AIREAL: Interactive Tactile Experiences in Free Air

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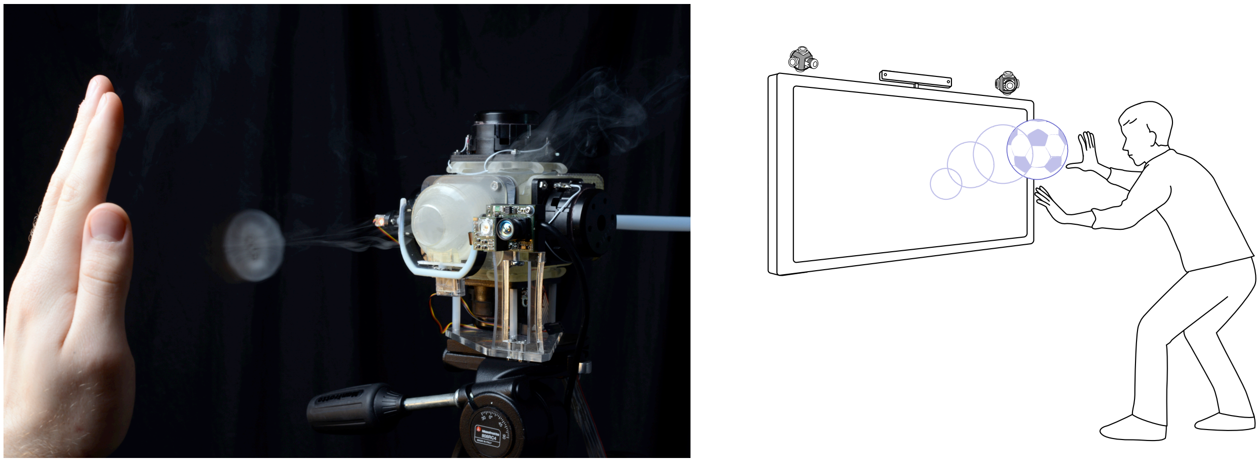

Figure 1: *On the left, the AIREAL device emits a ring of air called a vortex, which can impart physical forces a user can feel in free air. On the right, multiple AIREAL devices can be used to provide free air tactile sensations while interacting with virtual objects.*

Abstract

AIREAL is a novel haptic technology that delivers effective and expressive tactile sensations in free air, without requiring the user to wear a physical device. Combined with interactive computers graphics, AIREAL enables users to feel virtual 3D objects, experience free air textures and receive haptic feedback on gestures performed in free space. AIREAL relies on air vortex generation directed by an actuated flexible nozzle to provide effective tactile feedback with a 75 degrees field of view, and within an 8.5cm resolution at 1 meter. AIREAL is a scalable, inexpensive and practical free air haptic technology that can be used in a broad range of applications, including gaming, mobile applications, and gesture interaction among many others. This paper reports the details of the AIREAL design and control, experimental evaluations of the device's performance, as well as an exploration of the application space of free air haptic displays. Although we used vortices, we believe that the results reported are generalizable and will inform the design of haptic displays based on alternative principles of free air tactile actuation.

CR Categories: H5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces, Input devices and strategies, Haptic I/O.

Keywords: augmented reality, haptics, tactile displays, tangible interfaces, augmented surfaces, 3D interfaces, touch interaction.

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1 Introduction

This paper presents AIREAL, a technology that delivers interactive tactile experiences in free air without the need for a user to wear or touch any physical device. We were motivated by the rapid expansion of interactive computer graphics from the desktop and movie screen into the real world. Recent developments of inexpensive gesture tracking and recognition technologies, such as the Microsoft Kinect or Nintendo Wii, have enabled millions of people to play computer games using their bodies (Figure 1). Furthermore, with the rapid improvement of computer vision tracking and registration algorithms, development of novel projection devices enable graphical images to be overlaid on the real environment, enabling entirely new spatial augmented reality (AR) applications [Wilson 2012]. As highly interactive computer graphics continue to evolve on mobile platforms, these natural interfaces will become accessible anywhere and at any time. The line between real and virtual is, indeed, rapidly blurring.

One missing piece in this emerging computer-augmented world is the absence of physical *feeling* of virtual objects. Despite significant progress in developing tactile feedback technologies, in order to feel virtual objects, users have to either touch interactive surfaces or physical objects equipped with haptic devices [Poupyrev et al. 2003; Bau et al. 2012], or wear tactile feedback devices in the form of haptic gloves, belts, vests, etc. [Bianchi et al. 2006; Israr et al. 2011]. Although these approaches can offer rich tactile sensations, requiring users to wear physical devices can impede natural user interaction and limit the overall range of applications that employ tactile feedback.

This paper explores an alternative approach to provide users with rich tactile feedback without instrumenting the user or objects in the environment. AIREAL delivers interactive tactile sensations in *free air* by stimulating the user's skin with compressed air pressure fields. In contrast to previously reported free air haptic devices based on blowing air [Heilig 1962] or ultrasound-generated pressure waves [Iawamoto et al. 2008], AIREAL uses air vortices, where tactile sensations are produced by a pressure differential inside of an air vortex (Figure 1).

Vortices have a number of advantages. First, they provide effective tactile sensations over relatively *large distances*, reaching over 1 meter in length. Second, vortices allow for an efficient, relatively inexpensive and highly scalable design of free air haptic devices. AIREAL uses five miniature speakers driven synchronously with individual 20W D-class amplifiers (Figure 2). By choosing different speaker models, larger or smaller haptic devices can be easily produced according to application requirements (e.g., mobile tablet computers). Third, AIREAL uses a flexible nozzle controlled by a pan and tilt gimbal configuration, which allows it to dynamically direct vortices in a desired location.

Because of the large actuation distance, scalability and controllability of tactile sensations produced by AIREAL, we were able to design and investigate complete functional interactive scenarios based on free air haptics. These scenarios include enhancing free air gestural interaction with tactile feedback, designing a "haptic video projector" where the users can both see and feel content projected on their bodies and creating free air tactile "textures" that allow the user to feel the properties of the objects by moving their hands in free air. Developing complete interaction prototypes based on AIREAL free air tactile display is an important contribution of this paper. We are not aware of any previous attempts to systematically investigate applications of free air haptics in interactive applications.

The summary of contributions is as follows: First, we describe the design of our vortex haptic generator. We present the details of the actuators and discuss the advantages and limitations of vortex-based tactile actuation. Second, we report the performance measurements of our vortex generator, including measurements of detection thresholds and Just Noticeable Differences (JNDs) of free air tactile sensations, as well as vortex speed and latency. Finally, we investigate the utility of free air haptics by designing complete interactive systems with AIREAL. By integrating depth image sensors into the AIREAL design, the user's hands, head and body were tracked in 3D for interaction. Both gaming and performance applications were created in desktop, freestanding, tabletop and mobile configurations using one or more AIREAL devices. Although our investigation was performed using vortex-based tactile actuation, we believe that our results and discussions can inform the design of other haptic displays based on alternative principles of free air tactile actuation.

2 Background and Related Work

The recent interest in free air tactile displays has been fueled in part by the growing popularity of gestural and full body interaction spearheaded by gaming (e.g., [Rice et al. 2011]) and recently expanded to home entertainment systems, tabletop and mobile devices [Jason et al. 2011; Ruiz et al. 2011]. The goal of free air haptics is to provide efficient and effective tactile feedback to one or more users moving freely in their environments without requiring them to wear or hold physical devices [Hoshi et al. 2010]. Manipulating the *dynamics of air* surrounding the user is a natural venue for exploring the design of free air tactile interfaces.

Air has been explored in human-machine interaction since the late 1950s. One of the earliest examples was *Sensorama*, invented by cinematographer Morton Heilig [Heilig 1962]. It was a device that combined a stereoscopic motion picture display with smell, stereo sound and wind blowing into the user's face to increase the sense of immersion. Similar air blowing techniques have also been used for decades in location-based entertainment, e.g., Walt Disney World "Soren" attraction which simulates flying in a glider.

The major challenge in designing airborne haptic displays is creating *high-resolution* tactile feedback at *large distances*. In the case of air blowing with classic air jets, the range of effective tactile feedback depends on the jet diameter and velocity. Small air jets can be relatively effective over short distances, e.g., less than 30 cm [Suzuki and Kobayashi 2005]. However, to increase the effective distance, the diameter and power of air jets also have to increase significantly, such as with wind tunnels. This dramatically decreases the resolution of the tactile feedback and makes it impractical in most in-door applications.

There are two major approaches to creating long-distance, yet highly directed and high-resolution airborne haptic displays: a) ultrasound acoustic radiation fields and b) air vortexes. We briefly discuss both below in more detail.

In *ultrasound-based acoustic radiation fields* [Iwamoto et al. 2008; Suzuki et al. 2010; Jason et al. 2011], a two-dimensional array of 324 ultrasonic transducers operating at 40kHz form a beam of ultrasound using a phased array focusing technique. Because of the low ultrasound frequency, 99.9% of incident acoustic energy will reflect from the human skin creating a pressure field which provides perceivable tactile sensations. By modulating the ultrasound beam at ~200 Hz, the perceived intensity of tactile sensations increases due to the high sensitivity of skin to vibratory stimuli at this frequency [Sherrick 1991]. A phased array technique is used to control the focal point of the ultrasound beam [Suzuki et al. 2010].

Ultrasound-based free air tactile technology was an exciting development because it is relatively compact, uses little power and delivers distinguishable high-resolution tactile sensations. The operating distance, however, is still relatively short and is limited to 30 to 40 cm from the surface of the transducer array. Increasing the operating distance would require increasing the number of actuators, or using larger high-powered ultrasound transducers, which limits either the scalability or focusing resolution.

Figure 2: *Top: a fully assembled AIREAL device. Bottom: an exploded view showing speakers, the pan and tilt motors as well as the 3D printed enclosure, flexible nozzle and gimbal structures.*

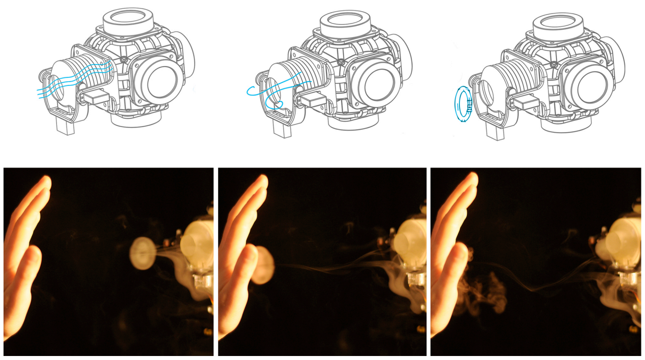

Figure 3: *Principles of air vortex generation.*

Air vortices have been known, observed and studied for centuries (e.g., [Rogers 1898]) and can be defined as an area where the flow of air behaves as a swirling motion around a translational axis. An important benefit of vortices is they can impart considerable force upon collision with an object. Furthermore, vortices can travel over significant distances while keeping their shape and speed.

Previous work has explored various uses of vortices, including delivering olfactory stimuli to users at a distance [Yanigida et al. 2004], data transmission for robot communication [Russel 2011], as well as projection surfaces for creating visual displays in mid-air [Tokuda et al. 2010]. Although these uses of vortices offer unique insights into their capabilities, there is a very limited understanding of both the performance characteristics of vortex-based haptic displays, e.g., operational distance, generated forces, delay and precision, as well as human perception characteristics, e.g., JNDs and detection thresholds of airborne tactile stimuli based on intensity. While others have proposed the initial idea of using vortices for tactile feedback (e.g., [Kruijff et al. 2005; Takamori et al. 2010]), the design of our vortex-based free air haptic display, evaluation of its performance and characteristics, as well as an experimental analysis of human perception represents the first thorough investigation of such haptic displays.

The design and investigation of interactive applications of free air haptics is another major contribution of this paper. While air vortices have been proposed for use in entertainment-based applications, such as movie theaters [Takeda 2006; Hashiguchi et al. 2011], this paper represents the first attempt to thoroughly investigate the exciting area of interactive vortex-based haptic displays. The applications that we present have been entirely prototyped to use vortices. However, we believe that our observations and design decisions are generalizable and will inform the design of interfaces based on other types of airborne haptic displays.

3 AIREAL Free Air Haptic Display

Vortices have been studied extensively in fields such as fluid dynamics and aeronautics, but relatively little is known about their performance characteristics as a *haptic display*. In this section, we provide a short introduction to the physics of air vortices, followed by principles of operation and implementation of the AIREAL free air haptic display.

3.1 Physics of Air Vortices

3.1.1 Vortex Formation

An air vortex is a ring of air that typically has a toroidal shape and is capable of traveling at high speeds over large distances. Unlike laminar airflow which quickly disperses, a vortex is capable of keeping its shape and form.

Figure 4: *A paper target was used to measure accuracy performance. We show the target at its resting and hit state.*

A vortex forms when air is quickly ejected out of a circular aperture. Air molecules at the center of the aperture move faster than the air molecules at the edge of the aperture due to the drag between the air molecules and the aperture's surface [Shariff 1992]. As the air leaves the aperture, this difference in speed causes the air to rotate around the aperture, accumulating air molecules into a ring (Figure 3). When the ring becomes too large, it pinches off from the aperture using its rotating motion to carry itself through space [Yanagida et al. 2004]. This rotating motion minimizes the energy lost due to friction and allows the vortex to remain stable (Figure 3).

3.1.2 Stroke Ratio

In fluid dynamics, a classical representation of vortex formation is a piston inside a tube with a circular aperture at the end of the tube. The *stroke ratio* [Mohseni et al. 2002; Gharib et al. 1997] is defined as a ratio of the length of the theoretical cylindrical slug of air pushed out of the nozzle, L_s, to the aperture diameter D:

$$R_{Stroke} = \frac{L_S}{D}.$$

The stroke ratio characterizes the stability of the vortex as it leaves the aperture [Rosenfeld et al. 1998]. If it is greater than a theoretically defined threshold value, called the *formation number*, a large turbulent wake will be created behind the vortex, resulting in lost vortex energy. A typical value for the formation number falls between 3.6 and 4.5 for various vortex systems.

We used the stroke ratio to determine aperture diameters that produce stable vortices. If we assume that air is incompressible, then the length of a slug of air leaving the enclosure is:

$$L_S = U_A \cdot T_E,$$

where U_A is the speed of the air leaving the aperture and T_E is the time it takes for the air to exit the enclosure [Shariff et al. 1992; Glezer et al. 1988]. The total air volume V_S leaving the enclosure due to the displacement of our five actuators is

$$V_S = U_A \cdot T_E \cdot A_A = L_S \cdot \pi \cdot \frac{D^2}{4},$$

where A_A is the aperture area and D is aperture diameter.

Consequently,

$$L_S = \frac{4Vs}{\pi D^2} \text{ and } R_{Stroke} = \frac{4Vs}{\pi D^3}.$$

Thus, for stable vortices:

$$\left[\frac{4Vs}{\pi D^2}\right] \leq 3.6 \qquad \text{(Eq. 1)}$$

We measured our speaker membrane displacement using a high accuracy Keyence H057 laser displacement sensor. From the

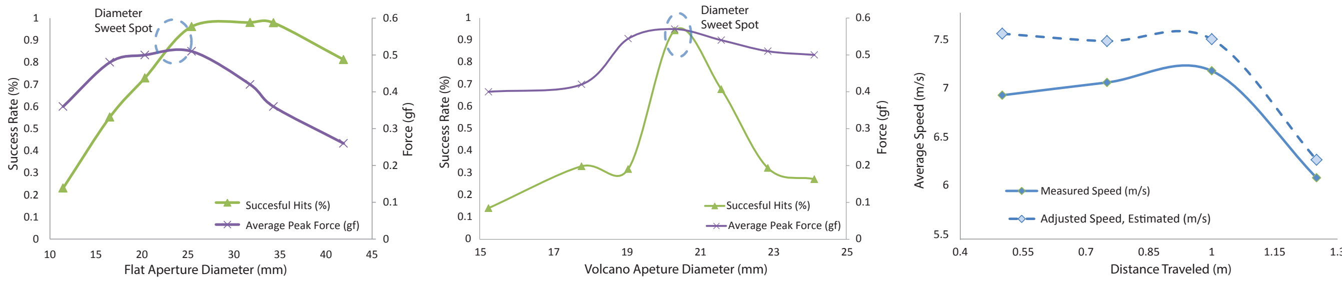

Figure 5: *Experimental measurements: flat aperture performance, volcano shaped nozzle performance and vortex speed.*

above equations, the total volume of air displaced by all five speakers and the aperture diameter is:

$$V_S = 33{,}670\,\text{mm}^3, D \geq 2.3\text{cm}\cdot$$

3.2 Vortex Generator

The AIREAL vortex generator is shown in Figure 2 and is comprised of a cubic enclosure (8×8×8 cm), flexible nozzle (4 cm in length) and a pan and tilt gimbal structure that is used to actuate the nozzle. All components except for the actuators and motors are 3D printed on an Objet™ printer using a mixture of hard and soft UV-cured photopolymers and resins.

Five 2-inch 15W Whisper™ subwoofers were used as actuators, mounted around the enclosure with the flexible nozzle facing outward into the environment (Figure 2). The actuators contain a flexible diaphragm that, when displaced, pushes a volume of air. The displacement rate of the speaker cones determines the flow rate of the air going in and out of the device. The total weight of the AIREAL device is 1278g.

3.3 Experimental Measurements

3.3.1 Aperture Size

The first set of experiments was conducted to determine the aperture diameters that produce the most accurate and intense tactile sensation. While Equation 1 defines aperture sizes that allow the creation of stable vortices, we wanted to validate them empirically for our five-actuator design. Furthermore, we were interested in testing if stable vortices produce high intensity tactile sensations.

Following previous work that focused mainly on characterizing vortex behavior for flat nozzles [Gharib et al. 1997], we measured vortex accuracy for seven flat apertures ranging from 1 cm to 5 cm, corresponding to a stroke ratio from 1 to 30. To perform accuracy measurements, an AIREAL device was placed 0.5 meters away from a stationary paper target composed of flat concentric rings (Figure 4). Based on the results of pilot tests, the center of the final paper target was a paper circle 8.5 cm in diameter and each successive concentric circle was 3 cm wider. The entire experimental target was 26 cm in diameter.

A vortex was considered accurate when it hit only the center, i.e., when the 8.5 cm center circle moved from its stationary position (Figure 4). If the outer rings moved, the vortex either hit off-center or had become unstable and dispersed before hitting the target. The target response to the vortices was observed by an experimenter and recorded on video for post analysis.

To measure the physical force of the vortex, we fired vortices at a 0.01 gram force (gf) scale E&J 200. Force tests were conducted at 0.5 m from the scale with 100 trials per nozzle.

Figure 5 shows accuracy and force measurement results. We can observe that accuracy improves with increasing aperture size, plateauing between 2.5 cm and 3.5 cm in diameter. With a further increase of aperture size the performance began to drop off noticeably. Note that the aperture diameters producing the most stable vortices correspond to the diameters derived using Equation 1, which validates our theoretical estimations for flat nozzles.

Figure 5 also shows the results of force tests, which indicate that the stable vortices do not necessarily produce the most intense tactile sensations. The highest forces were recorded for apertures ranging from 1.65 cm to 2.5 cm in diameter with a mean force of 0.5 gf, sufficient to be felt on the skin. Optimal apertures lie at the intersection of the most accurate and forceful vortices. While this overlap is small, we found that a 2.5 cm aperture provides a good balance for both accuracy and force.

3.3.2 Nozzle Shape

While we have demonstrated that flat apertures produce accurate and high intensity vortices with the AIREAL device, we also wanted to investigate the effect of the *nozzle shape* on force or accuracy. Little is known about the effects of nozzle shapes on vortex creation, and computationally modeling the effect of nozzle shape on the behavior of vortices is a highly non-trivial problem [Gharib et al. 2010]. Consequently, we followed an empirical approach where we identified a number of nozzle shapes that could deliver vortices with high accuracy and intensity. The nozzle parameters we chose to vary included curvature, length, aperture size and thickness. Figure 6 shows a subset of the nozzle shapes we tested. These shapes were based on designs reported in previous work investigating vortex characteristics in the fields of fluid mechanics and aeronautics [Gharib et al. 2010].

While the slug model described in previous work has performed accurately for flat nozzle designs, we found variations of performance with arbitrary nozzle shapes. In total, seven apertures were tested, ranging from 1.5 cm to 2.5 cm in diameter (Figure 6). We narrowed the selection of nozzle shapes down to a single promising design that we call the "volcano" nozzle. In our experiments it produced a sharp peak indicating a narrow stability range with optimal accuracy performance at 2.05 cm aperture diameter (Figure 5). The accuracy of this nozzle was equivalent to the optimal 2.5 cm flat nozzle measured previously, but produced 10% more force. Therefore, we chose to use the volcano nozzle for our final flexible nozzle design (Figure 6).

For the final evaluation of the performance of our flexible nozzle design, we created 5 paper targets 8.5 cm in diameter each, sus-

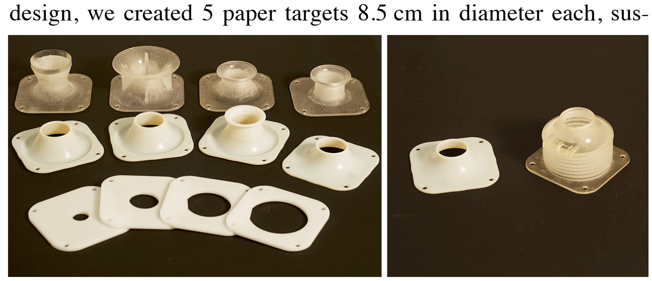

Figure 6: *The various nozzle shapes and apertures tested and the final nozzle selection and its flexible equivalent.*

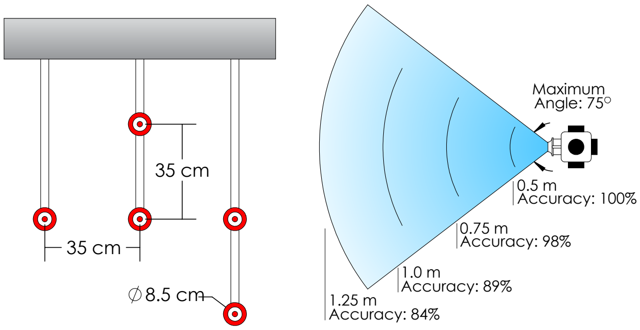

Figure 7: *Spatial accuracy measurement. The red circles were targeted with vortexes produced using our flexible nozzle.*

pended in a grid where each circle was 35 cm away from its closest neighbor (Figure 7). The experimental result showed that our flexible nozzle performed with 90% accuracy at a distance of 1 meter and was capable of covering a 75° targeting field.

3.3.3 Latency of a Vortex

We measured the speed and latency of the vortex by computing the length of time between injecting a test signal into the AIREAL device and the moment when the vortex hit a displacement sensor. Overall, 60 measurements were performed in the 0.5 –1.25 m range with an average speed of 7.2 m/s and 139 ms average latency. Figure 5 shows the results of our latency experiments. The dotted line indicates the vortex speed adjusted for the 5 ms delay required for the vortex to pinch-off from the nozzle tip. These results can be used in the design of tactile interfaces to decide when to emit a vortex (see section 5). An investigation of the effects of vortex latency on tactile perception is left to future work.

3.4 AIREAL Implementation

3.4.1 AIREAL Signal Controller

The AIREAL signal generator is presented on Figure 8. An Mbed microcontroller control board based on the LPC17168 ARM Coretex M3 microprocessor generates low-amplitude pulse waveforms using a digital-to-analog converter. The amplitudes and frequency of pulses are dynamically controlled from a host PC using a simple protocol over serial interface. The waveforms are smoothed using a low-pass filter and amplified using a TI3001D1 single-channel 15 W D-class differential sound amplifier. There are five amplifiers implemented on the control board with the total output current limited to ~8A with a maximum power consumption of ~60 W. The control pulse frequency varies between 1 and 30 Hz. The motors controlling the motion of the flexible nozzle are driven directly from the digital control pins of the microcontroller. The board is powered with a 12 V DC power source.

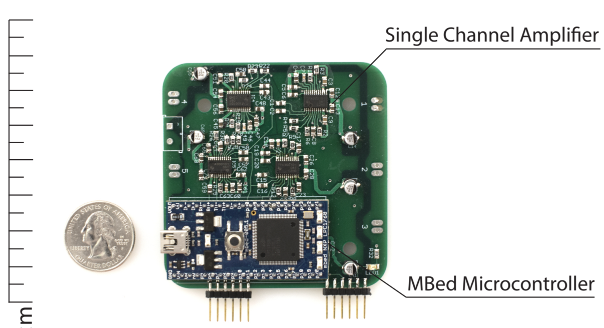

Figure 8: *AIREAL controller board.*

The amount of displacement of a speaker's cone is directly related to the amount of current passing through the speaker. At 12V and 1.1A, our speakers produced the largest displacement at ~8 mm (i.e. –4 mm to +4 mm), in line with manufacturer specifications of the speakers. Driving the speakers with higher current yielded no further increase in displacement.

3.4.2 Vortex Control and 3D Registration

The 3D printed pan and tilt mechanism controls the flexible nozzle, which allows the vortex to be directed to a specific location in physical space (Figure 2, 9). To direct the vortex to a 3D location, we combined the AIREAL device with depth sensors to allow real-time tracking of a user's hand and body as well as physical objects in the environment.

AIREAL is primarily comprised of two depth-sensing configurations: (1) a *local* configuration, where a small depth sensor (PMD Camboard Nano) is mounted directly to a base plate rigidly connected to the AIREAL device; (2) a *global* configuration, where a large depth sensor (Microsoft Kinect) instruments the user's physical environment. The on-board sensor enables the direct ad-hoc interaction with AIREAL device allowing for a simple and quick setup at the cost of a smaller tracking volume, i.e., ~2 meter distance from the sensor. In contrast, the large environmental sensor allows tracking over larger distances and simplifies connecting multiple AIREAL devices to cover larger volumes of space.

In order for vortices to be accurately directed to a 3D location, the AIREAL device must be calibrated to the depth sensor. This requires that the 3D position of the AIREAL device be known with respect to the depth sensor. For the local configuration, we use a known baseline (7.2 cm) between the rigidly mounted depth sensor and the AIREAL device. An initial manual calibration process uses a line laser mounted inside the flexible nozzle to estimate the position and orientation of the AIREAL device in relation to the depth camera. While more accurate methods exist, we did not see any noticeable calibration affects in our applications.

For the global configuration, we followed a manual calibration process using the Procrustes transformation to extract a 3D rigid transform between the AIREAL device and the depth sensor. Each AIREAL device was manually instrumented with a small calibration rig composed of infrared markers. The markers were detected by depth cameras and used to find 3D correspondences with locations on a known 3D model of the AIREAL device. We found this calibration procedure sufficient for our applications.

A key challenge of controlling air vortices in 3D space is to ensure that the movement of the servomotors controlling the flexible nozzle does not hinder vortex creation. For example, if the flexible nozzle is moving too quickly, air resistance may prevent the vortex from forming correctly at the tip of the nozzle, leading to irregularities in the vortex's movement. To ensure stable vortex creation, a 5 ms delay was introduced, i.e., an estimated pinch-off

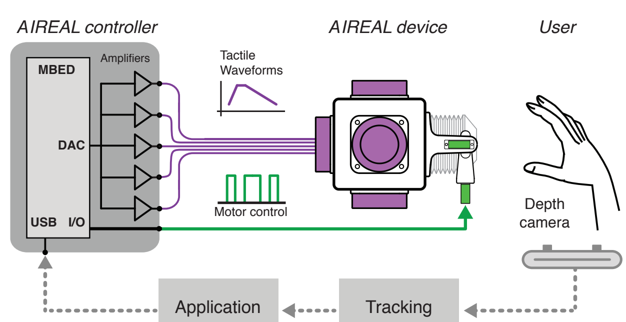

Figure 9: *The overall AIREAL system diagram.*

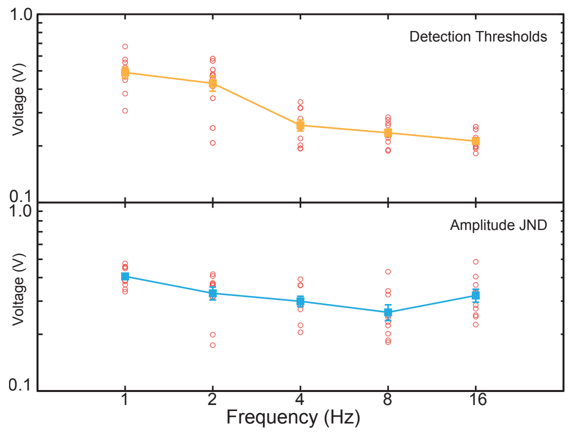

Figure 10: *Top: Absolute detection thresholds. Bottom: Amplitude JNDs at different signal frequencies.*

time measured in earlier latency tests, for each cycle in the pulse signal. This technique greatly improved the directionality control of our device and allowed for accurate continuous free air sensations to be directed at a specific location in the environment.

4 Perception of AIREAL Free Air Haptics

We conducted two experiments to estimate the absolute detection thresholds and amplitude discrimination thresholds of AIREAL at different signal frequencies. The *absolute detection threshold* is the smallest signal amplitude that produces a detectable tactile stimulus. It forms the baseline of human perception at a specific frequency and defines the low boundary of tactile stimuli that can be used in designing effective interactive experiences. The *amplitude discrimination threshold* or JND is the smallest detectable difference in the amplitudes of two stimuli. These thresholds define the amplitude range and tactile resolution of the device and can be used to design clearly distinguishable tactile stimuli. Both thresholds are measured in voltage units that drive the AIREAL.

4.1 Apparatus and Experimental Setup

The AIREAL device was mounted on a tripod, facing downward to stimulate the palm of the participants' left hand resting flat on a table. Participants sat upright at the table and wore earplugs and noise cancelling headphones playing pink noise to mask out any sound created by the AIREAL device. The experiments were conducted in a quiet, well-lit room with limited airflow.

4.2 Experimental Methods

We used a three-interval one-alternative forced-choice (3I-AFC) procedure combined with one-up three-down adaptive staircase paradigm [Leek 2001] to estimate detection and discrimination thresholds. The thresholds were estimated for five test frequencies: 1, 2, 4, 8 and 16 Hz. The order of test frequencies was randomized for each participant who completed all five frequency runs in one 20-25 minute session. Each run consisted of 50 trials.

In each trial, participants were presented with three one-second long intervals with tactile stimuli applied to the user's hand separated by two 400 ms intervals. Two intervals had reference stimuli (A_{Ref}) and the third interval had a target stimulus ($A_{Ref} + \Delta A$). The order of intervals was randomized. The participant's task was to identify the interval that contained the target stimulus by pressing a button labeled as '1', '2' or '3' using their right hand.

In the *detection threshold* experiment, the reference stimulus was set to 0 V. The start value of ΔA was selected such that the target stimulus was easily detectable. In the *discrimination threshold* experiment, the reference stimulus was set to 1.25 V and the start value of ΔA was such that the target stimulus could be easily discriminated from the reference stimulus. After three consecutive correct responses by a participant, ΔA was reduced by a predefined step size and for every incorrect response ΔA was increased by one step size. The initial step size of 4 dB (factor of 1.58) was used for faster convergence of ΔA to the true threshold level (ΔA_0). The step size was reduced to 1 dB (factor of 1.12) after three reversals. A change from decreasing to increasing ΔA, and vice versa, is referred to as a reversal. An experiment run stopped after eight reversals were recorded at the smaller step size.

Each experiment run yielded four peak voltages and four valley voltages (corresponding to reversals) at 1 dB step size. The average of these voltages resulted in one estimate of threshold per participant per frequency. A repeated measure ANOVA was used to analyze threshold trends along test frequencies.

4.3 Results

Figure 10 shows the resulting measurements of the absolute detection thresholds and amplitude JNDs ($\Delta A_0/A_{Ref}$) at different test frequencies. Each data point corresponds to the average threshold in volts and the error bars are the standard error of the mean. Visual inspection of data shows that both the detection thresholds and JND vary with frequency, resulting in higher thresholds at low frequencies and smaller values in the higher test frequencies. The within factor ANOVA showed a significant effect of frequency on detection threshold [$F_{2.02,18.2} = 48$; $p < 0.05$; G-G ε=0.51]. Post hoc tests using the Bonferroni correction revealed two frequency significant groups: 1 and 2 Hz, and 4, 8 and 16 Hz. Similarly, frequency was the significant factor for amplitude JNDs [$F_{4,36} = 6.7$; $p < 0.05$]. Post hoc comparison tests indicated the JNDs at 4 and 8 Hz were significantly lower than JND at 1 Hz; however, there was no significant difference between JNDs at 2, 4, 8 and 16 Hz.

The general shape of the absolute detection threshold curve is similar to that of the vibrotactile detection threshold curve [Bolanowski et al. 1988], which showed that thresholds stay constant up to 3 Hz and drop as the frequency increases. The overall average amplitude JNDs of 0.32 (2.4 dB) is also similar to JND reported in prior literature [Israr 2006]. This indicates that at each frequency there are 5 to 6 perceptually distinct amplitude levels in the operating range of AIREAL device.

4.4 AIREAL Vocabulary

Our preliminary vocabulary of free air sensations focused on four dimensions of vortex control: *pulse frequency*, *intensity*, *location* and *multiplicity*. These dimensions dictate how we use vortices to provide specific tactile sensations to the user. For example, intensity allows us to control the speed and force of the vortex, while frequency allows control of the rate of emission of the vortex. Controlling the location of the vortex allows shapes to be dynamically created and multiple vortices can be created simultaneously by combining several AIREAL devices. Additional dimensions that could be also used were the *signal waveform* and *slope*. We, however, chose to exclude them because analogous sensations were produced by varying the intensity of stimuli. Together, the combination of intensity, frequency, location and multiplicity produces a wide range of free air sensations that can be used to interact with virtual objects. We demonstrate examples of using these dimensions in the next section of the paper.

5 Designing Free Air Experiences with AIREAL

The application space of AIREAL is broad; therefore, we developed five applications where free air haptics could have the larg-

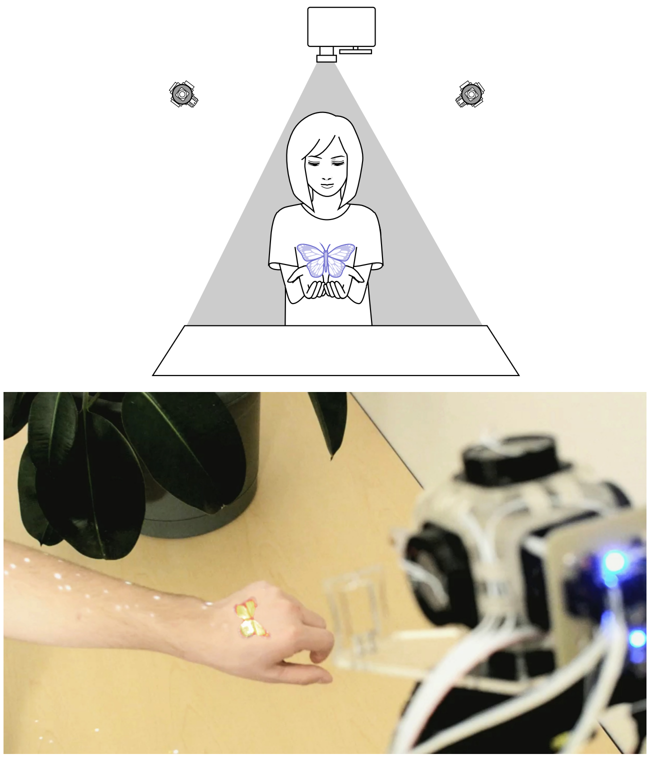

Figure 11: *Haptic projection: a projected butterfly is collocated with free air tactile sensations.*

est potential impact. In designing these applications we were guided by the following design principles:

- *Collocation*. The visual images and tactile sensations should be collocated in space and time, e.g., projected imagery should overlap free air haptics in the same location on the user body.
- *Persistence*. Free air haptic sensations remain persistent in physical space, independent from the user, e.g., certain areas can emit fixed tactile stimuli representing real physical objects.
- *Variance*. Free air haptics provides varying, rich tactile sensations, i.e. simulating physical textures in 3D space.
- *Continuity*. Free air tactile sensations should be able to move continuously in 3D space around the user.
- *Transience*. Free air haptics can actuate physical objects in the environment around the user.

While other principles may also exist, these five principles guide the design of interfaces and applications that could leverage the unique capabilities of free air tactile technology. In the rest of this section, we present five exemplary applications of AIREAL that provide entirely new interaction experiences containing one or more of the design principles above. Informal user evaluations were conducted for each application where 27 users were asked to try each application for 5 to 10 minutes and provide verbal feedback. The results are reported below for each application.

5.1 Haptic Projection with AIREAL

If virtual objects can emit haptic sensations on the human body, they can create richer and more enjoyable user experiences and significantly increase the realism of virtual objects. There is a long history of bringing virtual objects into the real world, including augmented reality [Azuma et al. 2001; Poupyrev et al. 2002], using handheld projectors to display dynamic virtual images both on the physical world and on the human body [Harrison et al. 2010, Willis et al. 2011], and designing augmented computing environments that allow seamless manipulation of virtual objects in physical space [Raskar et al. 1998; Rekimoto et al. 1999; Wilson et al. 2012]. However, enhancing virtual images with tactile feedback has been a difficult challenge in designing computer-augmented environments.

AIREAL offers an ad-hoc and lightweight approach that makes it easy for users to see and feel projected images. With AIREAL, the human body acts as an interactive display surface enriched by free air tactile sensations. We calibrated an AIREAL device with an overhead projector and depth camera system to enhance projected images with free air haptic sensations (Figure 11). Virtual images were dynamically projected on the user's hand that was simultaneously tracked using a depth camera. A classic distance transform metric was used to extract the local maximums in the depth image of the user's hand, providing its location in 3D space [Sodhi et al. 2012].

Figure 11 demonstrates an example interaction where virtual images projected on a user's body are *collocated* with free air haptics. A projected 3D butterfly is displayed hovering on the user's hand. AIREAL tracks the motion of the user's hand and arm and adjusts the direction of vortices to preserve the collocation of virtual and haptic stimuli. A 100 mVpp, 6 Hz tactile stimulus is used to match vortices to the movement of the butterfly's wings.

The vortex latency measurements were used to calculate when to send out a vortex towards the user's body. The system used the distance between the AIREAL device and the user's hand as well as the speed and position of the virtual butterfly to compute the ideal emission time of a vortex. Although this helped to alleviate some of the vortex latency, the latency inherent in all projector-camera systems still contributed to the vortices falling slightly behind the virtual butterfly during rapid movement of the user's body. Nevertheless, our early user feedback indicated that the interaction provided compelling physical sensations of the virtual butterfly. As one user described it, "it feels natural, it feels like a butterfly should feel."

5.2 Augmenting Gestures with AIREAL

Free air gestural input can be a powerful complement to traditional mouse, keyboard and touch screen interfaces and has recently become very popular in gaming, home and location-based entertainment [Jones et al. 2012]. Providing efficient tactile feedback to free air gestures in 3D space can significantly improve performance and enjoyment of such interactions.

AIREAL can provide tactile feedback to 3D gestures without requiring any instrumentation of the user. We used a scaled down

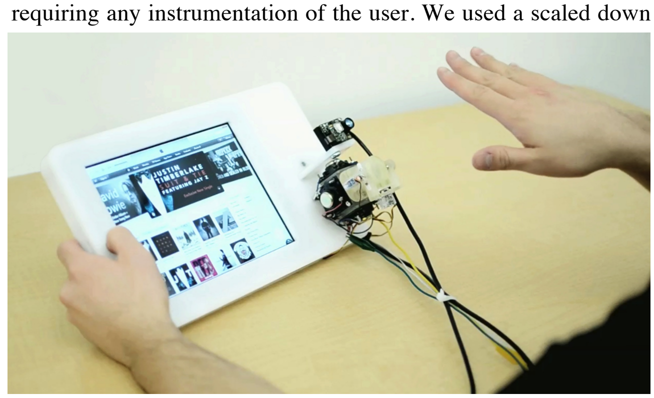

Figure 12: *Persistent haptic spaces provide gestural feedback as a user performs swipe gestures to scroll images.*

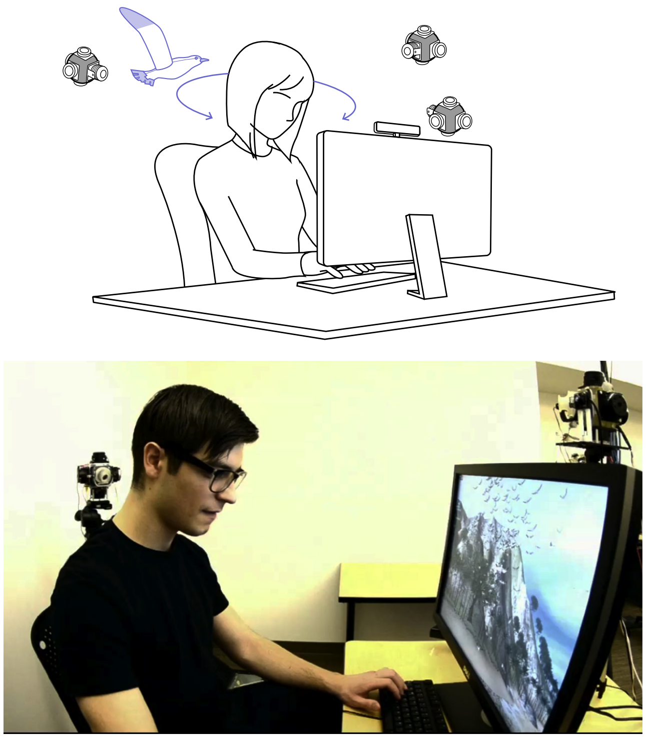

Figure 13: *Continuous free air tactile sensations around the user. The user who is playing a game can feel virtual seagulls fly continuously around him.*

version of the AIREAL device instrumented with a PMD Camboard Nano to track a user's hand motion in relation to an iPad tablet computer encased in an acrylic case. The AIREAL device was attached to the front and right side of the device (Figure 12).

A series of invisible 3D virtual buttons were placed around the tablet to enable interaction with an iTunes on-line store interface.

Virtual 3D buttons were accompanied with tactile feedback and together they created *persistent* interactive haptic spaces around the mobile device. For example, left and right swipe buttons were virtually positioned on the sides of the tablet device and a selection button was virtually positioned in front of the tablet device. When the user's hand intersects the virtual 3D button, a vortex is emitted to signal that the user has selected a virtual button. To implement and validate these interactions, we used GlovePIE [Kenner 2010] to map 3D gestures to mouse events on the tablet.

This application of AIREAL demonstrates many interesting possibilities in designing effective 3D gestural interfaces for graphical applications. Being able to interact with virtual elements and receive physical feedback in much the same way as we interact with real physical objects, e.g., real buttons that provide physical feedback, could provide more natural spatial interfaces in future applications. One user described his experiences as "… a burst of air is hitting your hand, like something is hitting me."

5.3 Making Continuous Free Air Experiences

Creating immersive experiences that surround the user is one of the most important goals in designing home and location-based entertainment environments. Audio has often been used in combination with on-screen visuals to create immersive user experiences. Similarly, free air haptics can be used to surround a user with *continuous haptic* experiences. In combination with AIREAL, conventional displays, such as a computer monitor, TV or movie screen, can bring virtual elements such as virtual characters from the screen into the real world. By combing multiple AIREAL devices that coordinate with each other, the users can physically feel virtual characters moving around them (Figure 13).

To simulate this experience, we placed three AIREAL devices around the user who was facing a desktop monitor (Figure 13). All AIREAL devices were calibrated to a single depth camera's coordinate system using manual calibration techniques described in Section 3. The user's head was also tracked using a standard Haar classification technique.

To demonstrate continuous haptic motions, we created an exemplary game where virtual seagulls were attempting to steal food from the user's virtual character. To create an experience of a seagull flying around the user, the virtual position of a seagull was translated into the physical environment, and the AIREAL device closest to the location of the seagull was activated. The seagull's physical position is projected on the user's head, providing a location of where to direct a vortex.

As the seagull circles around the user's virtual character, vortices are emitted continuously to simulate the seagulls moving around the user in the real world. This simple yet powerful interaction provides the user with an intuitive and natural way to physically feel the actions taking place in the virtual world, e.g., there is a seagull flying nearby. As one user commented, "it feels like the wake of the bird is hitting you as it flies by."

5.4 Feeling Varying Textures in the Air

Real world objects often have a high degree of surface *variance* that produces distinct and prominent tactile texture sensations. For example, stones can feel rough, sand can feel gritty and water feels smooth. Simulating tactile textures using a variety of haptic devices have been an active and important area of research [Poupyrev et al. 2003]. AIREAL can be used to create free air tactile sensations of 3D objects with different textures. For example, users can move their hands over a virtual 3D object with a smooth surface, followed by a virtual 3D object with a rough surface and feel completely distinct free air sensations (Figure 14).

To create free air tactile textures, we designed a set of free air tactile stimuli with distinct tactile sensations varying in amplitude and pulse frequency. These tactile stimuli were mapped into the initial set of visual textures, including sand, stones, grass, water and metal ridges. These signals were designed using JND values collected from our perceptual experiments as well as informal pilot studies where users were asked to feel a series of distinct free air sensations and characterize their tactile perception. We used adjectives such as "bursty" and "slippery" provided by our users to define a texture space of free air tactile sensations that we mapped into a 3D game.

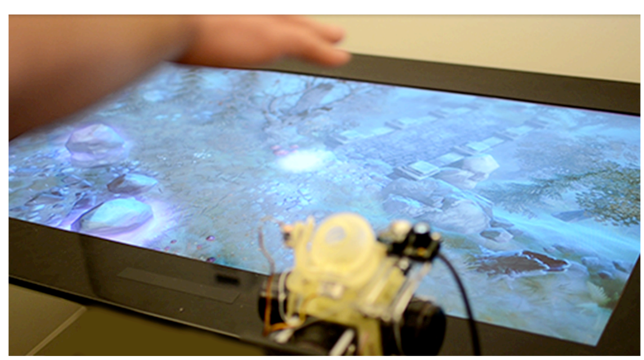

Figure 14: *The user can feel textures of the virtual terrain.*

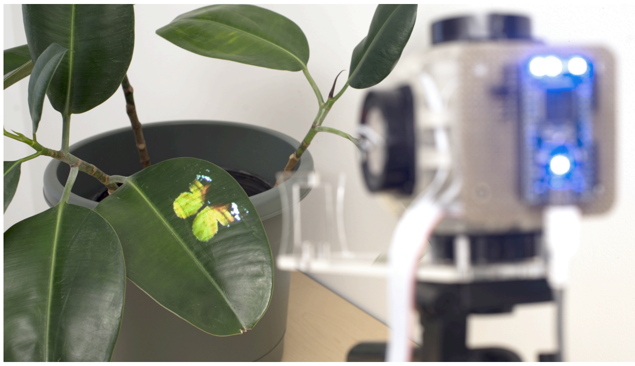

Figure 15: *Free air haptics can be expanded into the real world with projected virtual imagery on physical objects.*

Figure 14 shows a virtual game environment we created containing multiple distinct terrains. A Microsoft PixelSense tabletop computer was used with an AIREAL device placed in front of it and oriented upward towards the user's hand. Four signals varying in amplitude (0.1 mVpp to 3.3 Vpp) and pulse frequency (1 Hz – 30 Hz) were mapped to textures of grass, a stone bridge, wooden rooftop and water. A lookup table was created to map signals to virtual 3D objects associated with a free air sensation.

To play the game, a user gestured with their dominant hand to control the location of a virtual character moving around the environment. A "virtual joystick" metaphor was implemented for character navigation: moving the hand away from the initial start position defined the direction that the character followed. To deactivate, the user simply moved their hand away from the depth sensor. We used the same hand tracking procedure described in previous applications to track the user's hand. This allowed users to freely gesture and move their character through the environment, passing over terrains mapped to free air textures identified previously. For example, going from the grass to a bridge would switch from smooth, low amplitude vortices to a more pronounced "bumpy" one.

5.5 Moving Further Into the Real World

The examples presented above demonstrate that the AIREAL approach can provide rich free air tactile sensations that open new and exciting applications in interactive computer graphics. We believe, however, that the applications of free air haptics are much broader and new and exciting opportunities for interaction exist with free air tactile feedback devices.

In particular, we are interested in applications bringing AIREAL virtual content into the real world that are not just directed towards the user, but instead to other physical objects in the user's environment. Figure 15 shows one such example where a virtual butterfly rests on a plant. As the butterfly moves its wings, the plant's leaf moves in response. If a user decides to touch the butterfly, the user can initiate the experience by simply stretching a hand and touching the butterfly projection. We refer to such interfaces as *transient* haptic displays in the physical environment.

In other speculative examples, real world explosions can cause shocks and vibrations that move surrounding objects. We can imagine a future use of AIREAL where the free air sensations are not just directed to the user, but to peripheral objects in the environment – where an explosion in a movie causes a piece of paper to fly off the desk, or plants in the background to shake their leaves. With AIREAL, objects in our physical environments can truly come to life.

6 Limitations of AIREAL

The AIREAL technology enables the design of new and exciting interactions and free air haptic experiences. However, there are several limitations of our current device.

First, the AIREAL device produces an audible sound. This is mainly caused by the speakers, which produce a low frequency physical "knock" when driven by a high amplitude, low frequency signal. We are currently experimenting with different actuating techniques that are not subject to the mechanical limitations of the speaker design. We are also experimenting with various 3D printed materials designed to dampen or completely silence the sound before it leaves the enclosure.

Second, although AIREAL does not require active instrumentation of the user, it still requires passive instrumentation of the user's environment. For instance, many of the examples we presented in the paper utilize tripods to mount the AIREAL devices. While we feel that it may be cumbersome, it does not outweigh the advantages of free air haptics. As the technology matures, we envision that consumer electronic devices, as well as everyday environments, would have free air haptics devices pre-installed and therefore become completely invisible to the users.

7 Conclusions

This paper introduced AIREAL, a new haptic technology for free-space tactile sensations that are coupled to virtual objects. The range of applications presented in this paper demonstrated some of the exciting opportunities AIREAL enables as well as suggested future applications yet to be explored. Tactile augmentation of our physical environment remains an open and exciting area of research and development. As we continue exploring technologies that blur the boundary between the real and the virtual world, we hope that this work will encourage researchers and practitioners to create new and exciting applications of free air haptic displays. We have only begun to scratch the surface of what is possible.

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