PROCEEDINGS OF THE INTERNATIONAL DISPLAY WORKSHOPS, VOL.28, 2021

INP7/FMC4-2
Invited

Ultrasound Haptic Rendering

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Keywords: Haptics, Ultrasound, Touchless.

ABSTRACT

Ultrasound haptics is a technology that uses an array of ultrasound transducers to present tactile sensations remotely on human skin. Since haptic feedback can be given without touching anything to the hand, this technology can provide a clean interface with high operability. Recent studies have shown that ultrasound can represent not only simple tactile stimulation by focus generation, but also various skin sensations that represent the properties of the touched object. In this paper, we present the latest progress in these techniques.

1 Introduction

With the recent epidemic of infectious diseases, the demand for non-contact interfaces is increasing. Recent developments of 3D displays have begun to realize holographic user interfaces that can be operated without actual touch, as depicted in science fiction. In these interfaces, graphical buttons and icons are often placed in front of the user and are operated by some gesture. Haptic feedback plays an essential role in facilitating such operations. Through the tactile sensation, the user can intuitively understand the progress of operations, such as pressing a button or dragging an icon. Since ultrasound haptics technology does not require the wearing of any device, it can constitute a clean and convenient interface.

As such a system, an airborne tactile touch panel called HaptoMime has been proposed [1]. In this system, when a finger position detected by an infrared sensor overlaps with an icon, ultrasound waves emitted from an array of ultrasound transducers create a tactile sensation. Another system called HaptoClone [2], which allows people in different locations to communicate with each other through haptic feedback, has also been proposed. In these systems, tactile sensation is generated by focus generation through a simple superposition of ultrasound waves.

In recent years, tactile presentation methods that better reflect the characteristics of objects have been studied. Human cutaneous sensation is perceived under various conditions, such as pressure distribution on skin surface, vibration, and temperature. Controlling these parameters can lead to more realistic representations of objects and more operable interfaces. In the following sections, we will introduce the latest research results.

Fig. 1 Ultrasound haptic feedback is provided depending on the status of contact with virtual objects. [3].

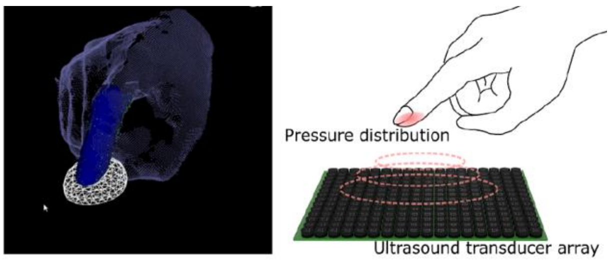

Fig. 2 The pressure distribution on a finger touching a soft object is reproduced by a transducer array [6].

2 Pressure Distribution Control

In VR and AR systems, reproducing the magnitude and area of pressure generated on the hand grasping a virtual object is expected to improve its usability. In 2019, we developed a prototype of a haptic interaction system with 3D virtual objects, as shown in Fig.1 [3]. In this system, an array of transducers arranged around the workspace generates a pressure distribution on the fingertips touching a virtual object. This pressure distribution is formed along the intersectional shape with the virtual object. By moving the focus of the ultrasound wave so fast that it cannot be perceived by humans, the pressure pattern along the path is presented in a time-averaged sense. It has been demonstrated that such tactile presentation allows the user to recognize the position and angle of surfaces [3] and the local shape of objects [4]. Furthermore, it has been shown experimentally that users can grasp invisible objects using only tactile information.

A more precise method of generating spatial pressure patterns was proposed in 2020 [5]. This method dynamically creates a mesh model with the shape of a hand captured by depth cameras and controls the scattered sound field on it in real-time. The relationship between the gain of the transducer array and the sound pressure distribution is discretized in the style of a boundary element method. Based on this relationship, the pressure distribution on the skin surface is controlled. As shown in Fig.2, this method can be used to represent the transition of the pressure pattern spread when touching a soft object [6]. The pressure distribution at the fingertip in contact with a soft object is obtained by finite element simulation, and it is reproduced in real-time by a fast algorithm that solves the inverse problem of the scattered sound field. A user study showed that softness, expressed by the area of the pressure pattern and the magnitude of the force relative to the indentation depth of the finger, was discriminable. The current limitation of this method is that it can only represent very soft objects because there is a theoretical upper limit to the pressure that can be presented using ultrasound waves. Recently methods of increasing the perceived intensity by appropriately modulating the ultrasound waves were studied [7][8]. An interesting question is whether it is possible to represent hard objects by combining these methods. Approaching the problem not only from the perspective of physical reproducibility but also from the perspective of human perception will lead to the representation of a greater variety of objects.

3 Texture Rendering

Since the above study renders the pressure distribution spread over the skin surface, such as the gradient of the force and the contact area, it is possible to calculate the target distribution by physical simulation. However, it is difficult to accurately simulate the vibration component of tactile stimulus when touching a real object with various textures.

In 2019, Sakiyama et al. proposed a system that uses ultrasound to reproduce vibrations recorded using a multichannel pressure sensor [9][10]. As shown in Fig. 3, the system records tactile sensation of a real object as a spatiotemporal pressure distribution using an array of highly sensitive electret condenser microphones. This sensor has a sensitivity suitable for the dynamic range that can be reproduced by airborne ultrasound tactile sensing. An ultrasound phased array is controlled to reproduce the obtained spatiotemporal pressure pattern. The results of a psychophysical experiment confirmed that the three types of tactile sensations (brush, sponge, and towel) reproduced by this method could be distinguished to a certain degree without prior information.

In a different approach, Omori et al. studied the use of ultrasound to control tactile sensation [11]. They found that frictional force was reduced on polystyrene foam surface on which ultrasound waves were focused. This method differs from the other methods mentioned above in that it

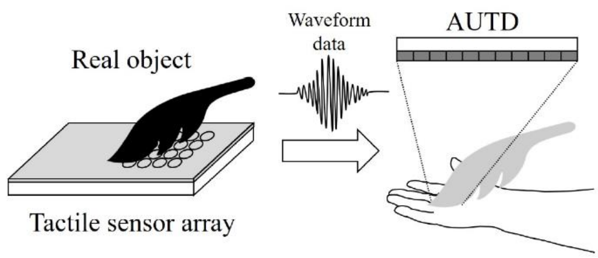

Fig. 3 A microphone array records the vibration when an object is traced over it, which is then reproduced by a transducer array [9].

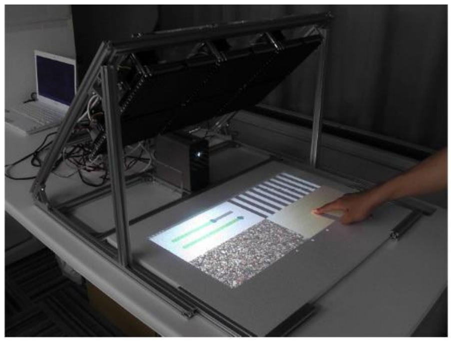

Fig. 4 Focusing the ultrasound waves at the point where the finger touches reduces the frictional force [12].

requires touching an actual object, but it has the potential to freely design the spatial distribution of frictional forces on the object being touched by generating ultrasound pressure patterns. They developed a disposable visuo-haptic display by combining a projector with an ultrasound phased array [12] as shown in Fig. 3.

4 Display of Thermal Sensation

As mentioned above, various studies have been conducted on the spatiotemporal control of the pressure field generated by ultrasound. However, mechanical stimulation presented by pressure cannot cover all tactile experiences. Thermal sensation is also an important component of tactile perception. Thermal sensation provides a cue not only to recognize the temperature in the environment but also to identify materials through their thermal conductivity. Nakajima et al. proposed a method to present a cooling sensation with pinpoint accuracy by generating focused ultrasound waves to accelerate the vaporization of water mist near the skin surface, as shown in Fig. 3 [13]. This can reduce the temperature of the hand by 4.6 K in one second and by 3.3 K in the first 0.5 seconds by providing a cooling spot of about 15 mm in diameter. This represents a heat absorption equivalent to that of touching steel. This cooling spot can be controlled on the surface of the skin by shifting the focus of the ultrasound waves, which

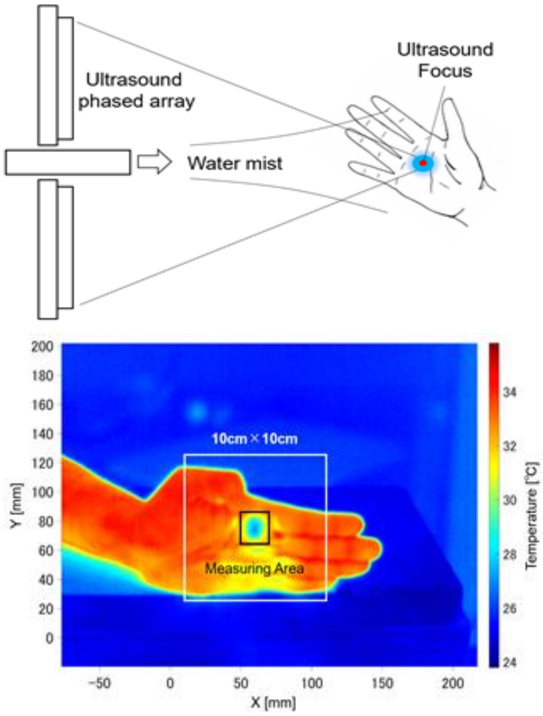

Fig. 5 Display of a pin-point cooling sensation by ultrasound focus in water mist [13].

allows for a more realistic reproduction of the properties of the object.

They have also demonstrated that pain can be presented through thermal grill illusions that occur when presenting cold and warm sensations in the vicinity [14]. In their experiments, they used halogen lamps for remote heating.

Kamigaki et al. have proposed a method of presenting thermal sensation by radiating ultrasound waves to a gloved hand. As shown in Fig.6, a material with sound-absorbing properties, such as cotton work gloves, locally heats up when ultrasound waves are focused on it. This method can selectively present vibrotactile and thermal sensations according to the ultrasound irradiation pattern.

The sensations of warmth, cold, and pain presented by these methods are also expected to be useful in alerting the user to some danger or to errors in sports or vocational training.

5 Conclusion

We have presented some recent studies on the rendering of cutaneous sensations. The ability to control the physical properties of stimuli given by ultrasound leads to the examination of their psychological effects. Ultrasound haptic stimulation is both reproducible and controllable, making it an excellent tool for investigating what kinds of tactile stimuli cause what kinds of psychological consequences. Recently, ultrasound haptic

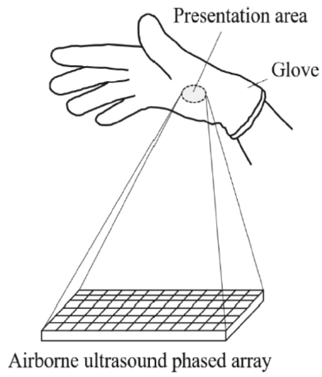

Fig. 6 A hand wearing a cloth glove can be heated remotely by focusing ultrasound waves [15].

technology has been used for the presentation of pleasant sensations [16] and the verification of the conditions for the occurrence of phantom sensations [17].

The technology of ultrasound tactile presentation is still in its infancy in terms of both software and hardware. The combination of improved sound field generation algorithms, advances in transducer arrays, and understanding of human perception will allow us to provide a variety of tactile sensations with high spatiotemporal resolution in the future. One of the directions for the evolution of interfaces is to combine this with visual and auditory displays to create a natural system that allows users to operate as if they were touching a real object.

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