Noncontact Tactile Display Using Airborne Ultrasound

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ABSTRACT

A tactile display that provides tactile stimulation from a distance is studied. Hundreds of ultrasonic transducers cooperate to make a focal point of ultrasound based on phased-array focusing technique. It provides tactile feedback to floating images and natural user interfaces. It also tactually delivers characters, symbols, drawings, etc. to users.

1. INTRODUCTION

Our research group has worked on a tactile display that produces tactile stimulation from a distance. This tactile display utilizes airborne ultrasound to stimulate human skin and it is named as Airborne Ultrasound Tactile Display (AUTD). Focused ultrasound presses human skin in the direction of propagation. One of the most strengths of AUTD is that it is noncontact and hence users do not need to hold or wear stimulating devices on their hand. Furthermore, the spatial and the temporal resolutions are high and so various patterns of tactile feelings can be reproduced.

The research history of AUTD is as follows. It was firstly demonstrated by Iwamoto et al. (Shinoda Lab., The University of Tokyo) that focused ultrasound induces tactile sensation in midair [1] in 2008. The first prototype was an annular array of 91 ultrasonic transducers that generated a force of 8 mN on the central axis. The second prototype by Hoshi et al. was a square array of 324 transducers that generated a force of 16 mN at an arbitrary position [2]. Large-scale systems (a square array of 2,241 transducers [3] and a surrounding array of 3,984 transducers [4]) are later developed in Shinoda Lab. On the other hand, Hoshi independently developed a small and compact device with 285 transducers [5] (Fig. 1). This device was motivated by a desire to spread the use of AUTD across researchers who are not familiar with ultrasonics and/or electronics. Applications other than a noncontact tactile display also have been explored: For example, measurement of surface compliance distribution [6], measurement of static electricity distribution [7], a medical training system [8], creature-like motion by acoustic levitation [9], reflection control of soap film [10], real-world computer graphics [11], and graphics on carpet [12]. Besides, other researchers tried to utilize AUTD for their purposes. Ciglar proposes to use AUTD as a musical instrument with tactile feedback [13]. People in Bristol Interaction and Graphics combined AUTD with a mobile TV [14], demonstrated an interactive table on which tangible objects are freely moved [15], and developed an aerial interaction system consisting of AUTD and an acoustically transparent screen [16].

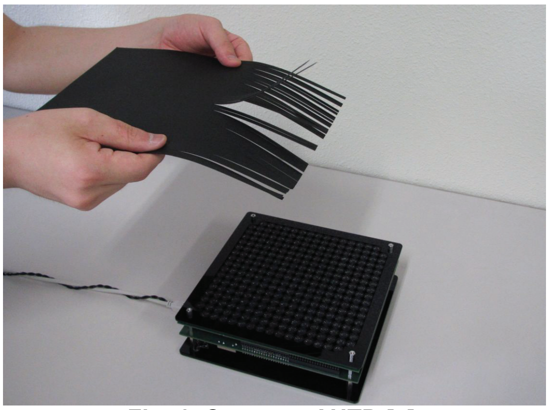

Fig. 1 Compact AUTD [5].
Paper strips are flipped up by focused ultrasound.

As a noncontact tactile display, AUTD has two major promising applications. One is to provide tactile feedback to floating image displays and natural user interfaces. It does not occlude line of sight because ultrasound waves are invisible and hence it is suitable for such aerial interaction technologies. Users are free from holding or wearing devices for tactile feedback. Moreover, tactile stimulation is projected onto users in order to capture their attention and/or tactually provide information. The other application is to generate a continuous trajectory of the localized tactile stimulation. The position of the stimulation can be set with high spatiotemporal resolution by precise control of the phase differences between the ultrasonic transducers. This feature is suitable for reproducing handwritten characters, symbols, drawings, etc. measured in real time, recorded in advance, or transmitted via internet.

This paper introduces the actual examples of the applications of AUTD. Firstly, the principles of AUTD are explained and the latest version of AUTD is described in Section 2. Secondly, the prototype systems developed for noncontact tactile feedback and handwriting transmission are shown in Section 3. Finally, Section 4 concludes this paper.

2. AIRBORNE ULTRASOUND TACTILE DISPLAY

2.1 Principles

AUTD is based on a nonlinear phenomenon of ultrasound: Acoustic radiation pressure. When the ultrasound beam is reflected vertically at an object surface, the surface is subjected to the constant vertical force in the direction of the incident beam. Assuming a plane wave, the acoustic radiation pressure P [Pa] is described as

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

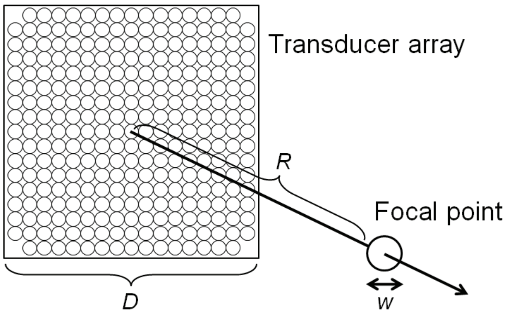

Fig. 2 Array size and diameter of focal point.

where c [m/s] is the sound speed in air, p [Pa] is the RMS sound pressure of ultrasound, and ρ [kg/m^3] is the density of air. α is a constant depending on the amplitude reflection coefficient at the object surface and it is nearly equal to 2 in the case of the human skin. Equation (1) indicates that the spatial distribution of the radiation pressure P can be controlled by synthesizing the spatial distribution of the ultrasound p.

The phased-array focusing technique is used to produce the radiation pressure perceivable by human skins. The focal point of ultrasound is generated by setting adequate phase delays of multiple transducers. The focal point can be generated at an arbitrary position by controlling the phase delays. It is theoretically derived that the spatial distribution of ultrasound generated from a square transducer array is nearly sinc-function shaped. The width of the main lobe (w [m]) parallel to the side of the square is written as

$$w = 2\lambda \frac{R}{D} \tag{2}$$

where λ [m] is the wavelength of ultrasound, R [m] is the focal length, and D [m] is the side length of the square array (Fig. 2). Equation (2) indicates that the spatial resolution and the array size are in the relationship of trade-off.

2.2 Prototype

The latest version of AUTD [5] (Fig. 1) consists of two circuit boards (Fig. 3). One is an array board of ultrasonic transducers and the other is a controller board that calculates and generates driving signals. Both boards are 19×19 cm^2. They are electrically connected to each other by straight pin connectors arranged along their periphery.

On the array board, 285 ultrasonic transducers (T4010A1, 10 mm in diameter, Nippon Ceramic Co. Ltd.) are arranged in a square area whose D is 17 cm. D is related to the resulting size of the focal point as shown in (2). The resonant frequency of the transducers is 40 kHz (i.e., λ = 8.5 mm). Then, w is 20 mm when R is set at 20 cm.

On the controller board, a USB module, an FPGA, and 72 four-channel push-pull drivers (L293DD, STMicroelectronics) are mounted. The operating frequency of the FPGA is 50 MHz. It communicates with a PC via USB interface, calculates the phase delays of all the transducers based on the distance between the target position and the transducers, and generates 40-kHz rectangular waves. These waves are amplified to be 24 Vp-p by the drivers and drive the transducers after their DC components are cut by high-pass filters.

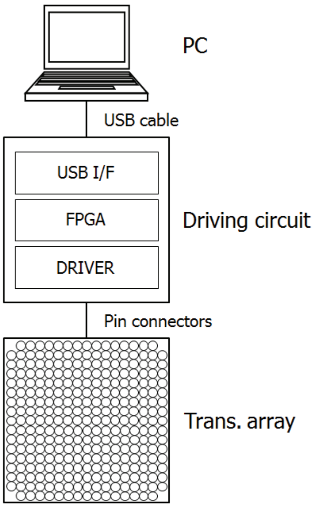

Fig. 3 Block diagram of compact AUTD.

Here how to control the phase and amplitude in this prototype is described. One cycle of 40-kHz rectangular wave is divided into 16 segments (i.e., 1.5625 μs). The phase is controlled by the position of a HIGH (= 24 V) period within these 16 segments. This digitization determines the spatial resolution to be 0.53 mm (= λ/16). The amplitude is controlled by the duration of the HIGH period, which is 624-step PWM.

Ultrasound can be controlled not only spatially but also temporally. AUTD can modulate the amplitude of ultrasound by rectangular wave to provide vibrotactile stimulation whose frequency is integer numbers ranging from 1 to 1000 Hz. The duty ratio of this modulation is fixed at 50 percent in this prototype.

The specifications of this prototype are as follows. The size is 19×19×5 cm^3. The weight is 0.6 kg. The maximum output force is 16 mN (measured). The position of the focal point, the amplitude of radiated ultrasound, and the modulation frequency can be updated at the rate of 1 kHz. The power consumption is around 100 W when ultrasound is radiated.

The spatial distribution of ultrasound around the focal point were measured with a microphone (2.5-mm aperture) attached on an XYZ stage. The 40-kHz component of the measured signal was extracted by a lock-in amplifier. The focal point was generated at the center of the transducer array and the length R was set at 200 mm. The two-dimensional (XY) distribution of sound pressure on the focal plane is shown in Fig. 4. The data was sampled at 1-mm intervals. The maximum value is 2585 Pa RMS (162 dB SPL). It is confirmed that the focal point is nearly sinc-function as the theory asserts, i.e., four side lobes accompany a single main lobe. The one-dimensional (Z) distribution of sound pressure along the acoustic axis is shown in Fig. 5. The data was sampled at 5-mm intervals. The peak is found at around 180 mm from the surface of the transducer array, which is shorter than the intended focal length (200 mm). The possible reasons are the individual differences of the transducers, the effect of the theoretical approximation, the error of the sound speed due to the temperature, etc.

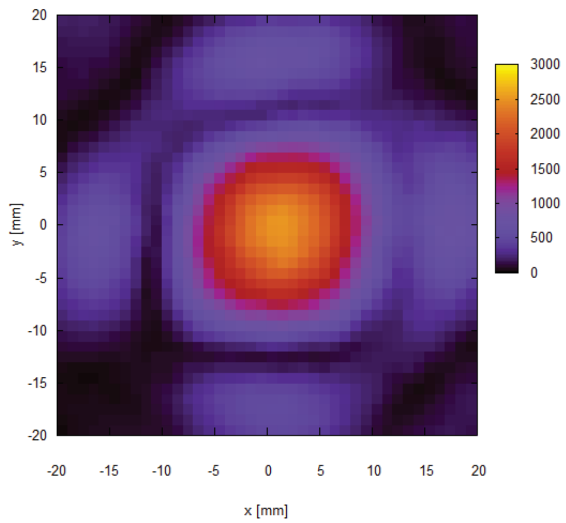

Fig. 4 Distribution of ultrasound [Pa] on focal plane.

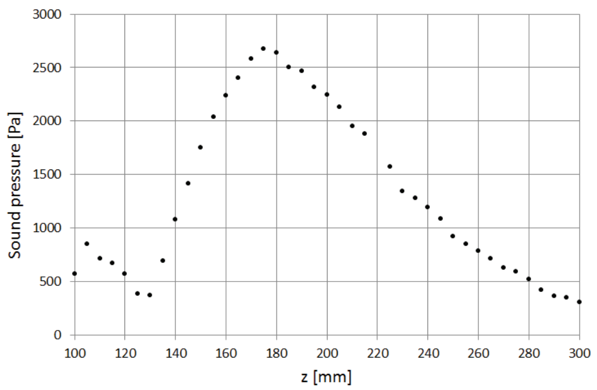

Fig. 5 Distribution of ultrasound along acoustic axis.

3. APPLICATIONS

3.1 Noncontact Tactile Feedback

A system that adds tactile feedback to floating images was developed [17] (Fig. 6). The images were projected by HoloVision (Holo17T, Provision Interactive Technologies, Inc.) which provided floating images from an LCD by utilizing a concave mirror. The projected images floated at 300 mm away from it. The position of a user's hand was estimated based on triangulation with two IR cameras (Wii Remote, Nintendo Co., Ltd.). A retroreflective marker was attached on a user's finger and illuminated by IR LEDs. According to interaction between a user's hand and floating images, noncontact tactile feedback was adequately provided by AUTD.

An aerial interface was also provided with noncontact tactile feedback [18] (Fig. 7). A depth camera (Kinect, Microsoft Corp.) was utilized for hand tracking in this demonstration. By using this newly-released sensing device in addition to AUTD, both of gesture input and tactile feedback became available with bare hands.

3.2 Handwriting Transmission

A handwriting transmission was demonstrated [19] (Fig. 9). The trajectory measured on a graphic tablet (intuos 4 PTK-640, Wacom Co., Ltd.) was reproduced on a user's hand.

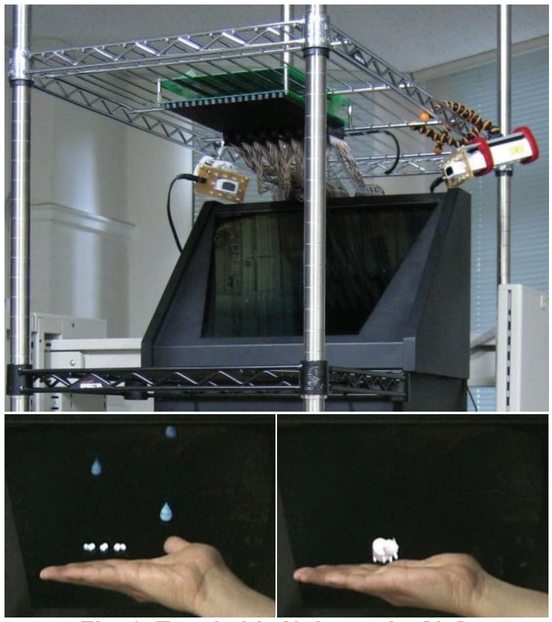

Fig. 6 Touchable Holography [17].

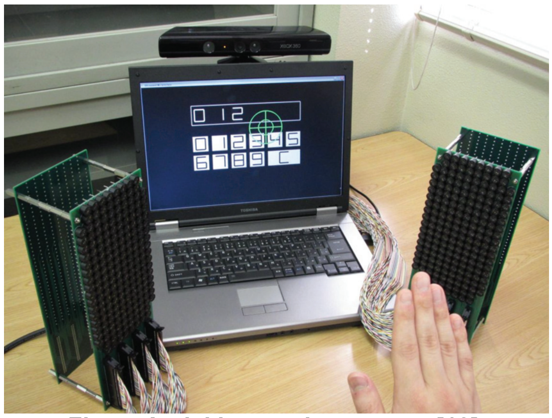

Fig. 7 Aerial interaction system [18].

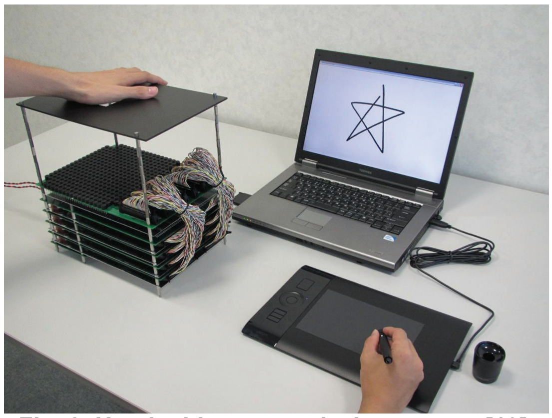

Fig. 8 Handwriting transmission system [19].

4. CONCLUSION

This paper introduced an ultrasound-based noncontact tactile display, especially focusing on its applications. The localized tactile stimulation is provided in midair and its position can be continuously moved. The research history, principles, prototype, and demonstrations were presented.

REFERENCES

[1] T. Iwamoto, M. Tatezono, and H. Shinoda: Non-contact Method for Producing Tactile Sensation Using Airborne Ultrasound, Proc. Eurohaptics 2008, pp.504-513 (2008)

[2] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda: Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound, IEEE Transactions on Haptics, Vol. 3, No. 3, pp. 155-165 (2010)

[3] K. Hasegawa and H. Shinoda: Aerial Display of Vibrotactile Sensation with High Spatial-Temporal Resolution using Large-Aperture Airborne Ultrasound Phased Array, Proc. World Haptics Conference 2013, pp. 31-36 (2013)

[4] S. Inoue, K.J. Kobayashi-Kirschvink, Y. Monnai, K. Hasegawa, Y. Makino, and H. Shinoda: HORN: The Haptic-Optic Reconstruction, Proc. SIGGRAPH 2014, Emerging Technologies, article no. 11 (2014)

[5] T. Hoshi: Development of Portable Device of Airborne Ultrasound Tactile Display, Proc. SICE Annual Conference 2012, pp. 290-292 (2012)

[6] M. Fujiwara, K. Nakatsuma, M. Takahashi, and H. Shinoda: Remote Measurement of Surface Compliance Distribution Using Ultrasound Radiation Pressure, Proc. World Haptics Conference 2011, pp. 43-47 (2011)

[7] K. Kikunaga, T. Hoshi, H. Yamashita, Y. Fujii, and K. Nonaka: Measuring Technique for Static Electricity Using Focused Sound, Journal of Electrostatics, vol. 71, no. 3, pp. 554-557 (2012)

[8] G.M.Y. Hung, N.W. John, C. Hancock, D.A. Gould, and T. Hoshi: UltraPulse - Simulating Arterial Pulse with Focused Airborne Ultrasound, Proc. EMBC '13, pp. 2511-2514 (2013)

[9] M. Kono, Y. Kakehi, and T. Hoshi: lapillus bug, Proc. SIGGRAPH Asia 2013, Art Gallery (2013)

[10] Y. Ochiai, A. Oyama, T. Hoshi, and J. Rekimoto: The Colloidal Metamorphosis: Time Division Multiplexing of the Reflectance State, IEEE Computer Graphics and Applications, vol. 34, no. 4, pp. 42-51 (2014)

[11] Y. Ochiai, T. Hoshi, and J. Rekimoto: Pixie Dust: Graphics Generated by Levitated and Animated Objects in Computational Acoustic-Potential Field, ACM Transactions on Graphics, vol. 33, article no. 85 (2014)

[12] Y. Sugiura, K. Toda, T. Hoshi, M. Inami, and T. Igarashi: Graffiti Fur: Turning Your Carpet into a Computer Display, Proc. SIGGRAPH 2014, Emerging Technologies, article no. 9 (2014)

[13] M. Ciglar: An Ultrasound Based Instrument Generating Audible and Tactile Sound, Proc. International Conference on New Interfaces for Musical Expression 2010, pp. 19-22 (2010)

[14] J. Alexander, M.T. Marshall, and S. Subramanian: Adding Haptic Feedback to Mobile TV, CHI Extended Abstracts 2011, pp. 1975-1980 (2011)

[15] M.T. Marshall, T. Carter, J. Alexander, and S. Subramanian: Ultra-tangibles: Creating Movable Tangible Objects on Interactive Tables, Proc. CHI 2012, pp. 2185-2188 (2012)

[16] T. Carter, S.A. Seah, B. Long, B. Drinkwater, S. Subramanian: UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces, Proc. UIST '13, pp. 505-514 (2013)

[17] T. Hoshi, M. Takahashi, K. Nakatsuma, and H. Shinoda: Touchable Holography, Proc. SIGGRAPH 2009, Emerging Technologies, article no. 23 (2009)

[18] T. Hoshi: Development of Aerial-Input and Aerial-Tactile-Feedback System, Proc. World Haptics Conference 2011, pp. 569-573 (2011)

[19] T. Hoshi: Handwriting Transmission System Using Noncontact Tactile Display, Proc. IEEE Haptics Symposium 2012, pp. 399-401 (2012)