HaptoMime: Mid-Air Haptic Interaction with a Floating Virtual Screen

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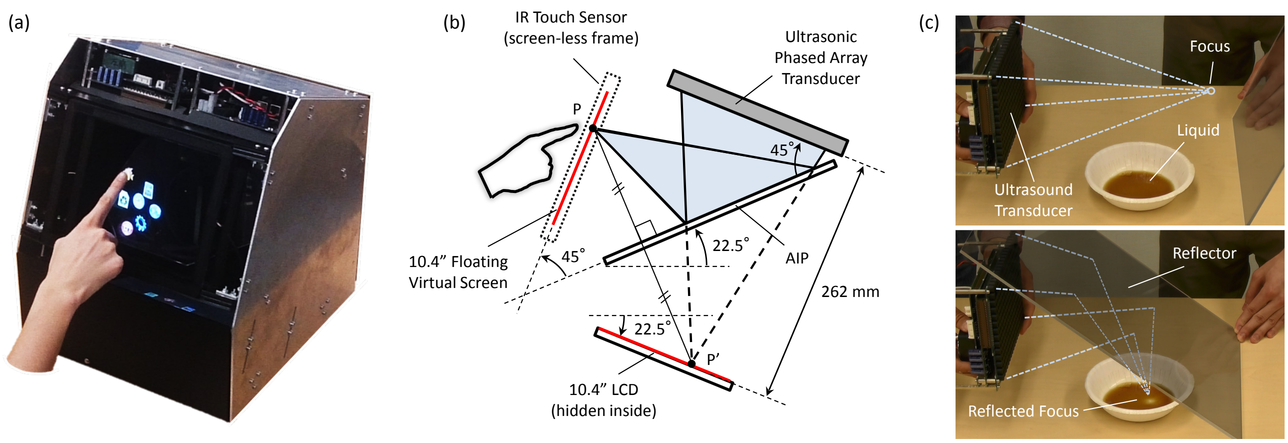

Figure 1: HaptoMime enables interaction with floating images in the presence of ultrasonic tactile feedback. (a) System appearance. (b) System configuration. (c) Redirection of an acoustic radiation pressure by ultrasonic reflection.

ABSTRACT
We present HaptoMime, a mid-air interaction system that allows users to touch a floating virtual screen with hands-free tactile feedback. Floating images formed by tailored light beams are inherently lacking in tactile feedback. Here we propose a method to superpose hands-free tactile feedback on such a floating image using ultrasound. By tracking a fingertip with an electronically steerable ultrasonic beam, the fingertip encounters a mechanical force consistent with the floating image. We demonstrate and characterize the proposed transmission scheme and discuss promising applications with an emphasis that it helps us 'pantomime' in mid-air.

Author Keywords
Mid-air interaction; tactile feedback; aerial imaging.

UIST '14, October 05 - 08 2014, Honolulu, HI, USA
Copyright 2014 ACM 978-1-4503-3069-5/14/10…$15.00.
http://dx.doi.org/10.1145/2642918.2647407

ACM Classification Keywords
H.5.2. User Interfaces, Haptic I/O

INTRODUCTION
The dream of interacting with mid-air projected 3D images has fascinated people and driven a variety of relevant researches thus far [18]. Although its practical implementation is still challenging, a breakthrough of 2D mid-air projection has been attained recently by the invention of a transmissive mirror [17,13,22]. It allows us to observe a screen floating in front of the mirror which is actually placed behind the mirror. Since all the visual effects such as binocular parallax and motion parallax are inherited to the floating screen, we cannot distinguish it from a real screen until we touch it. Combined with a sensor that detects our finger motion, it can be used as a virtual touch screen [14].

The interaction in mid-air, however, is inherently lacking in tactile feedback [6,4,3,8]. Although other modalities such as audio-visual effects can be employed to indicate touch events [6,1,12], they do not work directly on a fingertip. The indirect indication makes it hard to perceive just the depth of the fingertip. Consequently, users tend to insert the fingertip deeply into the floating image [6]. It not only makes the finger stroke long, but also involves a contradictory optical occlusion in which the floating image supposed to appear in front of the finger is occluded by the finger.

In this paper, we propose a method to superpose hands-free tactile feedback onto a floating virtual screen using a system shown in Figure 1 (a). The presence of tactile feedback assists natural and precise touch interaction with the virtual screen. As a means of the tactile feedback, we employ acoustic radiation pressure generated by intense ultrasound [11,9,10,16,7,5,21]. An ultrasonic phased array transducer delivers focused ultrasound onto the fingertip so that it encounters a mechanical force at a position and timing consistent with the floating image. In order to ensure visual and mechanical consistency, the acoustic radiation pressure ought to be superposed perpendicularly to the floating image. However, the overlap of the propagation axes of the optical rays and ultrasonic beams involves a geometric collision between the optical and ultrasonic apparatuses. Here we solve this problem by delivering the ultrasound via specular reflection at the flat and stiff surface of the transmissive mirror as illustrated in Figure 1 (b) and (c). We experimentally characterize the ultrasonic beam steering performance of the system. We then describe a guideline for tactile rendering and aerial graphic design, and discuss promising applications with an emphasis that it helps us 'pantomime' in mid-air.

RELATED WORK

Floating Imaging

The invention of a transmissive mirror has paved the way for high quality floating imaging using a compact and low-cost setup as compared to conventional techniques such as using a concave mirror [18]. The transmissive mirrors have been implemented with a tiny corner-reflector array [17,13] or a combination of a half-mirror and a retro-reflector [22]. In either case, the essential trick is that an angle of emergence of light beams becomes equal to that of incidence [17]. Consequently, a depth-inverted 3D image of an object placed behind the mirror appears on the other side of the mirror, i.e. mid-air. When the object is 2D, the identical image appears in mid-air. In this paper, we employ a commercial product based on the corner-reflector array, an Aerial Imaging Plate (AIP) developed by ASUKANET co. ltd [2], for our system.

Interaction with Floating Images

Several pioneering works have explored direct interaction with floating images using a transmissive mirror [14], a Fresnel lens [6], and a concave mirror [4]. In addition, interaction with pseudo-floating images has also been implemented with a see-through screen [8] or a stereo projector [3]. Despite the feasibility of rich Augmented Reality experiences, those methods are lacking in tactile feedback. The interaction inaccuracy involved by the lack of tactile feedback appears in such a way that the fingertip is inserted deeply beyond the floating image [6]. An attempt to use a mechanical device to present tactile feedback has been proposed recently [15]. Still, hands-free implementation is preferable.

Hands-Free Tactile Feedback

The demand for hands-free tactile feedback has driven researches on air jet flow [20], vortex ring [19], and acoustic radiation pressure [11]. To manage high-speed and high-resolution tactile feedback at a relatively long distance, the acoustic radiation pressure is attractive. A sharp mechanical force localized within a 1cm spot can be generated by focused intense ultrasound of 40 kHz at a distance of 25 cm [11]. The focal spot is steerable in mid-air using a phased array transducer. By optimizing the distribution of an amplitude and phase of the array, sophisticated beam shaping such as side-lobe suppression and multiple-foci formation can be attained [5]. Since ultrasound travels at a speed of 340 m/s and can be modulated with a 1 kHz bandwidth in a normal indoor environment [10], tactile feedback with a short delay and high frame-rate is feasible.

To combine visual and tactile feedbacks, the use of an acoustically transparent optical screen has been explored [23,5]. However, the visual and tactile feedbacks have been spatially separated in those implementations. An attempt to superpose tactile feedback directly on a floating image has been presented in [9]. There, a 2D floating image was generated by a concave mirror-based system. Users were requested to put a tracking marker on a finger, and turn their palm upward and place it at the same depth as the floating image. Focused ultrasound then impinged upon the palm along the image plane. Since the mechanical force was oriented in parallel with the image plane, visual and mechanical consistency was ensured only for such a situation as touching falling droplets.

IMPLEMENTATION

System Configuration

The proposed system consists of four key components, the AIP, a liquid crystal display (LCD), an infrared (IR) touch sensor, and an ultrasonic phased array transducer. The cross-sectional geometry is illustrated in Figure 1 (b). The floating virtual screen is generated by reflecting the LCD through the AIP. The virtual screen is overlaid with the IR touch sensor to detect finger insertion. According to the touch data, the ultrasonic phased array transducer delivers focused ultrasound onto the fingertip. For the ultrasound transmission, we employ an indirect path reflected at the surface of the AIP so that the ultrasound impinges on the virtual screen perpendicularly. The brightness of the floating image becomes highest when a user sees the AIP at an angle of 45°. Here we place the AIP at 22.5° from the horizontal plane so that a user facing the system naturally sees the AIP at about 45°. The floating virtual screen consequently appears at 67.5°. When seen at a large azimuthal angle, single-reflection appears as a ghost image [13]. To avoid this, users should face the system within the angular width of about 30°.

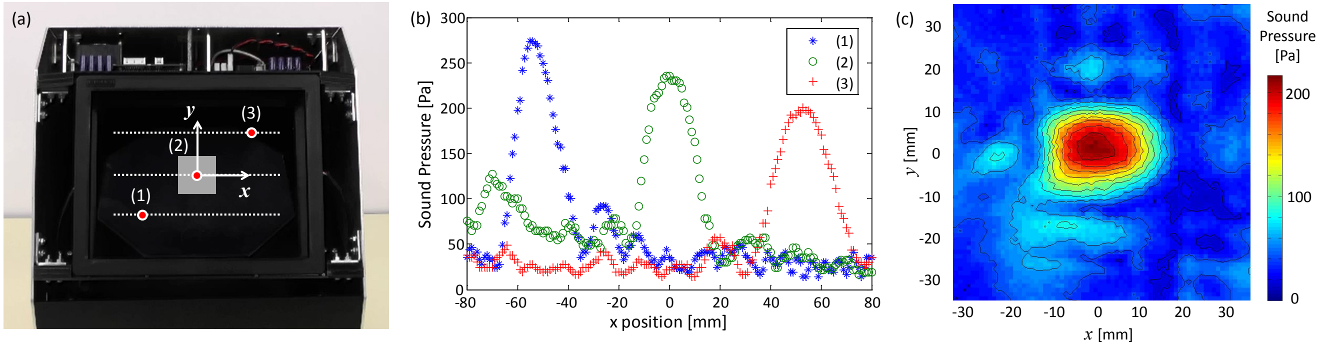

Figure 2: Characterization of ultrasound focus steering on the virtual screen. (a) The focus position is switched between: (1) (-53 mm, -40 mm), (2) (0 mm, 0 mm), and (3) (53 mm, 40 mm) for characterization. (b) Comparison of the beam shapes between the three positions. (c) Sound pressure distribution around the focus at (2). The scanned area is indicated by the white rectangle in (a).

The entire system is controlled by a Windows 7 computer (Endeavor NB50E, Epson) running on AMD E-450 APU (1.65 GHz). It drives the LCD and the ultrasonic transducer based on the data acquired from the IR touch sensor. The LCD (DLH1068, Litemax) is 10.4 inch with the brightness of 1600 cd/m^2 and the resolution of 800×600 (SVGA). The IR touch sensor (RE1300G010S, IRTOUCH Systems) detects finger insertion with spatial and temporal resolutions of 1.5 mm and 15 ms, respectively. The ultrasonic phased array transducer consists of 498 pieces of transducers (T4010A, Nippon Ceramic). It is controlled by a custom-made driver board incorporating FPGAs (EP3C16Q240, Altera). Each transducer has a diameter of 10 mm and is aligned in a square grid of 280 mm by 180 mm. The transducer is driven at the resonant frequency of 40 kHz with a peak-to-peak voltage of 24 V. The driver board controls the phase and amplitude of each transducer independently. Furthermore, it modulates the ultrasound waveform. While the former contributes to beam steering, the latter contributes to tactile rendering as explained in the following sections. The ultrasonic focus can be refreshed in every 4 ms (0.25 kHz). There, 3 ms accounts for a serial communication between the main computer and the driver board while the other 1 ms for the wave propagation from the transducer to the fingertip (0.3 m).

Steering of Reflected Ultrasound

When focused ultrasound is specularly reflected, the focus is accordingly transferred to the mirror symmetric position as illustrated in Figure 1 (c). Hence, as in Figure 1 (b), the transducer is able to form a focus at a point P on the floating image by simply aiming at the symmetric point P' on the LCD located straight ahead of the transducer. To confirm this principle, we measured the sound pressure distribution around a focus formed at three different positions defined in Figure 2 (a). The signal was recorded with a standard microphone (Brüel&Kjær Type 4138) mounted on an automated stage and connected to a pre-amplifier (Brüel&Kjær Type 2670). Beam profiles scanned in the *x* direction at each *y* position are plotted in Figure 2 (b). A clear focus is observed at the predefined position in all cases. The beam widths (3dB) are (1) 17 mm, (2) 21 mm, and (3) 26 mm, respectively. They are narrow enough to selectively hit a fingertip. We consider that the slight difference of the beam shapes between (1) and (3) is attributed to different multi-path interferences involved by the asymmetric structure inside the system. Although the structure is symmetric with respect to the *x*-axis, it is asymmetric in *y* because the AIP is inclined. Figure 2 (c) shows a 2D scan of the sound pressure distribution around the focus at (2). A clear focal spot is observed in the middle. We thus confirm the ultrasound focus steering via the reflective indirect path.

Ultrasonic Tactile Rendering

The feeling of the tactile feedback can be designed by modulating the acoustic radiation pressure. According to a literature [10], the amount of a mechanical force generated by focused ultrasound is 1.6 gram force using 324 pieces of transducers of the same type as our system. Although such a weak force is hard to perceive on a skin as a static force, a modulation of the ultrasonic waveform can clearly stimulate human tactile receptors [5]. There exist several types of tactile receptors with different spatio-temporal responses on a skin. When using ultrasound of 40 kHz, the size of a focal spot is mostly not smaller than 8.5 mm (one wavelength). As it is close to the fingertip size, the acoustic radiation pressure impinges on the fingertip uniformly. Among the tactile receptors, Merkel cells and Meissner corpuscles, which are located near the skin surface, are not reactive against such a uniform force. On the other hand, deeply located Pacinian corpuscles are reactive against such a uniform force. To stimulate the Pacinian corpuscles with the acoustic radiation pressure, the waveform should be modulated with frequencies higher than 100 Hz. To this end, we select three typical vibratory waveforms from an audio percussion sound library. Figure 3 shows three waveforms we found useful. The abscissa and ordinate show a time sequence and normalized radiation pressure, respectively. Subjective descriptions of the perceived tactile feeling of those waveforms are (a) stiff and light, (b) air flow burst, and (c) vibratory.

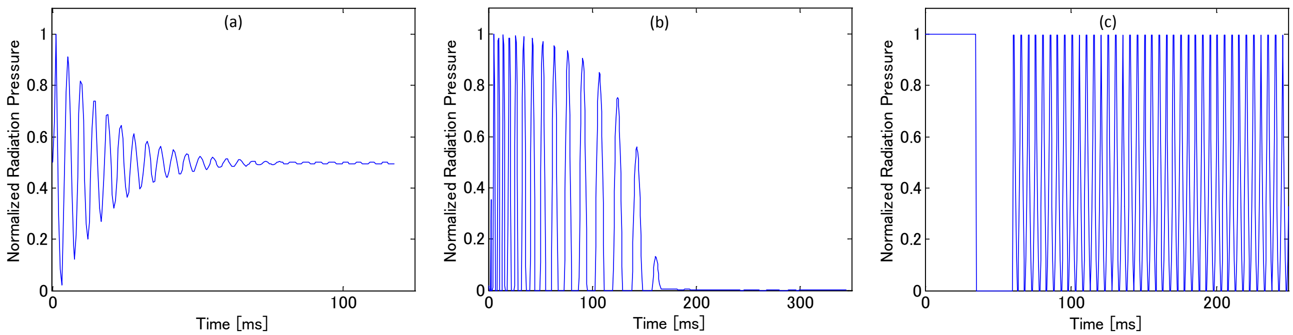

Figure 3: Waveforms of the ultrasonic tactile feedback. Audio percussion sounds with frequency components of several hundred Hz are employed to modulate the 40 kHz ultrasound.

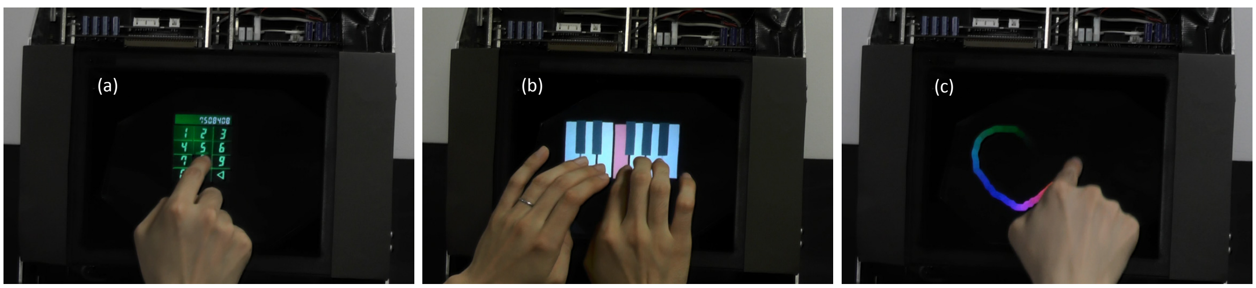

Figure 4: Applications of the system. (a) A floating virtual touch panel allows users to input keys in mid-air without leaving fingerprints. (b) Rhythmical input in mid-air is assisted by the tactile feedback. (c) Users can draw graphics in mid-air by constraining the finger trace onto the virtual 2D canvas.

Aerial Graphic Design

We set three guidelines for graphic design that enhances the interaction experience with the floating virtual screen. Firstly, the boundary of the AIP ought to be obscured under the darkness because otherwise it involves a visual discontinuity between the sights in and outside the AIP. Thus, the space above the AIP needs to be shaded to sink in black. Likewise, the background of the floating screen must be colored as dark as possible. For this reason, the LCD must hold high contrast.

Secondly, objects displayed on the floating screen must be located in the middle of the AIP, as far away from the boundary as possible. In this way, floating images always stay inside the AIP even when motion parallax is introduced. If only a fraction of the image reaches the boundary and partially occluded, users get confused by the discrepancy between the two eye images.

Thirdly, objects on the floating screen ought to disappear immediately when a finger is inserted deeper than the image plane. In such a situation, the objects supposed to appear in front of the finger are occluded by the finger. To avoid this visual contradiction, the objects must black out temporally during the finger insertion. Yet, it can be instantaneous as the tactile feedback suppresses deep finger insertion by physically inducing the bounce or extraction of the finger when the stroke reaches the image plane.

APPLICATION

Liberation from a physical screen will enable comfortable and secure use of computers. As an example, the implementation of a floating touch panel is presented in Figure 4 (a). It enables natural and precise key input in mid-air with the help of the tactile feedback. This technology, for instance, allows users to enjoy web-browsing even when their hands are wet or dirty during cooking. In a public situation, a risk of contagion by sharing a touch screen with multiple unidentified users can be reduced. Furthermore, there remains no fingerprint on a virtual screen, which is desirable for secure key input. The tactile feedback also assists rhythmical key input in mid-air by physically indicating the end of a touch stroke as represented in Figure 4 (b).

The tactile feedback provides us with clues to guide our motion in mid-air. For example, users can draw graphics by constraining the finger trace onto the virtual 2D canvas as shown in Figure 4 (c). In the real world, the perception of surface constraint is provided via tactile feedback in the form of normal and friction forces. Hence, the artificial reconstruction of such tactile cues helps us perform tasks in a 3D space as if we pantomime. It is also worth mentioning that intuitive handling will always take place via surfaces, irrespective of the form of an interface, whether it deals with 3D virtual objects or 2D virtual screen layers. Such surfaces can be equipped with tactile feedback with the proposed transmission scheme.

CONCLUSION

In this paper, we presented HaptoMime, a system that enables us to interact with a floating virtual screen in the presence of hands-free tactile feedback. We proposed an ultrasound transmission scheme via an indirect reflective path that superposes tactile sensation on a floating image consistently. We experimentally demonstrated the ultrasonic beam steering on the image plane. Using an IR touch sensor, we implemented a mid-air touch interface with tactile feedback. We then discussed promising applications of the system. Liberation from a physical screen will enable comfortable and secure use of computers. The tactile feedback allows users to perform natural and precise inputs in mid-air.

ACKNOWLEDGMENT

We thank Nobuaki Takanashi, NEC Corporation who advised the alignment of the ultrasound transducers using a visual display surface as a sound reflector in 2010. We also thank Yasutoshi Makino for the naming of HaptoMime for our system. This work was partly supported by JSPS KAKENHI Grant Number 25240032.

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