
Free-Space Haptic Feedback for 3D Displays via Air-Vortex Rings

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Abstract

With recent developments in 3D display interfaces, which are now capable of delivering rich and immersive visual experiences, a need has arisen to develop haptic-feedback technologies that can seamlessly be integrated with such displays – in order to maintain the sense of visual realism during interactions and to enable multimodal user experiences. We present an approach to augmenting conventional and 3D displays with free-space haptic feedback capabilities via a large number of closely-spaced air-vortex-ring generators mounted along the periphery of the display. We then present our ongoing work on building an open-source system based on this approach that uses 16 vortex-ring generators, and show how it could serve as a multimodal interactive interface, as a research tool, and as a novel platform for creative expressions.

Author Keywords

Multimodal Interfaces; Haptic Feedback; 3D Displays; Air-Vortex Rings; Tactile Feedback; Methods

ACM Classification Keywords

H.5.1. Multimedia Information Systems; H.5.2. User Interfaces: Haptic I/O; Prototype

Motivation

For many years, the Object-Based Media Group at MIT Media Lab has been developing novel 3D interface technologies including true-holographic displays, gestural interfaces, and other 3D immersive displays and telepresence systems. Recent examples include: an autostereoscopic aerial light-field display - capable to optically relay a life-size image of a person into free space with 3D and motion parallax; HoloSuite – an interactive telepresence system that uses advanced 3D displays and gestural sensors to seamlessly merge two 3D worlds to enable remote collaboration between individuals separated by a metaphysical window; 3D Telepresence Chair - uses the Pepper's ghost effect to augment an office chair that appears to create a remote meeting participant; and Mark IV - the fourth generation of a true-holographic 3D display system [1]. While these display systems are vastly different in the immersive visual experiences they afford, and in the underlying physics that enable those experiences, the feedback received from users reveals a similar concern with them all – the realism and immersion is there initially, but it breaks down when users reach in to touch the 3D object(s) and their hands simply go through air unimpeded. Moreover, when pushing or grabbing a 3D virtual object, it is difficult for users to know when exactly their hands are in contact with the spatial boundaries of that object [3]. These two problems are indicating that lack of haptic feedback during an interaction also has ramifications beyond the sense of touch. Haptic feedback is needed not merely to add another sensory dimension to the experience, but also to improve the realism of the visual and gestural experiences themselves.

For these reasons, we became interested in developing a haptic feedback system that could seamlessly be integrated with nearly any existing visual interface, to augment it with haptic feedback capabilities. We wanted users to feel localized cutaneous sensation when their hand initially comes in contact with a virtual 3D object on a display. Our aim was to augment the interface, not the user, thus we needed a free-space, non-wearable approach to haptic feedback.

Another key motivating factor was to liberate haptic feedback interaction by providing a fully open source platform that would offer an entirely new medium for creative expression – empowering individuals to express their creativity through developing multimodal interactive content for the system, and through building replicas and derivatives of the system itself.

Related Work

One of the earliest approaches to mid-air haptics for Human Computer Interaction is via the use of classic air-jets. Sensorama [4] was one of the first projects to employ this technique. But the main drawbacks of the air-jet approach to haptics are very low spatial resolution and short range. Air jets cannot maintain focus and begin dissipating almost as soon as the air leaves the nozzle [9].

In 2008, an ultrasonic approach to free-space haptics was demonstrated by Iwamoto et. al. [5]. They built a tactile display consisting of a 2D array of 40 KHz ultrasonic transducers. By focusing the ultrasound using a phased-array focusing technique, they could deliver tactile sensations in mid-air with a resolution of approximately one square centimeter.



Figure 1: General design concept. A haptic feedback frame featuring multiple air-vortex-ring generating apertures with one angular degree of freedom each (top), that can be seamlessly mounted and integrated with an existing stereoscopic display such as zSpace™ (bottom).

Since its inception, the ultrasonic approach to haptic feedback interaction has been explored by several research groups, and the technology has also been commercialized by Ultrahaptics [2]. Key advantages of this approach are sustained haptic feedback, low latency, and relatively high resolution. Key limitations are relatively weak perceived sensation, limited range of approximately 30cm, volume of interaction limited by the surface area of the display, and relatively large aerial footprint which makes integration with preexisting visual interfaces difficult.

In 2013, a toroidal air-vortex approach to haptic feedback was demonstrated by both Microsoft Research (AirWave) [3] and Disney Research (AIREAL) [9]. AirWave could deliver vortex rings with a range of up to 2.5m with a target accuracy of 10cm. The system was designed to target different regions of the body, so it was optimized for long range and high impact force, rather than high resolution. AIREAL consisted of a 3D-printed vortex-ring generator, a flexible nozzle with two angular degrees of freedom, and a depth camera. The device could hit an 8.5cm diameter target with 98% accuracy from 0.75m, and 84% accuracy from 1.25m. The Disney researchers showed that when the generator was integrated with a game or other visual content, users could perceive rich haptic information. Key advantages of the toroidal vortex approach are long range, strong tactile sensation, small footprint, and relatively low cost. Key drawbacks are impulsive rather than sustained stimulus, translational delay, and audible popping noise during vortex-ring generation.

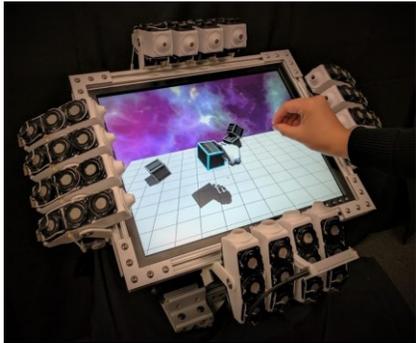
An even more recent approach to free-space haptics is via use of lasers. In 2015, Jae-Hoon Jun et. al. reported that laser-induced thermoelectric effects can elicit

tactile sensations with only a small increase in skin temperature [6]. When a laser beam irradiates the skin, the incident light energy is transformed to thermal energy in accordance with the optical and thermal properties of the tissue. The heat is then transferred to the surrounding tissue. Tactile sensation is then felt due to the photomechanical effect. Other research groups have also explored the laser-induced approach to haptic feedback [7]. However, questions and concerns still remain about the viability and safety of laser-induced haptic feedback [6,7,8].

We chose to build a system based on the air-vortex-ring approach to mid-air haptics due to its long range, small footprint, and strong unambiguous haptic stimulus. Moreover, because this approach has received less attention compared to the other approaches, there are still several research questions that our system could begin addressing, as we discuss in the *Application Scenarios* section below.

Concept Design

We were interested in building an interactive system that can seamlessly be integrated with a stereoscopic display, holographic video display, volumetric display, or another 3D or 2D display - augmenting it with haptic feedback capabilities. When a user moves their hand over the volume of interaction and comes in contact with the boundary of a virtual object, they would experience localized tactile feedback on the hand. Similar to how interactive touch bezels augment a regular screen into a touchscreen, we wanted to create a device of similar nature that augments a screen, not with an input-capability, but rather with an output-capability, namely free-space cutaneous feedback based on air-vortex rings. Figure 1 shows our idealized



design concept – the combination of a haptic feedback frame and a stereoscopic display – to yield immersive experiences that enable users to see, hear, feel, and manipulate virtual objects using their bare hands with a high degree of visual, auditory, and tactile realism. The haptic feedback frame has multiple closely-spaced apertures on each edge for vortex ring generation. In order to deliver tactile stimulus at any point in the 3D space above the screen, each aperture needs to be capable of dynamically changing its angle in the range 0 to 90 degrees relative to the plane of the screen. The close proximity of the apertures allows one angular degree of freedom per generator to be sufficient. To aim the vortex generators at a user's hand, an infrared hand tracker is used for tracking the position and velocity vectors of the palm and fingers in real time.

In terms of interactivity, we wanted the system to provide reactive rather than passive haptic feedback; toroidal vortices would be generated only when a user's hand comes in contact with a virtual object. By designing the system in this way, the popping sound produced during vortex generation becomes a feature rather than a bug, because it complements the cutaneous stimulus by offering another indication that a virtual object has been touched. However, for this to apply, the relative delay between auditory and haptic stimulus must be no greater than a few hundred milliseconds. This condition was satisfied in the system we built.

Prototype Overview

We developed a multimodal interactive interface system called AirTap, as shown on Figure 2, as a first prototype toward our idealized design concept. 16 low-profile air-vortex-ring generators are mounted on the

four edges of an aluminum frame that surrounds a 20-inch monitor. Each generator has one angular degree of freedom allowing for a 0 to 90 degree range of motion relative to the plane of the screen. A Leap Motion controller is mounted near the bottom edge of the display, which tracks a user's hand position, velocity, and orientation in 3D space. This tracking information is then used to dynamically set the angles of each of the 16 generators, such that they always follow the user's hand. Interactive 3D content is presented on the screen. When the user's hand comes into contact with a virtual object, a vortex-ring generator is fired and the user feels haptic feedback corresponding to the virtual touch event. In addition to the haptic feedback, there is also visual and auditory feedback that further indicate to the user when they have touched the virtual object. A high-level block diagram representation of the system architecture is shown on Figure 3.

One of the many challenges we faced when developing this system was designing a vortex generator that is as slim as possible – in order to achieve close proximity between neighboring generators. After investigating and designing nearly a dozen kinds of air-vortex generator mechanisms, we chose to use subwoofer transducers as actuators because they offered the fastest actuation time compared to all other approaches, and thus the highest translational velocity for the toroidal air-vortices. The smallest suitable subwoofers we could find on the market (NSW1-205-8A) had a width of 39mm, which was also the width we then used for the design of our vortex generators, as shown on Figure 5. Complete technical description of the system and the different generator prototypes we tested can be found in the corresponding thesis referenced in [10].

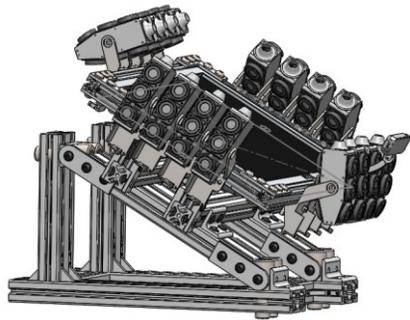


Figure 2: Current Prototype of AirTap and a corresponding CAD model. A user is pictured interacting with a virtual block. All generators are following the user's hand, and whenever it comes in contact with one of the objects, the appropriate generator fires a vortex ring which the user feels as a tap on their hand.

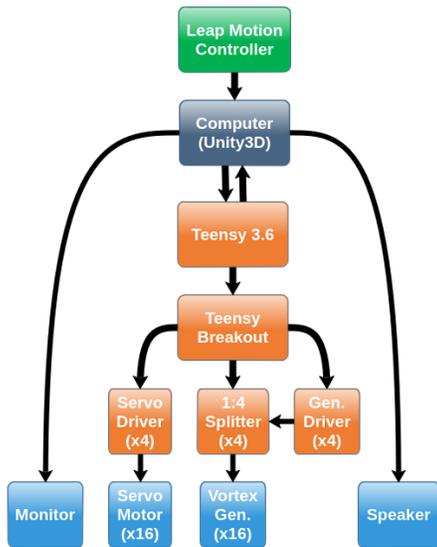


Figure 3: Signal-flow diagram for AirTap. The only user-input to the system is via the Leap Motion controller, which tracks the user's hand(s).



Figure 4: Bubble-popping interactive user experience for AirTap.

Application Scenarios

Interactive Interface

As an interactive interface, our system can deliver rich and realistic multimodal experiences that enable users to feel more fully immersed when interacting with virtual content – without the need to hold any objects in their hands or to have wearable devices attached to their bodies.

For the purposes of calibration and testing, we have developed a basic 3D interactive experience consisting of two virtual crates that a user can touch and move (Figure 2), and a second interactive experience where a user can pop virtual soap bubbles with their hand and feel multimodal feedback in the process (Figure 4). Since the system is still under development, we have not yet conducted a formal user study, though we have demonstrated it in operation during a recent 2-day demo event at the MIT Media Lab. Over a hundred people with ages ranging from mid-twenties to late-sixties interacted with our system and provided an overwhelmingly positive feedback – even though only 4 of the 16 generators were active at that time. 100% of the participants who tried the system indicated that they unambiguously felt the haptic feedback. The main feature requests we received from users were to make the generators even smaller and less visible to the user. Our next prototype will address these requests. Additional use cases we envision for the system include playing a virtual piano and while feeling the virtual key presses, and employing it for immersive storytelling.

Automotive control system

Physical controls such as knobs and buttons in automobiles allow drivers to find and adjust those

controls without having to look at them, due to the natural haptic cues afforded by physical controls. In new automobiles, however, physical controls have been largely replaced by touchscreens, which has resulted in loss of haptic cues. Drivers can no longer rely solely on the haptic sense, but also have to engage vision in order to find the buttons on a touchscreen. This causes distractions and could lead to severe consequences. Our system could be employed in automobiles for restoring the haptic cues that are now missing with touchscreen based controls. The system is well suited for cars, because the vortex generator chambers could be positioned behind the display and only small nozzles could be placed along the edges of the screen.

Research Tool

There has been relatively little research on the use of air-vortex rings for haptic feedback in HCI applications. Many of the remaining questions can be addressed by our system and new questions could be posed. Could the perceived tactile stimulus from air-vortices be enhanced by intelligent pairing with corresponding visual and auditory stimulus? Could dynamic changes in the physical properties of toroidal air-vortices – temperature, humidity, and diameter – be utilized for providing another layer of haptic richness, such as texture? How is the tactile perception affected by the angle of incidence of the vortex ring? We can also utilize the system to investigate entirely new phenomena such as haptic feedback due to colliding air-vortices – potentially at different angles and with different physical properties.

Open Platform for Creative Expressions

Our system offers a new medium for which designers, artists, and content creators can develop novel,



Figure 5: Air-vortex-ring generator with mounting assembly. The generator consists of a 3D-printed chamber, and six subwoofer transducers. The mounting assembly consists of a 3D-printed mount, to which the generator is attached at its center of mass, and a high-torque servo motor (HS-645MG) that controls the angle. The images above show the 0 degree and 90 degree angular positions of the generator relative to the screen.

multimodal, interactive user experiences. It aims to empower people to express their creative potential in a completely new way. Our aim is to see others develop interactions that we ourselves perhaps never even thought about. Moreover, by fully open-sourcing AirTap, we are hoping to see users take the creativity platform aspect of the system even one level higher, by not just designing experiences for the existing system, but designing their own derivatives of the system itself, making it more personalized for their own needs.

Conclusion and Future Work

This work explored a method for augmenting existing visual interfaces with haptic feedback capabilities based on the toroidal air-vortex approach to haptics, by using a large number of vortex-ring generators. We presented a first prototype of a multimodal interactive interface system we built based on this method that uses 16 independently-controlled vortex-ring generators with one angular degree of freedom each. We discussed a number of application scenarios for our system in terms of its use as an interactive interface, as an automotive control system, as a research tool, and as a platform for creative expression. We are just beginning to explore the presented application scenarios. Moreover, we are beginning to design a second, more compact and more feature rich prototype, where the vortex generators would be decoupled from the nozzles. This decoupling would enable us to have only the nozzles at the periphery of the display and hide the generators from the user's view, allowing for a much more elegant and slim design that more closely resembles the concept design. At that point, we would begin integrating the haptic feedback frame not only with 2D but also with 3D displays as originally intended.

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