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Adding Tactile Reaction to Hologram

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***Abstract*—In this paper, a hologram with tactile reactions is presented. The developed system consists of three components; a holographic display, a hand tracker, and a tactile display. The tactile display, which is our original device, produces force on user's bare hand without any contact by using radiation pressure of airborne ultrasound. It adds the sense of touch to optical images floating in mid-air. In order to represent the feeling of impact, some improvements are added to the tactile display. As a result, the tactile display has an ability to produce up to 4.8 gf without air flow.**

I. Introduction

Mid-air displays which project floating images in free space have been seen in SF movies for several decades [1]. Recently, they are attracting a lot of attention as promising technologies in the field of digital signage and home TV. And then, novel technologies are developed to render images hovering in air without special glasses. FogScreen [2] and Heliodisplay [3] use a thin layer of fog as a projection screen. Holo [4] provides floating images from an LCD by utilizing a concave mirror. SeeReal Technologies is working on a real-time, computer-generated, and 3D holography [5] through the use of an eye-tracking technology for reduction of calculation amount. With them, you can see a virtual object as if it is really hovering in front of you. Furthermore, by applying the vision-based and marker-less hand tracking techniques demonstrated in Holovizio [6] or GrImage [7], you can handle the projected images with your hands as if it really exists. Then, tactile feedback will be the next demand. If tactile feedback is added, the usability of the interaction systems will be highly improved.

There are three types of conventional strategies for tactile feedback in free space. The first is attaching tactile devices on user's fingers and/or palms. Employed devices are, for example, vibrotactile stimulators (CyberTouch [8]), motor-driven belts (GhostGlove [9]), and pin-array units (SaLT [10]). In this strategy, the skin and the device are always in contact and that leads to undesired touch feelings. The second is controlling the position of tactile devices so that they contact with the skin only when tactile feedback is required. In the master-slave system shown in [11], the encounter-type force feedback is realized by the exoskeleton master hand. The detailed tactile feedback for each finger is provided by the electrotactile display attached on the finger part of the master hand. The drawback of this strategy is that it requires bulky robot arms. The last is providing tactile feedback from a distance without any direct contact. For example, air-jets are utilized in [12] to realize non-contact force feedback. Although air-jet is effective for rough "force" feedback, its spatial and temporal properties are quite limited and it cannot provide detailed "tactile" feedback.

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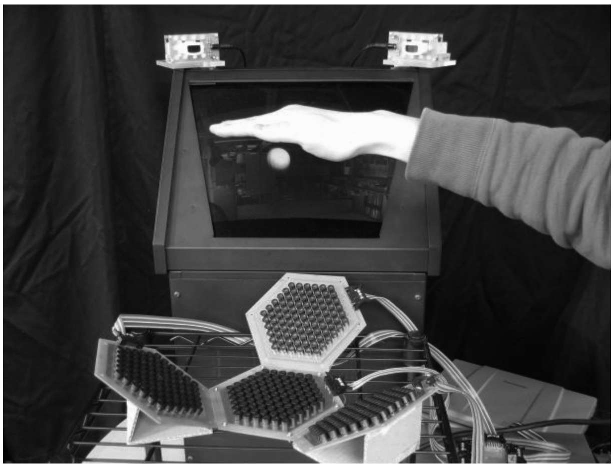


Fig. 1 Developed interaction system. An aerial imaging system, a Wiimote-based hand-tracking system, and a non-contact tactile display are combined. In this figure, the ultrasound is radiated from below. When the user hits the floating virtual ball, he feels an impact on his palm.

We have proposed a method for producing tactile sensation with airborne ultrasound [13]. The method renders desired pressure pattern in free space by using wave field synthesis with high spatial and temporal resolution. Users can feel the pressure with their bare hands. In [13], the prototype consisting of 91 ultrasound transducers was introduced and the feasibility of the proposed method was discussed. It can move a focal point along Z axis and the force generated at the focal point is 0.8 gf.

In this paper, an interaction system is shown which tracks user's hand and provides tactile feedback when collision occurs between the hand and a virtual object (Fig. 1). After that, we try to increase the output force in order to represent the feeling of impact which is one of the primitive touch feelings. As a result, the force is sextuplicated (i.e. 4.8 gf) for a short-time output. We also try to reduce the air flow generated around the focal point to make it clear. The methods and experiments are described.

II. System Overview

Here we explain the components of the developed interaction system. It consists of a holographic display, a hand tracker, and a mid-air tactile display. The tactile display is our original device.

A. Holographic Display

We use Holo [4], a holographic display which provides floating images from an LCD by utilizing a concave mirror. The projected images float at 30 cm away from the display surface. A user can get near to the image and try to touch it. Of course, his fingers pass through it with no tactile sensation.

B. Hand Tracker

While vision-based and marker-less hand tracking systems are demonstrated these days, we use Wiimote (Nintendo) which has an infrared (IR) camera for simplicity. A retroreflective marker is attached on the tip of user's middle finger. IR LEDs illuminate the marker and two Wiimotes sense the 3D position of the finger.

C. Tactile Display

Our method is based on a nonlinear phenomenon of ultrasound; acoustic radiation pressure [14], [15]. Assuming a plane wave, the acoustic radiation pressure P [Pa] is described as

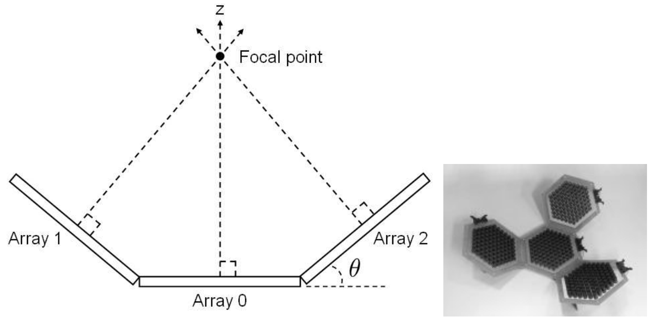
$$P = \alpha E = \alpha \frac{I}{c} = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where E [J/m^3] is the energy density of ultrasound, I [W/m^2] is the sound intensity, c [m/s] is the sound speed, p [Pa] is the RMS sound pressure of ultrasound, and ρ [kg/m^3] is the mass density of medium. α [-] is a constant ranging from 1 to 2 depending on the reflection coefficient R [-] at object surface; $\alpha \equiv 1 + R^2$. In case the object surface perfectly reflects the incident ultrasound, α = 2, while if it absorbs the entire incident ultrasound, α = 1. The acoustic radiation pressure acts in the same direction of the ultrasound propagation. That is, roughly saying, the ultrasound "pushes" the object. Equation (1) suggests that the spatial distribution of the pressure can be controlled by using wave field synthesis.

Here we roughly estimate the total force produced with an ultrasound transducer array. We use well commercially available 40 kHz ultrasound transducers which are usually used for measuring distance or detecting obstacles. The sound pressure p' [Pa] from each transducer is 20 Pa at the distance of 300 mm. When all the phases of the ultrasound waves from N transducers match and one focal point is generated, the total sound pressure $p = Np'$. In air at room temperature, ρ = 1.2 kg/m^3 and c = 340 m/s. Assume the diameter of the focal point is equal to the wave length λ [m] (e.g. λ = 8 mm for 40 kHz ultrasound). According to (1), the total output force within the focal point is 0.24 gf when N = 91 and α = 2.

Iwamoto et al. developed a 12-ch phased array which consists of 91 ultrasound transducers in [13]. It can generate a focal point and move it along Z axis by phase control. They exhibited that the prototype could produce 0.8 gf at the focal point whose diameter was 20 mm by actual measurement. The driving signal into the transducer was a 30 Vp-p (the DC component is cut by a HPF), 40 kHz, and rectangular wave. Although it was sufficient for producing vibratory sensation, it was too weak to reproduce the realistic touch feelings. The subjects who tried the prototype also reported that slight sensation of air flow made the focal point unclear.

As the first step of tactile rendering, we limit our objective to reproducing the feeling of impact because it is one of the primitive touch feelings and it has many practical applications (e.g. notifying occurrence of contact, the number of mouse click, and so on). For that purpose, we need to increase the output force and reduce air flow. The following sections describe the methods and experiments.



(a) (b)

Fig. 2 Arrangement of four ultrasound transducer arrays.

III. Enhancement of Output Force

As explained in Section II. C., the radiation pressure is proportional to the square value of the total sound pressure $p = Np'$. There are two approaches to increase p; increasing N (the number of transducers) and increasing p' (the sound pressure from each transducer). We try both approaches.

A. Increasing Number of Transducers

Firstly, N is increased. We have three backup ultrasound transducer arrays, so we can use 364 transducers when all the main and backup arrays are combined. They are arranged so that their Z axes cross at the focal point as shown in Fig. 2. This arrangement enables us to use the same driving circuit for all the arrays. The drawback is that the position of the focal point is fixed 3-dimensionally, but here we do not aim to move it.

The enhanced output force is theoretically estimated. When the incident wave has an angle θ [rad], the radiation pressure P_θ [Pa] generated by it is described as [14]

$$P_\theta = P_0 \cos^2 \theta \tag{2}$$

where P_0 is the radiation pressure when θ = 0 rad. Now θ = 0.605 rad ($\approx$ 34.7 deg) which is derived from the size of the ultrasound transducer array and the distance between the array

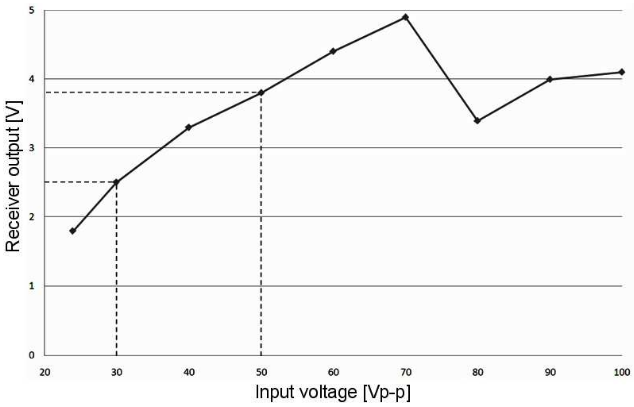


Fig. 3 Experimental results of relation between input voltage and ultrasound output. The transducer works without breakdown when the input voltage is under 50 Vp-p. Decay occurs between 50 and 70 Vp-p, and it breaks down when the input voltage is over 80 Vp-p.

and the focal point. Then the resultant radiation pressure P_{all} is written as

$$P_{\text{all}} = (1 + 3\cos^2\theta)\, P_0 \approx 3.0\, P_0 \,. \tag{3}$$

That means we can triple the radiation pressure by using 364 ultrasound transducers.

B. *Increasing Individual Sound Pressure*

Next, p' is increased. Conceptually, the higher the input voltage is, the higher the sound pressure becomes. Now we drive the transducer under its rated voltage (10 Vrms). The issue is that the transducer may break down when a higher voltage is input. Piezoelectric transducer has two types of breakdown; dielectric breakdown and thermal breakdown. If the thermal breakdown arises at a lower voltage than the dielectric breakdown, we might use a voltage higher than the rated voltage by limiting the duration of the input signal. That approach is also suitable for our objective, the feeling of impact.

A preliminary experiment was conducted to test our hypothesis mentioned above. Output ultrasound from the ultrasound transducer (T4010A1, Nippon Ceramic Co., Ltd.) was measured by the ultrasound receiver (R4016A1, Nippon Ceramic Co., Ltd.) at a fixed distance. The receiver output voltage was assumed to be proportional to the incident ultrasound. The input voltage was increased from 24 to 100 Vp-p in stages. The length of duration of the input signal was set to 5 ms (i.e. a single 5-ms-width pulse of the radiation pressure). The maximum value of the receiver output of each pulse was recorded.

Fig. 3 shows the experimental results. The output ultrasound increases with the input voltage, but it suddenly decreases at 80 Vp-p. That is breakdown of the transducer. Besides, even between 50 and 70 Vp-p, it was observed that the output ultrasound gradually decreases in an alternating succession of pulse output. Hence, we decide to use 50 Vp-p as a maximum sufferable input voltage. The output ultrasound

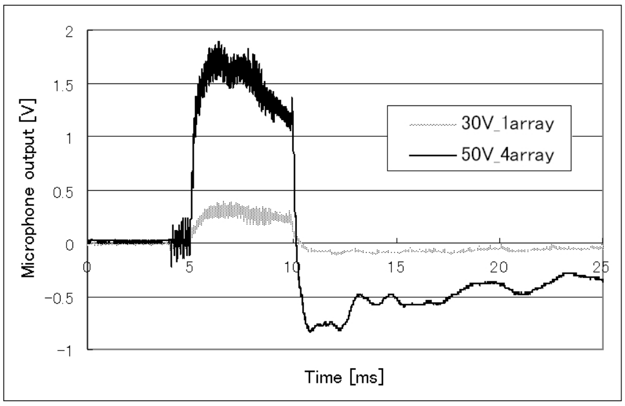


Fig. 4 Experimental results of enhancement of radiation pressure. The radiation pressure becomes nearly 6 times larger by using 50 Vp-p input voltage and four transducer arrays.

of 50 Vp-p is 1.52 times larger than that of 30 Vp-p. That means we can make the radiation pressure 2.3 times larger.

C. *Results*

The radiation pressure is expected to become 7 (≈ 3.0×2.3) times larger by using the approaches discussed above. Fig. 4 compares the radiation pressures recorded with an electret condenser microphone, which has little sensitivity to the 40 kHz ultrasound. It is confirmed that the radiation pressure is sextuplicated by using 50 Vp-p input voltage and four transducer arrays.

IV. Reduction of Air Flow

A. *Theory*

In this section, we aim to reduce the air flow generated by the pressure. Firstly, we consider the relation between them. Assuming an ideal gas, it is explained by the Euler equation of fluid dynamics;

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla p_g \tag{4}$$

where D/Dt is the Lagrangian Derivative operator, $\mathbf{u}$ [m/s] is the particle velocity, t [s] is time, ∇ is the del operator, and p_{g} [Pa] is the pressure of gas. Equation (4) means the particle velocity is proportional to the gradient of the temporal integration of the pressure. Note that the time-varying component of p_{g} is the sound pressure p, and the time average of p leads to the acoustic radiation pressure P [15]. Therefore the air flow felt on the skin increases in proportion to the duration of the radiation pressure applied on the skin.

Secondly, we take into account the characteristics of human tactile sensation. Literatures say that vibration and impact are detected by the RA and PC channels, which respond to the 1st- and 2nd-order derivations of the skin surface displacement [16]. When we assume an elastic half space and a plane wave, the relation between the skin surface displacement d [m] and the pressure on the surface p_{s} [Pa] is written as

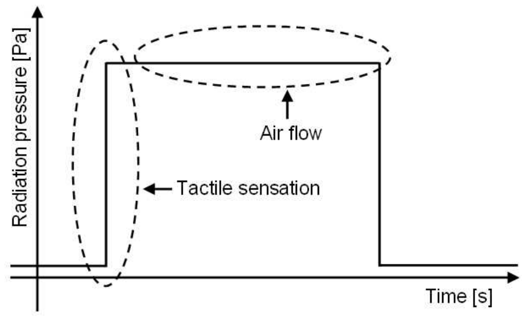


Fig. 5 Diagram describing role of each part of radiation pressure. Only the onset contributes tactile sensation, and the other part is used for the generation of air flow.

$$p_{\mathrm{s}} = Z\frac{\partial d}{\partial t} \tag{5}$$

where Z [Pa·s/m] is the specific acoustic impedance of the skin. Hence, the assumption leads to the conclusion that the RA and PC channels respond to the 0th- and 1st-order derivations of the pressure.

The above is summarized as follows; only the onset conditions of the radiation pressure (the amplitude and rate of rise) contribute tactile sensation, and the other parts are used only for the generation of the air flow (Fig. 5). Therefore, shortening the duration of the input signal is effective to reduce the air flow and to maintain the intensity of tactile sensation.

B. Experiments and Results

In order to confirm the hypothesis mentioned above, two experiments were conducted. 6 volunteers (age range between 23 and 29 years, all male and right-handed) took part in the experiments. They held their right hands at 250 mm above the radiation surface of the main transducer array where the focal point was also generated. During the entire trials, the participants wore headphones and heard a white noise, which prevented them from hearing the audible sound.

First, we checked that the tactile sensation was not weakened by shortening the duration. The single pulse of various duration lengths (ranging from 1.0 to 5.0 ms) was applied and the input voltage was gradually decreased. They were asked to answer whether they felt something on their palm. We assumed the threshold indicated the tactile sensitivity. Fig. 6 shows the results. The threshold force is calculated assuming the linearity between the input voltage and the ultrasound output. While the threshold seems flat between 1.5 and 5.0 ms, it is slightly high at 1.0 ms. One possible reason is the dynamic characteristics of the transducer.

Next, a discrimination test was conducted. The input voltage was fixed to 50 Vp-p. In each trial, firstly, the standard stimuli (five pulses of 1.0 or 5.0 ms width) were output at 0.5 s intervals. Next, after 1 s, the test stimuli (five pulses whose width was ranging from 1.0 to 5.0 ms) were output at 0.5 s intervals. The subjects were asked whether the feelings of the first and second pulses were different. We equated the answer "different to the 1.0-ms standard stimuli" with the answer "similar to the 5.0-ms standard stimuli," and vice versa. 20 trials par subject were done. Fig. 7 shows the average values of the number of the answer "similar to the 5.0-ms standard stimuli" connected to each other and the maximum and minimum values as both ends of vertical bars. It seems the discrimination threshold (50 % point) exists between 2.0 and 2.5 ms.

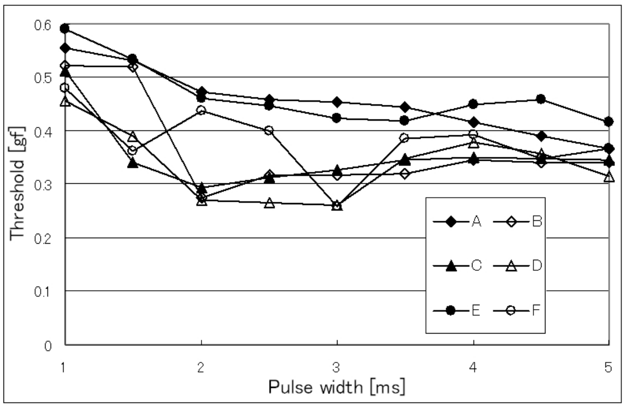


Fig. 6 Experimental results of relation between pulse width and threshold (subjects A to F). The threshold seems almost flat regardless of the pulse width.

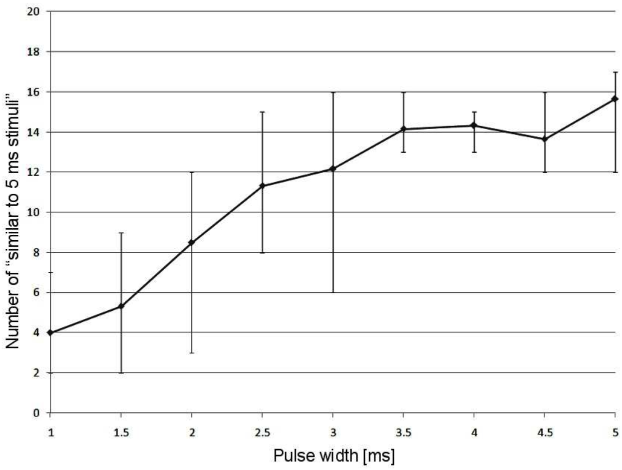


Fig. 7 Experimental results of discrimination test (20 trials). The average value and the max and min values among all the 6 subjects (A to F) are shown. The discrimination threshold exists between 2.0 and 2.5 ms.

The subjects reported that they did not feel the air flow when the 1.0-ms stimuli, differently from the 5.0-ms stimuli. Based on that reports and the experimental results, we conclude the air flow is effectively reduced by shortening the pulse width. From the viewpoint of the intensity of tactile sensation, the recommended width is 1.5 to 2.0 ms.

V. Conclusion

In this paper, an interaction system was presented. It consisted of a holographic display, a hand tracker, and a non-contact tactile display. After that, the output force of the tactile display was enhanced, and the air flow was reduced. As a result, a user can hit a virtual floating ball with his hand feeling tactile reaction as if he really hits it.

The developed tactile display could generate a focal point only at a 3-dimensionally fixed position. Moving the focal point 3-dimensionally by individual phase control is the next step. Rendering more rich tactile feelings by changing the spatiotemporal pattern of ultrasound according to the position and/or velocity of the user's hand is also one of the future works.

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