Tactile Interaction with 3D Images

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ABSTRACT

In this talk, our project on non-contact tactile display is introduced. Radiation pressure by convergent airborne ultrasound beams produces tactile sensations on bare skins, without installing bulky mechanical arms or forcing people to hold/wear special devices. Combining the tactile display with 3D images, we can realize literally touchable 3D images.

1. INTRODUCTION

Floating 3D images trigger our wants of touching them. Adding tactile feedback to 3D images is a next challenge of 3D display technology. Fusion of visual and tactile feedback is also supposed to be a promising technological field that improves the computer interfaces and the reality of computer games.

The current tactile feedback technologies are classified into three categories. The first one is adding computed reaction forces to the devices that originally exist for manipulation, such as steering wheels and operating levers. The purpose is to make the operation easier and to enhance the effectiveness of simulator training. The second category is general-purpose force displays using multi-degree-of-freedom link mechanisms mounted on the floors or tables as PHANTOM® Haptic Device by SensAble Technologies, Inc.. A user holds the arm top and moves it freely to feel the contact with objects by the reaction forces controlled by a computer. The third category is wearable force and cutaneous displays. In this category, various tactile feedbacks are realized by simple device structures using the properties of the human tactile perception including illusions [1]. The deformations of the handheld or glove-like devices display forces by touch [2][3]. Touch-panels and buttons vibrate depending on the finger positions as the tactile reactions [4]. Electrical stimulations give tactile feedbacks [5][6] with no mechanical movements. These devices are wearable in principle, but they can also be used being fixed on a table [7] or a vending machine.

As a common feature of all the available tactile devices, they need contact to some devices. The nature has limited their applications in various situations. For obtaining a large work space, the multi-link force displays should be bulky. The wearying devices should be worn on the users in advance, which cannot be supposed in every application scene. This paper introduces a method to stimulate our bare hands using airborne ultra sound. The system displays small forces to unconstrained hands without imposing devices held in the hands.

2. NON-CONTACT TACTILE DISPLAY

Before the work of [8] by Iwamoto et al. in our laboratory, the only non-contact tactile display is that of air jet. The theoretical limitation of air-jet method resides in the trade-off between the work space volume and the spatial resolution of tactile stimulation. For example, it is easy to make a jet with a radius of 50 cm reach 1m, while it is virtually impossible to make a jet with 5mm diameter reach 1m keeping its diameter constant. As a result, we have to put our hand close to the jet nozzles if we want to display detailed force distributions.

Another method using the air as the force transmission medium is use of airborne ultrasound. A force spot is produced on the skin with radiation pressure produced by a converging beam generated from a phased array. Although the acceptable maximal pressure is 60gf/cm^2 in principle, a work space larger than 1m is possible using a large aperture phased array. It has a temporal bandwidth of pressure change more than 1kHz, and fast spatial movement of the force distribution is possible.

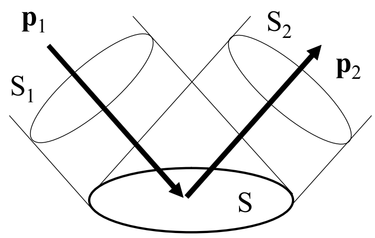


Fig. 1 Radiation pressure.

3. BASIC PRINCIPLE OF AIRBORNE ULTRASONIC TACTILE DISPLAY

In linear acoustics, the average of pressure is equal to 0. Significant radiation pressure [9] proportional to the sound power is observed for a large amplitude sound. Quantitatively, the radiation pressure is given as

$$\mathbf{f} = \frac{1}{c}(\mathbf{p}_1 - \mathbf{p}_2) \quad \text{[N]} \tag{1}$$

where $\mathbf{f}$ [N] is the force applied to area S as shown in Fig. 1, $\mathbf{p}_1$ [W] the incident power stream through the area S_1 onto S, $\mathbf{p}_2$ [W] the power stream reflected by S, and c the sound velocity. Since the applied force is proportional to the acoustic energy density on the surface, we can control the force and its spatial distribution on the skin by the intensity and the wave front geometry of the acoustic wave. We expect the applied force can produce a wide variety of tactile feeling since the ultrasound frequency, 40kHz in our prototype, is much larger than the bandwidth of the human tactile sensation. The delay of stimulation from the sound propagation $\tau = D/c$, D: propagation distance, is 3ms for D = 1m. The delay is not always negligible in dynamic feedback but it is acceptable in many applications. The limitations of this method are summarized as follows.

3.1 Maximal Force

As shown in Eq. (1), the total force by the radiation pressure is proportional to the total power of the incident acoustic wave. For example, 1gf = 0.01N requires 0.5 ・ 0.01N ・ 340m/s = 1.7W in the case of vertical incidence to the surface and complete reflection. Considering the efficiency of the ultrasound transducers, the power consumption is comparable to that of indoor lighting. Temporal average of the consumed power is much smaller since the force is produced only at the moment of touch. However, it will be a problem in installation to mobile devices.

The safety for the human body is the most important factor to be considered. The safety standard of the ultrasound is still under discussions. In a wide range of safety standards, the conservative standard is around 100mW/cm^2 in the literatures [10]. Most of the incident ultrasound is reflected on the skin surface and 0.1% of incident sound is absorbed in the body. Therefore the incident airborne ultrasound power corresponding to 100mW/cm^2 transmission into the skin is p = 100W/cm^2 whose radiation pressure is $2p/c$ = 0.6N/cm^2 (= 60gf/cm^2). This is the theoretical limit of displayable pressure by this method.

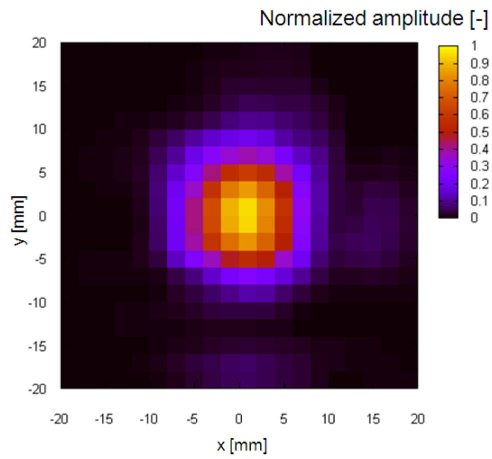
The damage to ears should be ensured by the other standard [11]. Until the safety is confirmed, users should take care not to place their ears near the transducer array or wear headphones to protect their ears as well as to hear stereophonic sound.

3.2 Work Space and Spatial Resolution

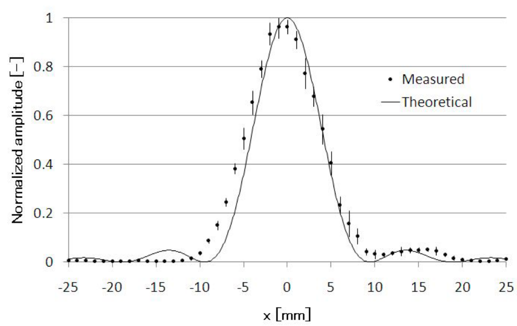
The factors to decide the work space and spatial resolution are ultrasound wavelength λ, ultrasound attenuation length L, and phased array aperture W. In case that the ultrasound attenuation is negligible, the minimal diameter of the displayed force spot is comparable to the wavelength λ. The highest resolution is attained when the distance between the phased array and the display point is comparable to W. Fig. 2 shows the measurement results of radiation pressure by Hoshi et al. [12]. 18 ・ 18 = 324 ultrasound transducers are arranged in 18cm ・ 18cm square area. The radiation pressure is measured in a plane 20cm distant from the phased array. The spot diameter looks comparable to the wavelength 8mm for 40kHz ultrasound. If we increase the distance D from the phased array, the spot radius increases inverse -proportional to

$$\sin\theta = \frac{W/2}{\sqrt{D^2 + (W/2)^2}} \qquad (2)$$

There is also a trade-off between the resolution and the work space in the ultrasound tactile display. In order to increase the resolution, we should use a higher frequency of ultrasound. On the other hand, heightening the frequency causes attenuation of the ultrasound, which shortens the displayable distance from the phased array. The reason why we use 40kHz ultrasound in our prototype is the attenuation length is relatively large (1dB/m). If we make the frequency n times higher, attenuation length L becomes smaller by $1/n^2$. Therefore if a half meter of work space is necessary, we cannot use a much higher frequency than 40kHz. The 1cm resolution is a rough practical standard of this method.



(a) Normalized radiation pressure measured on a plane 20 cm apart from the phased array.

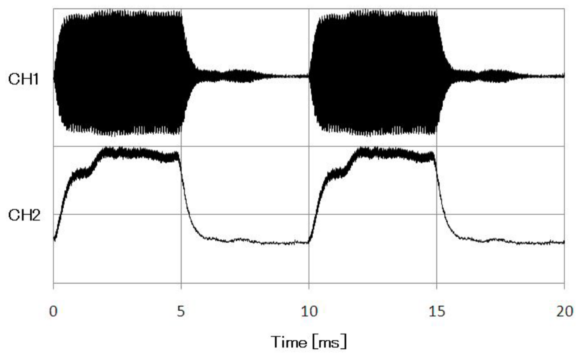


(b) Normalized radiation pressure measured at y = 0.

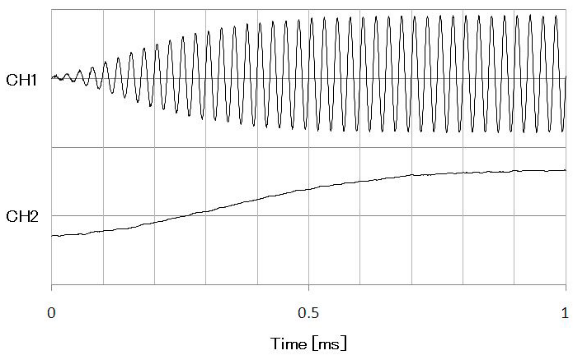
Fig. 2 Results of radiation pressure measurement by Hoshi et al. [12].

3.3 Temporal Response

Fig. 3 shows the temporal waveforms of the acoustic pressure and the radiation pressure. The Input voltage to the transducers was a series of 40kHz rectangular waves that had a constant amplitude during 0 – 5ms and 10 – 15ms. The acoustic and radiation pressure is measured at the center of the focal point. Fig. 3(b) shows that the radiation pressure rises within 1ms. Since the used ultrasound transducer was a resonant type, the acoustic amplitude rose with the time constant of 0.3ms as shown in Fig. 3(b) - CH1. The radiation pressure of CH2 looks proportional to the square of the sound pressure. The time constant shorter than 1ms is satisfactory for tactile display.



(a) Modulated waveforms measured at focal point. Ultrasound (CH1) and radiation pressure (CH2).



(b) Closeup of (a) from 0 to 1 ms.

Fig. 3 Temporal waveform of radiation pressure [12].

4. FUSION WITH 3D IMAGE

A wide range of applications are envisioned using 3D images with tactile reactions. The applications are divided into the following two categories.

(1) Reaction to active touch
Displaying tactile sensation when users touch VR objects with their own intentions.

(2) Display of passive sensation
Displaying a hit of a ball produced as a 3D image to the people watching a movie, for example. Or informing people of dangers by touches accompanied with 3D images.

The words “touching 3DTV” include at least two meanings: actively touching the object in 3DTV or experiencing tactile stimulation passively following the scenario prepared in advance. These two cases require different technologies and contents. As a problem of principle, it is difficult to allow an audience who are watching a same movie screen to touch the characters and objects in it actively since the scenario of the movie changes if one of the audience touches an object and changes the state of it. If multiple people touch an object simultaneously, unnecessary interaction occurs among the people. In order to allow the active touch, the number of users should be small and the object should have its physical model. On the other hand, in passive touch display, there is no theoretical difficulty in that a large number of people feel a common tactile stimulation watching the same movie.

As the next step, we should notice the required reality of touch sensation has two steps as follows at least.

(a) Realistic display of the event of touch
The system informs the users that a touch happens. It is sufficient if it can display some typical touch sensation with typical object such as a switch button.

(b) Realistic display of various tactile feelings
The system displays various realistic tactile feelings faithful to the actual touches. The ideal system can display any tactile feelings the human can feel.

Since the applied force by airborne ultrasound is 60gf/cm^2 at most, the displayed object is limited to a very soft object or easily movable light one. In addition, from the limit of spatial resolution, it is difficult to display a sharp edge with a small contact area with the skin. The direction of the force is also limited to vertical one to the skin. We cannot have an occluding object between the skin and the phased array. Therefore it is impossible to realize the ideal system explained in (b) above.

Under these constraints, the first target application would be a replacement of physical buttons or touch panels by a non-contact one. Users can even operate 3D image with tactile feedback floating around them. Since it is non-contact, it is free from dirt and deterioration by the contact. The infection by contact is also avoidable in a public space such as a hospital. Before these applications, we have to establish a method of position matching between the 3D image and the tactile stimulation. The 3D image position depends on the alignment of user’s eyes in many 3D display systems and the focal point of ultrasound changes according to the velocity shift by the temperature.

The next development is to enhance the variation of tactile feeling. The displayed force by ultrasound has high temporal resolution and reproducibility from its non-contact nature, which will enable displaying a class of realistic tactile feeling of soft materials.

It is useful to notice that even a limited class of tactile feeling can be utilized in various scenes, that is, even if the displayed feeling is not faithful to that of the real contact, it is still effective for heighten the reality of the 3D image. An analogy from sound display helps us understand this. In sound effects of movies, synthesized or preliminarily recorded sounds are added after filming. They are still effective even if the added sounds are only typical ones in a library which are not faithful to the actual sounds generated in the filmed scenes. Tactile sensation will be used similarly.

Fig. 4 shows a prototype of tactile display system synchronizing with 3D images and hand motions [12]. Ultrasound is radiated at the moment that a rain drop image touches the hand or while a small elephant is running on the hand. The ultrasound is modulated at 200 Hz for heightening the skin sensitivity to the weak pressure. Although the vibration pressure pattern must be quite different from that of real contact, we can experience touches to the 3D images. The reality of the force should be improved more but does not have to be perfect for practical uses.

Many applications related to the passive touch are also promising. In a risky situation, a touch can give us not only an alarm but also a momentary instruction of the direction for escaping from the risk. Motion skill coaching in sports, training, and various operations is also an attractive application of the non-contact tactile display.

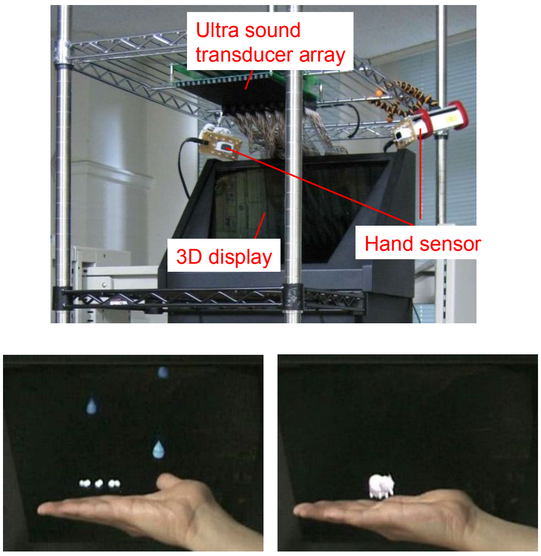


Fig. 4 Examples of 3D images with tactile reactions. The upper photo shows the system overview [12].

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