., 2016; Christodoulou et al., 2005; Minogue and Jones, 2006) would suggest that introducing haptics in the educational environment at all levels can improve learning among students. A spherical surface as the one we are experimenting with can provide a durable polycarbonate surface that can withstand heavy, repeated use. It also provides a unique surface for students to explore. It would be possible to be coupled with a spherical projection (Ferreira et al., 2014; Zuffo et al., 2014; Zhou et al., 2019) across the surface that would display an interactive image or video that can be explored with tactile feedback.

As we do not limit our idea to any size and expect to find that we will be able to replicate our findings in larger and smaller spherical shapes we open the idea of spherical haptics to a multitude of use cases. We imagine a haptic hemisphere in place of an analog control stick on a game controller. Apart from providing accurate input, feedback can be manipulated to create a variety of effects. For example, the texture could change as you go over rough terrain in a game, or the direction of an enemy could be made apparent by the localization of the feedback. We can imagine a larger sphere could be used to control heavy equipment with accuracy over a 3D space, for example a crane lifting a concrete slab. A spherical display at the center of a round table could be used as an interactive map to help a team to collaborate with localized feedback providing additional information that could reduce visual overload. Localized feedback could alert a taskforce of underground structures or other areas of interest.

Manufacturing technologies continuously move forward. We are moving away from the rigid limitations of consumer electronics design, as the ongoing trend of miniaturization along with the introduction of flexible displays and new molded integrated circuits mean devices can begin to take any imaginable shape or form. As we know, many user interfaces already have large areas of significant curvature, such as a mouse, gamepad, or even a vehicle steering wheel. By introducing vibration that can be localized at any point across these surfaces we increase the bandwidth available to the user, with the ability to introduce new, more natural, interaction cues.

To delve deeper, we are aware that current virtual reality headsets incorporate believable visual feedback but have yet to incorporate high-fidelity haptic feedback at a widespread consumer level. Incorporating this increased level of fidelity to current controllers could bring a new level of immersion to current technologies (Al-Sada et al., 2018).

There is also potential for such a spherical device for use in public spaces. The added benefit of precise tactile feedback could not only make, for example, an information kiosk more widely accessible, but also help users navigate through the system in a noisy environment such as a mall (Evreinov and Raisamo, 2002).

Interestingly, our current research finds that the offsets used to create localized vibration points happens within milliseconds of each other. This implies that it may be possible to trigger multiple offsets rapidly and sequentially to produce multiple focal points that may be perceived as simultaneous. This would provide an additional avenue in the creation of haptic patters, and potentially used for the development of haptic imagination.

The eventual goal in this research is to achieve a perceivable movable actuation that can be mediated to any location across the spherical surface. What we would define as a virtual haptic actuator. We would still need to investigate this aspect further to achieve ideal combinations that produce the most efficient (easily distinguishable) multiple afferent flows, increasing in strength to a specific point or along edges across the sphere's surface. We would also need to explore how wave interference can be combined with differing magnitude combinations to increase the precision and force of a given vibration across the surface of the sphere, as well as by taking into account perceptual interference of other receptive fields that can affect fingertip tactile sensation (Lakshminarayanan et al., 2015).

Intermediate materials have been known to enhance the sense of touch over an object. Cellophane film, for example, has been used by auto body shops to examine polishing on automobiles (Sano et al., 2004). Additionally, the Touch Enhancing Pad (Perry and Wright, 2009), a patented tool composed of lubricant sandwiched between two thin plastic sheets is useful for detecting tumors in the breast tissue. Therefore, it would be of interest to test different materials in an aim to enhance the perceivable localized feedback in our haptic spheres.

As we continue this research, we will get a better understanding of the use cases this emerging technique can provide to users.

6 FUTURE APPLICATIONS

Spherical interfaces do exist (SSI, 2020; Benko et al., 2008; Daniel et al., 2010; Williamson et al., 2015; Bolton et al., 2011) yet are still not commonly in use. The proposed platform for high-fidelity haptic feedback opens many possibilities of future interaction by touch. As the shape of the sphere conforms to the hand in a natural resting position (Jeannerod, 1984; McRae and McRae, 1977) it can be used for extended periods of time as a general computing interface augmented with rich tangible information.

When exploring medical imagery, hidden or obscured entities and deeper structures of palpated object either biological (tumor) or physical body (defect inspection) can be enhanced via localized haptic feedback. In the same manner, the standard user interface could be enhanced, for example by allowing a user to feel and select icons on a desktop that are underneath a document they are working on without the need to minimize or change windows.

The spherical surface requires a much lower range of motion to interact with, which can be beneficial for anyone with an injury or illness that impairs movement. The high-fidelity feedback can also help those with poor vision or no vision to navigate an operating system using detailed haptic imagery.

The spherical interface is not something we see limited in size. A larger child size spherical interface could allow children to explore educational material in a more immersive style. An adult sized spherical display could act as a kiosk in a mall providing information that can often be confusing on a visual only flat display, such as orientation or direction. A large sphere could be used as an interface at the center of a circular meeting table, allowing users to collaborate with each other. Often meetings are interrupted to bring up minor details, for example to let a coworker know that a file has been sent, or that they need to step out. This information could be conveyed using high definition haptics, eliminating distracting interruptions.

A haptic spherical interface also allows interesting new methods for creating secure entry into a device. For example, a passcode based on identifying localized light-pressure patterns can actively be shifted throughout the surface yet discovered via localization. Although the input pattern would remain the same, the continuous shifting of the physical location would make it difficult for a third party to accurately capture the passcode. From an outside perspective every physical input of the passcode would appear as if it were unique.

Overall, we see a wide range of possibilities that can take advantage of the use of a high-fidelity spherical haptic interface. Unlike many interfaces that currently exist in the consumer space, we imagine the spherical haptic interface to be highly adaptable and open to a plethora of design use cases.

7 CONCLUSIONS

Based on the instrumental measurements of constructive interference of the spherical structure prototypes, we have found that offset actuations can be used to magnify vibrations at specific points on a spherical surface. These magnifications can be created through a combination of two methods: first, through wave interference where we can use the properties of constructive wave interference to create an amplified point on the surface, and second, through the combination of peak displacement magnitudes, where differing forces are applied to the X, Y, and Z axis of an object to increase forces felt at a certain point across the surface. The current work demonstrates that a localized vibration effect is reproducible over a curved surface. Second, using magnitude combinations, we obtained preliminary data showing that there is an effect of increased amplitude at a given point across the surface.

In this research, we have repeatedly observed that once offsets are found and set, the resulting output stays remarkably consistent. Sustainability is important, as localization offsets should only need to be gathered once for a given actuator configuration. It has also been demonstrated that measured losses due to attenuation for individual actuators are compensated for by the use of the multiple installed actuators.

The level of localization shown has a potential to improve users' immersion in XR environments compared to existing global non-localized vibrations that induce a blurred sense. This distributed haptic resolution can be compared to visual and auditory propagation field. The improvement of haptic fidelity in of itself aims to improve the user experience in a similar fashion as other sensory modalities.

This work demonstrates that the use of a virtual vibration point can be achieved over three-dimensional curved structures. This may allow for the use of fewer actuators in a variety of feedback interfaces when creating high-fidelity haptics.

ACKNOWLEDGEMENTS

This work was supported by project Multimodal In-Vehicle Interaction and Intelligent Information Presentation (MIVI), funded by Business Finland (grant 8004/31/2018).

REFERENCES

Al-Sada, M., Jiang, K., Ranade, S., Piao, X., Höglund, T., and Nakajima, T. (2018). Hapticserpent: A wearable haptic feedback robot for vr. pages 1–6.

Benko, H., Wilson, A., and Balakrishnan, R. (2008). Sphere: Multi-touch interactions on a spherical display. pages 77–86.

Bolton, J., Kim, K., and Vertegaal, R. (2011). Snowglobe: A spherical fish-tank vr display. pages 1159–1164.

Burtt, H. E. (1917). Tactual illusions of movement. *Journal of Experimental Psychology*, 2(5):371–385.

Christodoulou, S., Garyfallidou, D., Gavala, M., Ioannidis, G., Papatheodorou, T., and Stathi, E. (2005). Haptic devices in virtual reality used for education: Designing and educational testing of an innovative system.

Coe, P., Evreinov, G., and Raisamo, R. (2019a). Gel-based haptic mediator for high-definition tactile communication. pages 7–9.

Coe, P., Farooq, A., Evreinov, G., and Raisamo, R. (2019b). Generating virtual tactile exciter for hd haptics : A tectonic actuators' case study. pages 1–4.

Culbertson, H., Schorr, S., and Okamura, A. (2018). Haptics: The present and future of artificial touch sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, 1.

Daniel, S., Wright, C., and Welland, S. (2010). Spherical display and control device. US Patent 7,755,605.

Enferad, E., giraud audine, C., Frédéric, G., Amberg, M., and Semail, B. (2019). Generating controlled localized stimulations on haptic displays by modal superimposition. *Journal of Sound and Vibration*, 449.

Evreinov, G. and Raisamo, R. (2002). Information kiosks for all: issues of tactile access. *Proc. WWDU 2002*.

Evreinova, T., Evreinov, G., and Raisamo, R. (2012). Evaluation of effectiveness of the stickgrip device for detecting the topographic heights on digital maps. *International Journal of Computer Science and Applications*, 9:61–76.

Evreinova, T., Evreinov, G., and Raisamo, R. (2013). Virtual sectioning and haptic exploration of volumetric shapes in the absence of visual feedback. *Advances in Human-Computer Interaction*, 2013.

Evreinova, T., Evreinov, G., and Raisamo, R. (2014). An exploration of volumetric data in auditory space. *Journal of the Audio Engineering Society*, 62:172–187.

Fernández, C., Esteban, G., Conde-González, M., and García-Peñalvo, F. (2016). Improving motivation in a haptic teaching/learning framework. *International Journal of Engineering Education*, 32:553–562.

Ferreira, F., Cabral, M., Belloc, O., Miller, G., Kurashima, C., Lopes, R., Stavness, I., Anacleto, J., Zuffo, M., and Fels, S. (2014). Spheree: A 3d perspective-corrected interactive spherical scalable display.

Fish, D. E. (2002). Force feedback computer input and output device with coordinated haptic elements. US6,337,678B1.

Follmer, S., Leithinger, D., Olwal, A., Hogge, A., and Ishii, H. (2013). inform: Dynamic physical affordances and constraints through shape and object actuation. pages 417–426.

Grow, D., Verner, L., and Okamura, A. (2007). Educational haptics. pages 53–58.

Hamza Lup, F. and Stefan, I. (2018). The haptic paradigm in education: Challenges and case studies.

Hudin, C., Lozada, J., and Hayward, V. (2015). Localized tactile feedback on a transparent surface through time-reversal wave focusing. *IEEE transactions on haptics*, 8.

Huitema, E. (2012). The future of displays is foldable. *Information Display*, 28:6–10.

Jang, S., Kim, L., Tanner, K., Ishii, H., and Follmer, S. (2016). Haptic edge display for mobile tactile interaction. pages 3706–3716.

Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior*, 16(3):235–254. PMID: 15151851.

Jones, G., Minogue, J., Oppewal, T., Cook, M., and Broadwell, B. (2006). Visualizing without vision at the microscale: Students with visual impairments explore cells with touch. *Journal of Science Education and Technology*, 15:345–351.

Kantner, L. A., Segall, M. H., Campbell, D. T., and Herskovits, M. J. (1968). The influence of culture on visual perception. *Studies in Art Education*, 10(1):68.

Kim, S., Park, G., Kim, S.-C., and Jung, J. (2019). Surface haptics. pages 421–425.

Kim, S.-C., Han, B.-K., and Kwon, D.-S. (2017). Haptic rendering of 3d geometry on 2d touch surface based on mechanical rotation. *IEEE Transactions on Haptics*, PP:1–1.

Klevberg, G. and Anderson, D. (2002). Visual and haptic perception of postural affordances in children and adults. *Human movement science*, 21:169–86.

Krufka, S., Barner, K., and Aysal, T. (2007). Visual to tactile conversion of vector graphics. *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, 15:310–21.

Lakshminarayanan, K., Lauer, A., Ramakrishnan, V., Webster, J., and Seo, N. J. (2015). Application of vibration to wrist and hand skin affects fingertip tactile sensation. *Physiological reports*, 3.

Loomis, J. M. (1981). Tactile pattern perception. *Perception*, 10(1):5–27.

Loomis, J. M. and Lederman, S. J. (1986). *Handbook of Perception and Human Performance Volume 1: Sensory processes and perceptiong*, volume 1. Wiley-Interscience, New York, NY, 2nd. edition.

Mansour, N., Fath El Bab, A., and Assal, S. (2015). A novel sma-based micro tactile display device for elasticity range of human soft tissues: Design and simulation.

McRae, L. T. and McRae, B. J. (1977). Implements usable by persons afflicted with arthritis. US Patent 4,035,865.

Minogue, J. and Jones, M. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research - REV EDUC RES*, 76:317–348.

Müller-Rakow, A., Hemmert, F., Wintergerst, G., and Jagodzinski, R. (2020). Reflective haptics: Resistive force feedback for musical performances with stylus-controlled instruments.

Oakley, I., Brewster, S., and Gray, P. (2001). *Communicating with feeling*, pages 61–68.

Pantelios, M., Tsiknas, L., Christodoulou, S., and Papatheodorou, T. (2004). Haptics technology in educational applications, a case study. *JDIM*, 2:171–178.

Parisi, D. and Farman, J. (2018). Tactile temporalities: The impossible promise of increasing efficiency and eliminating delay through haptic media. *Convergence: The International Journal of Research into New Media Technologies*, page 135485651881468.

Park, J., Kim, J., Oh, Y., and Tan, H. (2016). Rendering moving tactile stroke on the palm using a sparse 2d array. volume 9774, pages 47–56.

Perry, D. and Wright, H. (2009). Touch enhancing pad. Patent No. 4,657,021, Filed April 13th., 1989, Issued Aug. 24th., 1993.

Raisamo, J., Raisamo, R., and Surakka, V. (2013). Comparison of saltation, amplitude modulation, and a hybrid method of vibrotactile stimulation. *Haptics, IEEE Transactions on*, 6:517–521.

Sano, A., Mochiyama, H., Takesue, N., Kikuuwe, R., and Fujimoto, H. (2004). Touchlens: Touch enhancing tool. pages 71 – 72.

Shin, S. and Choi, S. (2018). Geometry-based haptic texture modeling and rendering using photometric stereo. pages 262–269.

Sofia, K. and Jones, L. (2013). Mechanical and psychophysical studies of surface wave propagation during vibrotactile stimulation. *Haptics, IEEE Transactions on*, 6:320–329.

SSI (2020). Screen solutions international: Spherical projection displays.

Vechev, V., Zarate, J., Lindlbauer, D., Hinchet, R., Shea, H., and Hilliges, O. (2019). Tactiles: Dual-mode low-power electromagnetic actuators for rendering continuous contact and spatial haptic patterns in vr. pages 312–320.

Williamson, J., Sundén, D., and Bradley, J. (2015). Globalfestival: evaluating real world interaction on a spherical display. pages 1251–1261.

Xie, X., Liu, S., Yang, C., Yang, Z., Liu, T., Xu, J., Zhang, C., and Zhai, X. (2017). A review of smart materials in tactile actuators for information delivery. *C*, 3:38.

Xu, H., Peshkin, M., and Colgate, J. (2019). How the mechanical properties and thickness of glass affect tpad performance.

Zhou, Q., Hagemann, G., Fafard, D., Stavness, I., and Fels, S. (2019). An evaluation of depth and size perception on a spherical fish tank virtual reality display. *IEEE Transactions on Visualization and Computer Graphics*, PP:1–1.

Zuffo, M., Ferreira, F., Kurashima, C., Cabral, M., Lopes, R., Anacleto, J., and Fels, S. (2014). Spheree: An interactive perspective-corrected spherical 3d display.