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Taking Mid-Air Haptics to the Next Level and Liberating the Interactive Multimodal Experience

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“The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.”

– Mark Weiser, 1991.

“If you have to measure an effect, it means it was too small. Self-evidence is the best measure.”

– Nicholas Negroponte, 2015

ABSTRACT

While visual and auditory interaction devices have become ubiquitous in daily experience, to the point where they feel as an extension of the self, the same cannot be said about haptic feedback devices. In recent years, however, novel haptic feedback systems have emerged that are capable of delivering focused cutaneous stimulus in air without requiring the user to wear any devices attached to their hands. The two most recent approaches to mid-air haptics are via ultrasonic phased arrays and via toroidal air-rings (also known as air-vortex rings). While the ultrasonic approach has gone through extensive research and development from the academic and startup communities, the much more recent air-vortex approach has received significantly less attention, despite offering several advantages over the ultrasonic approach. In this work, I will be significantly extending the research on haptic air-vortices, along three distinct research trajectories, by investigating the effects on haptic perception due to (1) dynamic changes of the physical properties of the vortices that have not been considered previously, (2) interactions involving multiple vortices of similar or different properties, as well as collisions between vortices, and (3) multimodal stimuli and the extent to which visual, auditory, and olfactory stimulus could augment the perceived haptic stimulus. I will be developing a novel kind of system that delivers the aforementioned capabilities, and that integrates seamlessly with a large-screen display. The primary component of the system would have the profile of a frame that attaches to the periphery of a stereoscopic display, and it would have several individually controlled apertures along each of its four edges for generating air-vortex rings. Each edge, and therefore all apertures along that edge, together, would be able to rotate relative to the plane of the screen. When a user interacts with visual 3D content on the screen, they would receive a cutaneous stimulus from one or more vortices with different physical properties. The user would also receive a corresponding feedback from the other senses, including visual, olfactory, and/or auditory. A major component behind the motivation of this research is to make haptic feedback technology just as natural in everyday experience as the smartphone has become today. To ensure that the system I build is not just another research project on haptics that becomes forgotten in five years, but rather it makes a real world impact, I intend to build it in a way that enables anyone to replicate and scale this technology with ease. To ensure that no one after me who wishes to use vortices for haptic feedback would ever have to start from scratch, I intent to make public most, if not all, hardware and software designs and license them under Creative Commons.

INTRODUCTION AND BACKGROUND

The sense of touch, just as audition and vision, is extensively and richly used in everyday life, yet devices that deliver haptic feedback are still in their infancy. Historically, much of the research and development efforts in the area of haptic interaction have focused on grounded kinesthetic feedback devices, interactive surfaces or physical objects, and wearable devices such as haptic cloves, belts, vests, etc. Numerous prototypes have been demonstrated in the past few decades, yet most are difficult and expensive to fabricate, impractical for use in everyday life, do not scale well, and/or do not integrate seamlessly with existing interfaces. As a consequence, those technologies remain confined within the walls of research institutions, and their existence is often completely unknown by the general public. In recent years, however, haptic feedback interaction has received a boost through the development of better hand tracking algorithms as well as technologies capable of delivering mid-air cutaneous stimulus, without requiring users to wear any dedicated hardware on their bodies. The two most recent approaches to mid-air haptic interaction are via modulated focused ultrasound and via vortex rings of air.

Shinoda et al. demonstrated in SIGGRAPH 2008 the first ultrasonic tactile display that used beam-formed ultrasonic waves to generate acoustic radiation pressure that one could feel on their hand [1]. A year later, they created a touchable aerial image [2]. Since then, researchers from around the world, such as the Bristol Interaction Group, have made significant advances to ultrasonic tactile feedback systems, including providing different textural sensations by through frequency modulation, generating multiple focal points that rapidly shift their spatial location to create the illusion of surfaces and edges, developing better focusing algorithms that cancel secondary constructive interference peaks, and integrating an ultrasonic tactile display with a visual screen to deliver multisensory interactive experiences [3,4,5]. In 2015, Maino et al. demonstrated a complete telepresence system called HaptoClone, that uses ultrasound to create a tangible replica of a physical object [6]. Moreover, even startups such as UltraHaptics in the UK, and Emerge in the US have been established and aiming to commercialize this technology. While the ultrasonic approach to mid-air haptic interaction has received significant attention from researchers and entrepreneurs in the last few years, there are several limitations with that technology. Systems of this kind typically use hundreds of ultrasonic transducers, require a significant amount of space, and make integration with a standard screen very bulky and therefore impractical. Moreover, the useable range is typically limited to about 30cm, the sensation cannot be felt by some of the elder users, and the device is expensive and difficult to replicate, requiring a significant effort to build and calibrate since all hardware designs, software, and algorithms are kept proprietary [1,2,3,4,5,6,7].

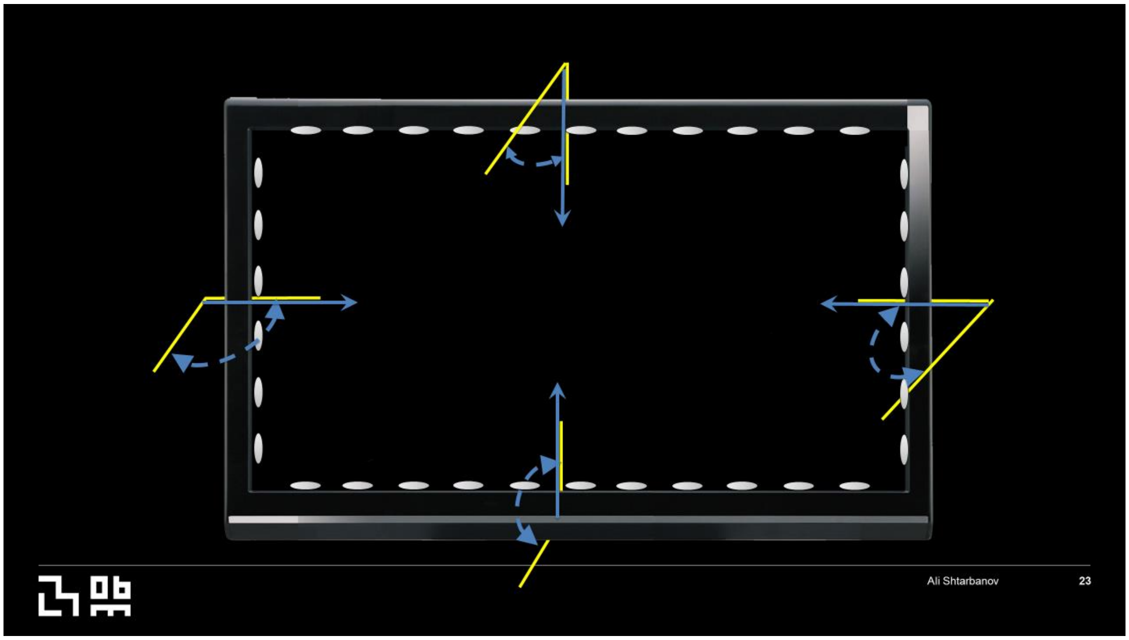
A different and more recent approach for delivering mid-air haptic stimulus is through the use of air vortices. Unlike jets of air, which are turbulent, don’t maintain directionality, and dissipate quickly, toroidal air-rings can be focused to travel several meters and impart highly perceptible haptic sensation. They can be optimized for different parameters such as resolution, force, range, vorticity, stability, etc. In 2013, Gupta et al. from Microsoft Research formally investigated for the first time how air vortices should be optimized for haptic feedback applications targeting different regions of the body. Prior to that work, the relationship between perceived force and vortex formation was not formalized in the literature. The AirWave haptic vortex generator they demonstrated — optimized for impact force and range rather than resolution — could achieve spatial resolution of 10cm at a distance of 2.5 meters [8]. Also in 2013, Poupirev et al. from Disney Research demonstrated AIREAL – an interactive system featuring a 3D-printed vortex generator with flexible nozzle that could change its angle and could track a user’s hands to impart haptic stimulus. The AIREAL system could accurately hit a target 8.5cm in diameter 1.25m away 84% of the time. When that same target was 0.75 meters away the accuracy increased to 98%. The researchers showed that when the device was integrated with a game and other visual content, and when its driving signal was modulated, the device could deliver rich haptic information [9].

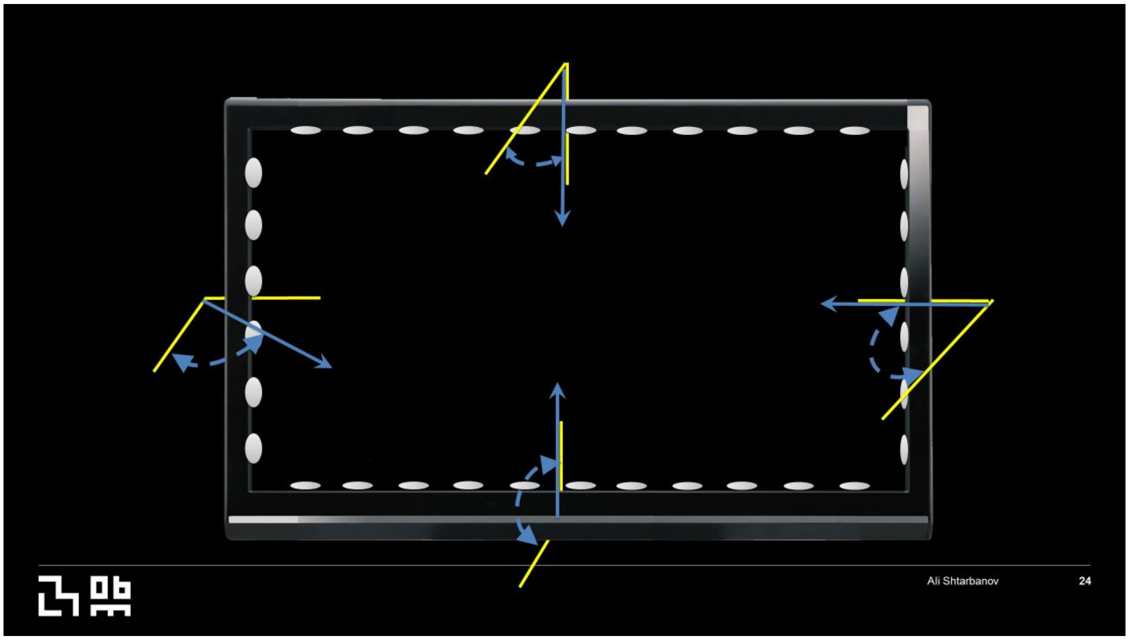
Unlike the ultrasonic approach to mid-air haptics which has gone through extensive research and development, the air-vortex approach has not received nearly as much attention, despite offering several advantages over focused ultrasound, including significantly greater range and impact force, smaller profile and area requirements, substantially lower cost, and ease of replication and scalability. Its only disadvantages are that it has not yet been able to provide as much spatial resolution as the ultrasonic approach and there is a popping sound during vortex generation – although these challenges may be overcome in the future. To our knowledge, the aforementioned are the only two substantial works that investigated the formation of haptic-optimized air-vortices and engineered novel devices specifically designed for delivering vortices optimized for rich tactile experiences. While there have been a few other projects that involved haptic feedback through air-vortices, the focus of those other works was not on the system generating the vortices. Therefore, there are still many unknowns in this area and a great deal of research is still needed both on the engineering side to optimize the vortices for resolution, as well as on the application side.

PROPOSED WORK

I intend to take the research on haptic feedback via toroidal air-vortices to the next level, and also to liberate this technology from the research lab into the real world. The AirWave system showed how air-vortices can be optimized for haptic feedback [8]; while the AIREAL system showed a proof of concept that air-vortices can deliver rich haptic experiences through modulations of the driving signal and through integration with a video game or other visual content [9]. The next step in this research area would be to investigate the extent to which one could go with the air-vortex approach to haptic feedback by incorporating all of the lessons learned so far and greatly expanding upon them. Specifically, there are three trajectories along which I would like to expand. I would like to investigate the effects on tactile perception due to: (I) dynamic changes of physical properties not studied previously such as humidity, temperature, and vortex size; (II) vortex collisions, as well as synchronous and asynchronous combinations of air vortices with identical or different physical properties; (III) multimodal stimuli, including auditory, visual, and olfactory. These three research trajectories provide the basis for two hypotheses I would be testing. My first hypothesis is that far richer haptic experiences could be achieved through dynamic changes of the physical properties of the air vortices (temperature, humidity, size) and through collisions or combinations of air vortices of similar or different properties. My second hypothesis is that significant changes in the perceived tactile stimulus could be achieved simply by changing the stimuli from the other senses. This is based on the fact that when presented with conflicting or insufficient multisensory stimulus, the brain tries to fill in the gaps by constructing information that is physically not there or by assuming that the information it is receiving is what it expects it to be even when it is very different [10]. The McGurk effect is one of the most famous examples of this phenomenon [11]. The assumption is that even with low fidelity air vortices one could deliver information about surface properties (texture, hardness, perceived temperature) by intelligently pairing the haptic stimulus with visual, auditory, and/or olfactory stimuli.

To test the aforementioned hypotheses and to determine whether air-vortices could provide a viable solution to the haptics problem in interaction design, I intend to design and build a novel device that seamlessly integrates with a large screen display to deliver rich cutaneous feedback when a user interacts with 3D visual content on the display. The device would be slim and resemble a frame similar in profile to interactive touch bezels that augment regular screens into touch screens, but would serve as an output device rather than an input device. There would be several apertures on each of the four edges through which air-vortices could be generated. The on/off state of each aperture would be individually controlled. To enable a slim profile and reduce the need for motors, the angle of the apertures will be fixed relative to the neighboring apertures on the same frame component. Instead, each of the four edges itself would be able to rotate individually, thereby still enabling the angle at which vortices are generated to change relative to the surface of the screen, as shown in the images below.





Depending on the time and complexity involved there may be a number of additional features integrated into the design of the frame. For instance, each aperture itself may be installed on rails to enable controllable sliding of the aperture by a few centimeters from its default position. The size of each aperture may also be changeable dynamically by incorporating into the design smart materials, electroactive polymers, a mechanical iris, or another electromechanical or electromagnetic mechanism [12][13][14]. The on/off state of each aperture would be controlled through direct opening and closing of the aperture. The system would be designed in a way that enables dynamic changes in the physical characteristics of the air vortices. For instance, there will be a digitally controlled mechanism that enables changing the temperature and the humidity of the air inside each component of the frame. Since there will be several apertures on all four sides of the screen, the system would allow for the creation of experiences that involve synchronous or asynchronous combinations of air vortices coming from similar or different angles. It would also enable to test the effect on tactile perception from colliding vortices, and those collisions could be head on, at right angles to each other, or at angles less than 90 degrees. Moreover, since the physical properties of the air vortices could be different for different frame components, the aforementioned combinations and collisions could also be performed with vortices of different physical properties. None of the aforementioned multi-vortex interactions have been tested previously according to published literature.

In addition to the haptic-feedback frame, there will be several other components integrated into the system. A device such as Leap Motion or Kinect will be used to track the location of the user's hands, and the frame components would turn with the apertures towards the tracked hands. Another critical component of the system would be the 3D content that is displayed on the screen. This content would most likely be created manually in a software such as Unity, Blender, or the like. There would need to be content for various kinds of materials, textures, and surface properties, and that 3D content should be dynamic and responsive to virtual touch. Moreover, the virtual content would have to be paired with corresponding audio feedback. For instance, if one is interacting with virtual water, there would need to be sound corresponding to splashing water to make the experience closer to reality. An alternative approach to solving this problem can be found in [10]. The design and engineering of the visual and auditory content would be one of the most time-consuming efforts in the entirely of the project. Moreover, one of the main challenges that would need to be addressed is the latency between when a vortex is generated and when it hits the target. One approach to address this problem is to develop a predictive algorithm that causes a vortex to be fired just before the user touches the virtual content. In addition to the visual and auditory stimuli, the system may also incorporate olfactory stimulus. Surprisingly, the preferred method for delivering targeted olfactory stimulus is though air vortices. Yanagida et al. created an olfactory display by using a vortex cannon infused with odor that tracked the user’s nose. Their vortices were optimized for range and minimal haptic impact so that user did not feel any cutaneous sensation from the vortices [15]. I plan to use the same method for delivering the olfactory stimulus. I would create one or more standalone vortex generators optimized for odor delivery that attach externally to the system.

A primary motivation for this research is to accelerate the adoption of haptic feedback technology and have it become just as common as displays have been for the past half century. To make this technology accessible to the wider public, and to have it become more than just another research project confined within the walls of an institution, I intend to design the system in a cost effective, scalable, and easy to replicate way. I also intend to eventually open source under a Creative Commons license the hardware and software designs to enable other researchers, hobbyists, and makers to replicated the system with ease, and in this way to accelerate the impact of this research and to liberate the multimodal experience for everyone.

EVALUATION

Nicholas Negroponte has said, “If you have to measure an effect, it means it was too small. Self-evidence is the best measure” [16]. This is indicative of my expectations for this research and the effort I intend to put into this project. If people who try the system ask, “where and when can I buy it,” that would be a self-evident indicator that the project was successful. Nevertheless, regardless of the reaction received from users, there are several questions this project would address. Specifically, since the central question of my thesis is whether air vortices could be a viable solution to the haptics problem in interaction design, I would have a much more definitive answer to this question. Moreover, I also would have answer to the two central hypotheses of this thesis. To test the first hypothesis of whether dynamic changes in humidity, temperature, and other physical properties of the air vortices result in richer haptic experiences, I would have users experience the system when the physical properties of the vortex ring are fixed and also when they are changing dynamically in accordance with the visual stimulus. For instance, I could have a study featuring 5 different 3D objects, with distinct material properties and textures, each appearing on the screen twice for 20 seconds. I would ask users to interact and feel those objects. When an object appears for the first time, the users would be stimulated with a generic air-vortex sensation. However, when the object appears for a second time, an air vortex specifically designed to represent the properties of that object would be produced. Users would not be told about the difference, and would be asked to evaluate which of the two sensations felt more realistic. However, since I would not know initially how physical properties of the air vortices map to physical properties of the object being displayed, I could ask users to evaluate more than two haptic sensations about each object. Alternatively, I could have another group of volunteers help subjectively determining what air vortex property most closely matches to a physical property of an object. To evaluate how combinations or collisions of air vortices of similar of different properties affect the user experience, I would perform several more experiments very similar to the aforementioned, where I would be comparing different sets of parameters. To test my second hypothesis about the effects of the visual, auditory, and olfactory stimuli on the haptic perception, I would have the users experience the system under different combinations of stimuli. For instance, I could reuse the 5 3D objects mentioned above and have users interact with them when there is no corresponding auditory or olfactory stimulus, vs when those stimuli are present, vs when unrelated stimuli are present – and then compare the results reported by participants. These are just a few of the of experiments that could be run with the proposed system.

TIMELINE

December, January –
Approach the project from first principles perspective. Study the fundamental physics governing the generation and propagation of air vortices. Study all known vortex optimization equations in the literature and find out how they were derived or obtained empirically. Investigate whether there are areas in our understanding of vortex generation and optimization that are not yet understood, make suggestions about how they can be studied either theoretically or empirically, and expand upon the fundamental fluid dynamics research in this area if time permits. Write first couple chapters of the thesis.

January, February, March –
Begin working on the physical prototype. Create CAD models, make 3D prints, order mechanical parts. Work on the control systems and the electronics design. Develop the drivers for the system. Integrate the tracking devices with the haptic output – physically, electronically, and software-wise. Create an olfactory vortex generator if time permits. Write next few chapters of the thesis as well as some of the appendices.

March, April –
Complete the physical prototype and begin the visual and auditory content for the system. Integrate the physical with the digital. Synchronize all sensory inputs to enable a coherent multimodal experience. Develop several distinct experiences for the three aforementioned research trajectories. Write more chapters.

April, May –
Finalize the system, run user studies, evaluate the data. Finalize the thesis.

REFERENCES

[1] Takayuki Iwamoto, Mari Tatezono, Takayuki Hoshi, and Hiroyuki Shinoda. 2008. Airborne ultrasound tactile display. In *ACM SIGGRAPH 2008 new tech demos* (SIGGRAPH '08). ACM, New York, NY, USA, , Article 1 , 1 pages.

[2] Takayuki Hoshi, Masafumi Takahashi, Kei Nakatsuma, and Hiroyuki Shinoda. 2009. Touchable holography. In *ACM SIGGRAPH 2009 Emerging Technologies* (SIGGRAPH '09). ACM, New York, NY, USA, , Article 23 , 1 pages.

[3] Marshall, M., Carter, T., Alexander, J. & Subramanian, S. 2012. Ultra-tangibles: creating movable tangible objects on interactive tables. *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems.* New York, NY, USA: ACM, p. 2185-2188 4 p. (CHI '12)

[4] Carter, T., Seah, S. A., Long, B. J. O., Drinkwater, B. W. & Subramanian, S. Oct 2013. UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces. *UIST '13 Proceedings of the 26th annual ACM symposium on User interface software and technology.* New York, NY, USA: ACM, 10 p. (UIST '13)

[5] Long, B., Seah, S. A., Carter, T. & Subramanian, S. Nov 2014. Rendering volumetric haptic shapes in mid-air using ultrasound: Proceedings of ACM SIGGRAPH Asia 2014. In : ACM Transactions on Graphics.

[6] Yasutoshi Makino, Yoshikazu Furuyama, and Hiroyuki Shinoda. 2015. HaptoClone (Haptic-Optical Clone): Mid-air Haptic-Optical Human-Human Interaction with Perfect Synchronization. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction* (SUI '15). ACM, New York, NY, USA, 139-139.

[7] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-mounted display with mid-air tactile feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology* (VRST '15), Stephen N. Spencer (Ed.). ACM, New York, NY, USA.

[8] Sidhant Gupta, Dan Morris, Shwetak N. Patel, and Desney Tan. 2013. AirWave: non-contact haptic feedback using air vortex rings. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* (UbiComp '13). ACM, New York, NY, USA.

[9] Rajinder Sodhi, Ivan Poupyrev, Matthew Glisson, and Ali Israr. 2013. AIREAL: interactive tactile experiences in free air. *ACM Trans. Graph.* 32, 4, Article 134 (July 2013), 10 pages.

[10] https://www.ted.com/talks/tasos_frantzolas_everything_you_hear_on_film_is_a_lie?language=en

[11] McGurk H., MacDonald J. (1976). Hearing lips and seeing voices. Nature 264, 746–748

[12] Rossiter, JM, Takashima, K & Mukai, T, 2012, 'Shape memory properties of ionic polymer-metal composites'. *Smart Materials and Structures*, vol 21.

[13] Sareh, S & Rossiter, J, 2013, 'Kirigami artificial muscles with complex biologically inspired morphologies'. *Smart Materials and Structures*, vol 22.

[14] Rossiter, JM, Takashima, K, Scarpa, F, Walters, P & Mukai, T, 2014, 'Shape memory polymer hexachiral auxetic structures with tunable stiffness'. *Smart Materials and Structures*, vol 23.

[15] Yanagida, Y., Kawato, S., and Noma, H. Projection based olfactory display with nose tracking. *Virtual Reality,* (2004).

[16] Nicholas Negroponte, 2015, https://www.youtube.com/watch?v=JgZjuymJx78