博士論文
Producing Click Sensation by Airborne Ultrasound
(空中超音波によるクリック感の生成)

伊藤 充

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Abstract

Click is an essential function for mechanical switches such as the mouse and keyboard. The click function allows the user to touch the surface of the switch to feel a slight contact and maintain a state where it can be operated at any time. Owing to this neutral position, the user can complete the operation quickly, and the action completion can be perceived by touch. In this thesis, a method for realizing a click using airborne ultrasound is discussed. Haptic functions such as clicking are also desired for midair haptics like mechanical switches and touchpads. Midair haptics is a technology that can freely present a spatio-temporally programmable haptic sensation on the user's skin without wearing any device. Haptic feedback using this technology enables users to operate virtual midair buttons efficiently even in a blind state. In order to solve the dynamic range problem of the ultrasonic haptic intensity, a haptic sensation that combines the recently discovered amplitude modulation (AM) and unidirectional spatio-temporal modulation (LM) is presented. LM can present a stronger haptic sensation than conventional methods. Besides, the sensations presented by these two methods differ in haptic quality due to differences in the mechanoreceptors that stimulate them. Ultrasonic clicks are presented by performing two-step haptic feedback according to the position of the user's hand. A haptic button with a click sensation is constructed by the dynamic change of the haptic stimulus. To investigate these haptic buttons, first, a method of first realizing a palm button click is described, next, a fingertip button click is described. In the case of a palm-sized button, the user can distinguish and perceive two types of haptic sensations, which are switched according to the hand movement, a weak stimulus, and a strong stimulus. This haptic button is also designed with fingertip size and superimposed on the visual image. This button is composed of a standing haptic image that can be actively touched and a pulsatile LM vibration stimulus. As a practical demonstration of this button, a haptic button superimposed on a visual stereoscopic image is reported. This virtual button was exhibited at an academic conference and indicated the possibility of physical computer interaction by artificial haptic sensation. This method will serve as the basis for applying midair haptic technology to the human-computer interface.

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Chapter 1

Introduction

1.1 Background

1.1.1 Necessity of Haptic Operation

Click is the most basic function in computer operation. The physical key and the mouse are designed to operate quickly and accurately even without visual information. Such click operations cannot be performed without haptics. Auditory and visual modalities for click are used as auxiliary sensations for haptics. One of the reasons why haptic sensation is important is the certainty of haptic sensation regarding touching movement. Haptic sensation ensures that we can perceive contact events without being affected by occlusion, a visual problem. Haptic sensation is a sense at can accurately perceive multiple states such as contact and completion. Haptics allows multiple states, such as contact and completion, to be accurately perceived.

Haptic sensation is a modality that has been used since humans were born. Humans can receive various information from the outside world by touch. Humans always feel the haptic sensation throughout the body and move their bodies based on this information with little awareness. Many other animals, not just humans, understand the world visually and then behave using the haptic sensation. For example, when a human grabs an object with his hand, he can immediately perceive the structure behind the object and understand its texture. Of course, the amount of haptic information is very little compared to vision. However, this understanding is impossible only by vision. All human actions are established by haptic sensations. In this way, the haptic sensation is considered an important factor to deeply understand the world that surrounds us.

Information in our daily lives is notified to us in languages that use vision and hearing, such as television and radio. Also, the development of the Internet has made it possible for users to communicate with each other without haptics. This situation seems to indicate that tactile sensation is an unnecessary sensation. However, without haptic sensation, it becomes difficult to use electronic devices such as keyboards and touchpads for such communication. Furthermore, this non-haptic world makes it difficult to avoid the dangers of human behavior and we cannot live a safe life.

The development of computer technology has allowed us to access visually and auditorily space reproduced on a computer. This development has enabled a virtual user experience called virtual reality[52]. Furthermore, the amount of information in this experience

continues to increase due to the development of technology. In these recent situations, the haptic sensation is expected to be one of the next modalities to be reproduced. This reproduction of haptic sensation enables humans to perform actions through the computer that acquire information from the outside world with natural motion, and move the body of it in the real world as human-computer interaction. This situation suggests that users can access digitized information without having to learn special operations. In this way, haptic sensation will continue to be an indispensable element for all users to live in society.

As mentioned above, the computer-generated artificial haptic sensation is a tool that can support human behavior. This haptic sensation is effective when presented as an appropriate stimulus suitable for the situation. For example, consider the action of a user touching something with his hand. At this time, when a haptic sensation is presented with a delay when the hand touches the object, the user cannot stop the hand at an appropriate position and pushes the object unintentionally. In another example, when an object touches the user's body, the presence of the object cannot be felt if the haptic sensation is weak, and pain is felt if the haptic sensation is too strong.

Thus, an important factor to be discussed, when considering the presentation of haptics on a computer, is the design of meaningful haptic information. The elucidation of the problem of how to reproduce the haptic sensation that humans perceive in the real world is still under development. One of the reasons is that devices for presenting haptic sensations to humans have not been sufficiently developed. As another modality, even in the case of vision, a method to completely reproduce the difference between light and dark in the real world and the three-dimensional structure has not been established. However, in the case of haptic sensation, more problems remain than in the case of vision. This situation is complicated by the fact that the mechanism of haptic perception differs depending on the body part.

Nevertheless, haptic sensations such as clicks caused by vibrations on touch panels and touchpads are regarded by users as being effective and are widely used. Even with such a simple haptic presentation, the amount of information is little, but the user can exchange information with the computer. This fact indicates that even if a complete tactile sensation cannot be reproduced, meaningful information can be notified by defining rules for the timing and intensity of tactile presentation.

The design guideline of haptic information has not been fully elucidated as described above. However, as in this simple notification example, by appropriately designing the haptic information transferred between the computer and the human, human behavior is supported by haptics.

This thesis is based on the motivation to construct a foundation for humans and computers to send and receive information of the button's contact and click using these haptic movements. In this thesis, the investigation of haptic technology is explained. Lastly, the tactile sensation targeted by this thesis should be described as "Tactile", but the social generic term for haptic technology in recent years is changing to "Haptics". Based on this situation, this thesis shows here that these sensations are described as "Haptic" in parts other than the modalities section of Chapter 2.

Fig. 1.1: Single state switch. Single state notifies the user and computer only of the contact state.

1.1.2 Requirements for Haptic Interface

The most basic switch using haptic sensation is a simple push switch. This switch is used to change the state of something. For example, when sending information using Morse code, the user needs to be able to operate the switch for turning on/off light and sound in a short time. Also, when inputting characters with a typewriter, the user touches the key with his fingertip and perceives that the input is completed by touch. The action of pressing a switch like a button in this way is an important element for our efficient life.

With the development of technology, these switches have changed to mouse and keyboards. A mouse [12] is one of the fundamental inventions of computer along with a graphical user interface. As the inventor Engelbert [11] says, "The mouse was just a tiny piece of a much larger project aimed at augmenting human intellect." However, thanks to this mouse function, the user can operate the GUI, access the Internet, and perform remote communication.

The most important function required for the haptic interface described above is "click". Click is an action based on the haptic sensation. When the user operates the mouse or keyboard, the user can feel a slight touch of the button with the haptic sensation and can complete the operation with the touch of the click. This operation includes at least two types of haptic information. One of the haptic sensations indicates the contact state (Fig. 1.1), but this sensation alone does not allow the user to recognize whether the operation has been completed. Another haptic sensation indicates operation completion. Owing to these haptic functions (Fig. 1.2, 1.3), users can operate haptically without relying on vision.

1.2 Rest of the Thesis

Fig. 1.2: Two-States Haptic Feedback. Two-step feedback allows switch operation.

Fig. 1.3: Mid-air tact switch to push with user's finger. Two states notify the user and the computer of the contact state and action completion.

Approach of the Thesis

As described above, the transmission of information by haptic sensation is considered essential for our lives. The final purpose of this thesis is to realize the basic functions of the interface where humans and computers exchange information by haptics. To achieve this, this thesis consists of the following two methods.

1. Proposal of a method to convey two kinds of states by touch only.

2. Proposal of a haptic presentation method that can be operated even in a blind state.

The first proposal is to present two haptic sensations that can be clearly perceived. Here, a hand-operated interface is considered. For example, when we operate an input device such as a button, the button needs to be designed so that it does not malfunction just by touching it. For this reason, every switch around us has at least two states: a steady-state and an operational state. There is no doubt that being able to convey the

information of these two states to the user by haptic sensation is the most fundamental element that a haptic switch such as a button or key should satisfy. In addition, these two states need to be easily distinguishable and perceived by the user. For example, when we touch an object, we feel that the touching action is completed by sensing the change in haptic sensation with our hands. This change is clear with ON/OFF of haptic sensation.

In the case of a switch, another haptic sensation needs to be perceived from the state in which the haptic sensation is felt by the movement of the touch. In order to present this distinctly different haptic sensation, it is desirable that the strength and quality of the haptic sensation change. In the case of vision, it is difficult to distinguish gray with slightly different brightness. However, the difference between white and black or whether there is a black line is easily perceived. Similarly, in the case of haptic sensation, it is difficult for the user to perceive the two states in a situation where only such a slight difference can be reproduced. Thus, haptic contrast is a very important factor in stimulus presentation.

The second proposal implements a haptic presentation method that enables operations without looking at the target to be operated, such as buttons. What you can do with a haptic interface, but not a visual interface, is an operation in a blind state. If we close our eyes and feel no touch feeling, we cannot press the button in front of us. If there is a haptic sensation, you can search for the button by hand even if you close your eyes. Blind operation is an indispensable element to help our daily life. The computer keyboard and mouse are designed so that they can be operated even when they are not visible.

Active touches play an important role in these haptic movements. To achieve this, continuous haptic stimulation is required, and it is also desirable that the haptic sensation can be changed according to the user's actions.

Expectations for Midair Interface

A midair interface is a system in which a virtual object can be placed freely in space using a computer and the object can be manipulated by users. A visual display is ahead of the technical challenge to realize a midair interface. Even in the case of haptics, it is desired to present a programmable sensation in midair. A mechanism has been developed to present haptic sensations to the touchpad when the physical switch is replaced with a touchpad. Similarly, haptic presentation is a necessary element in the midair interface. In this thesis, the haptic device that presents haptic sensations with the acoustic radiation pressure of focused ultrasound is discussed.

The midair interface is expected to be used in the following situations.

(i) Medical facilities

There are many electronic medical devices in their facilities, especially operating rooms. These devices include computers. These operations are performed by physical interfaces such as keys and buttons. In such a situation, it is important that the hand is not contaminated, and therefore a midair interface that does not touch the object is expected.

(ii) Public facilities

A midair interface is also desired for buttons that can be touched by an unspecified number of people. The reason for this is the same as above. Also, in digital signage that distributes advertisements, the mechanism to switch video is common, and in this situa-

tion, assuming an interaction with the user, an air interface that can be operated without touching the surface of the display is important.

(iii) In-vehicle head-up display
The operation panel of a car has already been digitized, and a touch operation is desired like a general computer. In order to avoid danger while driving, an operation method has been developed that eliminates the need to look at the display. One of them is a touch panel display capable of tactile feedback. Since the position of the seat and hand is fixed during the operation of the car, proposals to expand such a display as a midair interface have begun.

(iv) Personal computing
The spread of head mounted display (HMD) and glass-type displays has begun. This allows the user to perceive aerial images without being limited to conventional 2D displays. In such situations, hand gestures can be used to realize applications involving body movements.

Contributions of the Thesis

One of the advantages of the contact type interface is that it can present a haptic sensation by touching the physical surface of the interface. When using such a device as an interface for the computer described above, it is only necessary to have one structure that physically stimulates the skin when pressed. This structure makes it possible to present two-states haptic feedback.

In this thesis, the following contents are shown in order to realize such two-step feedback by haptic sensation of the midair interface. Haptic sensation is provided using an ultrasound phased array.

(i) Palm-sized midair haptic button.

(ii) Finger-sized midair haptic button with providing a click sensation.

Midair haptics [50] [53] using ultrasound [37] [33] [22] [61]can present haptic sensation freely to human skin in midair. However, the maximum radiation force is weak, and the haptic patterns that can be presented are limited. Therefore, one of the challenges is to provide haptic sensation with high contrasts.

To solve this problem, two or more different stimuli with varying haptic intensity and quality are required. As stimuli with different haptic sensations, amplitude modulation (AM) and unidirectional spatio-temporal modulation (Lateral Modulation: LM) [13] [54] are adopted. LM is a technique discovered in recent research that can provide a stronger haptic sensation than AM. First, a midair button [1] is designed with these two spatially stacked stimuli. The system is designed so that the user can press it with his palm. Here, it is investigated that the user can distinguish and perceive AM and LM certainly, and that multiple buttons can be freely selected and operated even in a blind state.

Next, the haptic buttons using these two haptic sensations are scale downed to the size of the fingertips. In addition, this button solves the problem of audible sound, which was

a side effect of modulation with the method described above. This fingertip-sized button is designed by combining a standing haptic image using 40 kHz ultrasound and a pulsed LM vibration tactile sense. The standing tactile image is always presented so that the user can actively touch [25] it and expresses the repulsive force of the button. The pulsatile LM presents a short vibration to the user's finger. This combination is designed based on research of conventional physical switches [60] and artificial click feeling of touchpad[62][63] [16]. The audible sound with this method is generated only at the moment of clicking. This is a sound generated by a conventional physical switch. in addition. It can be used as an effect to notify the completion of the operation simultaneously by touch and hearing.

A midair button combined with a fingertip-sized haptic button and a visual image was realized. The midair images of these two modalities are similar to other methods, but users can see and manipulate them with their eyes and perceive an unprecedented click feeling. Furthermore, these stimuli do not require symbolic learning and can be operated easily by the user. These facts through experiments and confirmed that the user can operate in a blind state was clarified. This cannot be achieved with conventional aerial visual images or midair haptic images.

1.3 Organization

This thesis is organized as follows. In Chapter 2, we will explain only the tactile sensations that are necessary when touching objects with human hands.Next, the current state of the technique for presenting the tactile sensation is described. Here, the overall tactile presentation method, from mechanical devices to midair tactile devices is outlined. In this chapter, the presently realized midair tactile presentation method will be described, and the necessity of the proposed method described in the following chapters is shown. In addition, this chapter describes the principle of tactile sensation using acoustic radiation pressure of ultrasound and the limitations of the prototype device used in this thesis.

Chapter 3 shows how to realize a midair haptic button that is assumed to be operated with the palm of the user's hand. This haptic button is designed to provide a haptic sensation different from the touch feeling of the button when it is searched and operated by the hand. This is the basic function of the switch. In this chapter, two types of haptic patterns with different intensity and quality in order to provide quasi clicks of buttons with ultrasound haptic patterns is presented.

Chapter 4 describes a technique for presenting visual midair images and haptic images simultaneously for the investigation in Chapter 6. It is possible to evaluate the effect of a midair haptic button only by haptic sensation, but the effect is more practically evaluated by comparing with a visual virtual button. In addition, in this chapter, we present the results of the investigation of how the user perceived the virtual image position when the visual image and the haptic image were presented simultaneously.

In Chapter 5, the haptic characteristics of physical buttons are investigated to reproduce the buttons operated by fingers with the midair haptic sensation. Contact, reaction force, and click vibration are investigated as haptic characteristics of physical buttons. In addition, a presentation method of ultrasound haptics to reproduce these haptic characteristics by midair haptics is described.

Chapter 6 describes how to downsize the midair haptic buttons described in Chapter

3 to a size that can be operated with the fingertips. In this chapter, the system that superimposes the haptic image on the visual image realized in Chapter 4 is used. This system presents a standing haptic image using standing ultrasound waves, which is different from the haptic presentation method in Chapter 3. The haptic tactile image can be actively touched by the user's hand, and the haptic sensation of the click is presented using a vibrating haptic sensation by pulsatile spatio-temporal modulation. The haptic sensation of this haptic image was designed to be linked to vision with reference to buttons that we operate daily. This system was experienced by many participants at the exhibition and provided not only reliable button operation but also blind operation in a groping state. The realization of haptic blind operation is the basis for asserting that the proposed method is an indispensable and fundamental element in realizing the midair interface.

Chapter 2

Function of Haptics for Human Computer Interaction

Humans perceive tactile sensations throughout their whole bodies. How to receive the sensation varies depending on the body part.In this chapter, the mechanism related to the tactile sensation of the hand, which is the scope of this thesis, will be explained in limitedly.

2.1 Tactile Perception of Human Skin

2.1.1 Cutaneous Sense

This section describes human cutaneous sense. Among human sensations, sight, hearing, taste, olfaction (smell), and balance sensation have sensory organs specialized for each sensation. These are collectively classified as special sensations. In contrast, tactile sensation, thermal sensation, pain sensation, itching, proprioception, and visceral sensation are collectively called somatic sensations. The sensations felt on the skin are called cutaneous sensations and include tactile sensation, thermal sensation, and pain sensation.

Tactile sensation is classified into two types, cutaneous sensation and proprioception, depending on the location of receptors.Cutaneous sensations are caused by signals from receptors and nerve endings that exist directly under the skin, and consist of mechanical receptors such as Meissner corpuscle and free nerve endings related to pain and temperature. Intrinsic sensations are handled by muscle spindles and mechanoreceptors in the joints, and are sensations generated by physical conditions such as skeletal muscles, tendons, and joints.

The tactile sensation targeted in this thesis is a sensation generated by mechanoreceptors in the cutaneous sensation. Of these cutaneous sensations, the fingertips with the highest spatial resolution are the targets. In the following, the contents that are particularly relevant to the tactile display among the characteristics of the cutaneous sensation will describe.

Fig. 2.1: Cross section through the grabrous skin of the human hand. Reconstructed from [30].

2.1.2 Characteristics of Mechanoreceptors

Figure 2.1 shows the skin cross section of the human hairless part [30]. The skin consists of three layers of the epidermis, the dermis, and the subcutaneous tissue in the order from the outside to the inside. It has a thickness of 1 mm. The dermis is a dense connective tissue layer that lies beneath the epidermis and has a thickness of about 1 to 3 mm. The surface of the dermis protrudes into the epidermis, which is called the nipple. The subcutaneous tissue is below the epidermis and consists of rough connective tissue. Mechanoreceptors are distributed from the epidermis-dermis boundary to the subcutaneous tissue. The mechanoreceptors related to human tactile sensation are classified into four types, which are called Meissner corpuscle, Merkel tactile disc, Rufini ending, and Pacini corpuscle in order from the epidermis side. The Meissner corpuscle is about 0.7 mm deep in the hairless area. There are hair follicle receptors in the hair that have a different root of hair around the back of the nerve. The Merkel touch panel is about 0.9 mm deep, and the Pacini corpuscle is about 2 mm deep.

These mechanoreceptors are first classified into slow adaptability (SA) and fast adaptability (FA) based on time response. This speed refers to the time during which nerve firing occurs when a mechanical stimulus is applied to the area within the receptive field. Spatial responsiveness is classified into receptive fields with a narrow range of a few millimeters in diameter and receptive fields with unclear boundaries of about 5 mm or more. The receptive field is a spatial region that can cause nerve firing when mechanical stimu-

Fig. 2.2: Characteristics of receptive fields and nerve firing. Reconstructed from [30].

lation is applied to the skin surface. Mechanoreceptors are classified as shown in fig. 2.2 according to these conditions. Based on these explanations, there are four types of tactile receptors. SA I corresponds to Merkel tactile disc, SA II corresponds to Rufini ending, FA I corresponds to Meissner corpuscle, and FA II corresponds to Pacini corpuscle.

Figure 2.3 shows the receptive fields of FA I and FA II. The receptive field of FA I is about several millimeters in diameter, and its boundary is clear because FA I and SA I exist near the skin surface.

In contrast, the receptive field of FA II is wide and may reach nearly half of the palm.

The distribution density of each receptor is known to be related to the tactile spatial resolution. Figure 2.4 shows the distribution of mechanoreceptors in the palm. The density of mechanoreceptors is highest at the fingertips and tends to decrease as it approaches the palm. This tendency is particularly prominent in FA I and SA I. On the other hand, the density of FA II and SA II does not change depending on the site and is lower than that of FA I and SA I.

The vibration stimulus around 250 Hz, which is considered to be mainly responded to SA II, feels as if the entire finger is vibrating, and the localized sensation is weak [15]. In addition, the distribution density of FA II at the fingertips is relatively low for FA I and SA I. FA I and SA I are thought to play a role in detecting a single localization mainly for mechanical stimuli.

Fig. 2.3: Receptive field of the hand skin. Reconstructed from [30].

Fig. 2.4: Distribution density of skin mechanoreceptor. Reconstructed from [30].

Fig. 2.5: Four channel model of vibration stimulus detection. Reconstructed from [5].

2.1.3 Vibration Detection Threshold

Figure 2.5 shows the measurement results of the vibration detection threshold when a sinusoidal vibration stimulus was presented to the human thenar eminence [5].

The black point is the detection threshold for vibration stimulation using a disk-shaped contact with an area of 2.9 cm^2, and the dashed line over 40 Hz is the detection threshold for vibration stimulation using a contact with an area of 0.008 cm^2. The latter dashed line over 40 Hz tends to be relatively flat with respect to frequency, but the black point shows a lower value than the dashed line at a frequency of 40 Hz or higher, and has a threshold peak from 200 Hz to 300 Hz. The vibration detection threshold curve when a large contact is used overlaps with the nerve firing curve of FA I from 2 Hz to 40 Hz and FA II above 40 Hz. The phenomenon that the detection threshold decreases as the stimulation area increases is called spatial weighting. For vibration stimuli, spatial weighting is seen at 40 Hz and above. Of the four types of mechanoreceptors, only FA II exhibits this spatial weighting, and has a characteristic that the threshold value decreases according to the size of the presentation area of the vibration stimulus.

2.2 Tactile Presentation Methods

This section describes the current situation of haptic presentation devices.

A device that presents haptic sensations to humans in some way is called a haptic display. There are various types of haptic presentation devices because haptic perception differs depending on the part of the body [21] [9] [34] [36] [56]. These haptics are essential factor for realizing a programmable user interface [23] [17]. Here, these haptic displays are roughly classified as follows.

1. Installation type
2. Wearable type
3. Skin stimulation type

In this section, the current situation of these methods is explained. Furthermore, the detail of the midair tactile display that is the main target of this thesis is explained.

1. Installation type

This type of device enable the user to freely move and get a haptic sensation while holding a pen or arm installed on the spot. These devices present a feeling of touching an object by simulating the reaction force felt by the hand. In addition, there is a method [10] that presents the haptic sensation of multiple textures when tracing the touch panel surface with a pen-type device that can present vibration stimuli.

2. Wearable type

This type of device presents a haptic sensation by a glove-like mechanism attached to the user's hand that generates a force to bend the finger or stimulates the skin by vibration [42] [48] [45] [43] [64]. Compared to the installation type, there are fewer restrictions on hand movements and it can be associated with more human actions. In addition, there are devices that install multiple vibration devices on clothes and provide the feeling of vibration to the whole body.

3. Skin stimulation type

In this type of device, mechanisms such as pins [2] [46] [59] [28] [58] and touch panel [62] [47] [4] [32] [14] [7] provide a tactile sensation by stimulating the finger skin. There are devices that use electrical stimulation [31], and devices that stimulate human skin in a non-contact manner using air jets or frictional ultrasonic waves that use frictional force [55] or suction force [38]. This type of device specializes in stimulating the skin and receptors on the palms and fingertips, compared with the above-mentioned installation type and wearing type.

The midair haptic display introduced in this report is classified here. Midair haptic displays are classified into the above-mentioned skin stimulation types. There are various types of displays such as air jet type[53], air vortex type[50], laser type[35], and display using ultrasound. In order to explain in more detail, this section will introduce further.

Air vortex display by Sodhi et al. [50]

AIREAL is a system that presents haptic sensations in midair using air vortex. This system can present haptic sensations to the user without wearing any devices. This study investigates the possibility of interaction with virtual 3D objects. The system is equipped with a class D amplifier and a small speaker, and the key component is a circular nozzle that generates an air vortex. The orientation of the housing is controlled by the gimbal structure. The display can present a haptic sensation to the target with an accuracy of 89 % in a 1 m distance and 75 degree directional workspace. Except for electronic devices, 3D printer parts are produced and the total weight is about 1 kg. The reach range of the stimulus is 1 m, which is longer than the midair haptic presentation device (30 cm) using ultrasound, for example.

The system is evaluated for irradiation angle, delay time, and reach. The frequency characteristics up to 1-16 Hz are evaluated by psychophysical experiments.

Overall, it is considered that the technique can effectively present tactile sensation by selecting an application with a vibration stimulus with a frequency of about 10 Hz and a resolution of about 8.5 cm.

Air jet display by Suzuki et al.[53]

This system is a device that presents a haptic sensation in midair using an air jet array in which 100 air jets nozzle are arranged in a matrix. Air jet nozzles are placed 10 x 10 at intervals of 4 cm. The position of the user's hand is detected by the user's receiver. The nozzle that releases air is selected according to the position of the user's hand. When the user's hand is in contact with the virtual object, the air is always released, and a haptic sensation of contact is presented. With this series of controls, the user can perceive one point of the contact surface of the virtual object and the hand. The system workspace is 30 cm in height. Each air jet is connected to a single compressor by a flexible tube. The air flow is switched by an electric valve located between the nozzle and the compressor. One nozzle can release air at a time, and tactile presentation is limited to one point. This study is a pioneering study of airborne tactile interaction.

Airborne ultrasound tactile display by Carter et al.[6]

This study investigated multi point midair haptic feedback. In addition, they investigate the threshold of perception according to the frequency of the vibration stimulus. The device used in the survey is a midair haptic display using a transducer array using 40 kHz ultrasound. In the survey, two focal points were presented at the same and different frequencies. The presentation distance of these focal points was changed, and it was confirmed whether the user can perceive each focal point. The experimental results show that individual perception becomes difficult if the interval between the two focal points is narrower than 3 cm. In addition, when the frequency of the vibration stimulus is changed, it is shown that the accuracy of distinguishing two focal points at intervals of 3 cm, for example, is improved by more than 60% compared to the case of the stimulus with the same frequency.

The position of the user's hand is tracked by the hand tracker, and a haptic sensation is presented according to the position. In addition, a visual screen through which sound waves can pass is placed on the surface of the transducer array. The visual image from

Fig. 2.6: Airborne ultrasound tactile display by Hoshi et al.

the projector is displayed on the screen, and an application is installed that allows the user to visually check the position of the focal point in the x-y direction.

This research is an example of later development of midair haptic sensation into a commercial application. Their group has contributed greatly to the spread of midair haptics [41].

Airborne ultrasound tactile display by Hoshi et al.[22]

This is the world-first study that presented haptic sensations using an airborne ultrasound phased array. The position of the focal point is freely controlled, and the haptic sensation of vibration is presented to the user by an amplitude modulated signal. The number of transducers is 324 and the radiation force is 16 mN. The focus is updated at 1 kHz. In the experiment, it was confirmed that the focal point moving at 3 cm / s presented in the palm of the user could be tracked with a probability of 90%. It was also confirmed that the locus of the focus of the shape of the line, edge, and helix can be easily distinguished. As an application, an attempt was made to superimpose a tactile sensation on a 3D image. Since this research, many haptic displays with similar structures have been developed.

Research of ultrasound tactile presentation by Wilson et al.[61]

In this study, an 8x8 ultrasonic transducer array was used to investigate the perceptual characteristics of haptic sensations presented to human palms. Although the device is smaller than other studies on ultrasound phased arrays, this advantage assumes passive haptic applications when worn on the wrist. The position of the focal point was identified within 8.5 cm, and it was confirmed that the movement of the focal point was perceptible. The authors proposed guidelines for haptic presentation using midair ultrasound based on the experimental results. Items are distance, duration, location(direction), spatial resolution, virtual object size. The contribution of this research is significant in discussing

how to provide a midair haptic display to the palm in the field of Human-Computer Interface.

Airborne ultrasound tactile display by Korres et al.[33]
The originality of this research is the haptic pattern rendering method. The haptic display is a two-dimensional ultrasound phased array, which is the same as in related research. This system renders 3D objects represented by point clouds as tactile objects by scanning the focal point of ultrasound waves, and perceives them on human skin. The rendering frequency was 7 Hz-10 Hz depending on the object. In the experiment, the focus of ultrasound was scanned to present straight lines, circles, and hemispheres, and it was confirmed that the user can perceive them. The author also confirmed how long it took the user to perceive them. In this study, instead of stimuli as a single point, a practical investigation is made to render primitive haptic objects in the air and let the user perceive them.

2.3 Midair Tactile Presentation Using Ultrasound Phased Array

2.3.1 Acoustic Radiation Pressure

The relation between the sound pressure and radiation pressure [3] [20] is summarized below for the readability of the manuscript. The acoustic radiation pressure P [Pa] is proportional to the sound energy density given by

$$P = \alpha E = \alpha \frac{p^2}{\rho c^2} \tag{2.1}$$

where E [J/m^3], p [Pa], ρ [kg/m^3], and c [m/s] denote the sound energy density, sound pressure, density of the medium, and sound velocity, respectively. α denotes a constant ranging between 1 and 2 depending on the reflection properties of the object surface. When the ultrasound propagates through the air and is blocked by the surface of an object, almost all of the ultrasound is reflected at the boundary and in this case the coefficient α becomes nearly 2. Thus, the radiation pressure P can be controlled by controlling the ultrasound pressure p.

2.3.2 Directivity

The acoustic radiation pressure presented by the phased array is affected by the directivity of the transducer. In this section, the directivity of ultrasound waves of a single transducer, which is considered when configuring a phased array unit, is shown.

$$D(\theta) = \left| \frac{P}{P_{\theta=0}} \right| = \left| 2 \frac{J_1(ka \sin\theta)}{kasin\theta} \right| \tag{2.2}$$

The directivity of the ultrasound wave is shown by the following directivity function, assuming a circular baffle with radius a attached to an infinite baffle plate.

J_1 is a Linear Bessel function. $w = kc$, and a is the radius of the vibrating disk.

The directivity of the ultrasound transducer used in the prototype is shown in Fig. 2.7. The sound pressure distribution simulation performed in this thesis follows the results of this data sheet. The influence of directivity is also taken into account when constructing multi-unit phased arrays.

2.3.3 Distance Attenuation

One of the critical parameters in ultrasound is distance attenuation. The scattering attenuation of ultrasound waves in the air is proportional to the square of the ultrasound frequency. The higher the ultrasonic frequency, the greater the scattering attenuation in the air, and the attenuation of the ultrasound wave increases rapidly. When the sound pressure on the surface of the transducer is P_0, the sound pressure amplitude p at the distance x as shown:

Fig. 2.7: Directivity of the actual transducer and official data sheet.

$$|p| = P_0 e^{-\alpha f^2 r} \tag{2.3}$$

Where α is a coefficient consisting of sound velocity, viscosity coefficient, deposition density, thermal conductivity, and specific heat ratio.

2.3.4 Focal Point Size

The minimum diameter of the focal spot w is estimated as

$$w = \frac{2\lambda R}{D} \tag{2.4}$$

where λ [m] denotes the wavelength of the acoustic wave, and R [m] and D [m] denote the focal length and the diameter of the aperture, respectively [65]. The spatial resolution of the array is determined by the focal diameter w.

Figure 2.8 and 2.9 indicate the simulated acoustic radiation pressure distribution of the phased array by the above parameters. In addition, Fig. 2.10 and 2.11 indicate the measured acoustic radiation pressure distribution of single phased array.

2.3.5 Standing Wave

The haptic images of standing waves is used as a means to implement midair clicks. Standing waves are apparently stopped when focusing on the maximum amplitude of the vibration waveform. This phenomenon occurs when two waves with the same frequency and opposite travel directions interfere with each other.

The sound pressure p for a standing wave in the direction of sound wave z is shown as

$$p = \sqrt{2} A w\left(x, y\right) \cos\left(\frac{2\pi z}{\lambda}\right) e^{-j\omega t} \tag{2.5}$$

Fig. 2.8: Simulated Acoustic Radiation Pressure. (Focal length: 150 mm)

Fig. 2.9: Simulated Acoustic Radiation Pressure. (Focal length: 150 mm)

Where A is the effective amplitude, $w(x, y)$ is the normalized sound pressure cross section, and $\omega$is the angular velocity.

As described by Hoshi et al., [22] $w\,(x, y)$ is shown as an approximation of the sound pressure distribution of the phased array by sinc function

$$w\,(x, y) \simeq \operatorname{sinc}\left(\frac{2\pi x}{\omega}, \frac{2\pi y}{\omega}\right) \tag{2.6}$$

Fig. 2.10: Measured Acoustic Radiation Pressure. (Focal length: 150 mm)

Fig. 2.11: Measured Acoustic Radiation Pressure. (Focal length: 300 mm)

Where the sinc function is shown as:

$$\mathrm{sinc}\,(x, y) = \frac{\sin(x)\sin(y)}{xy} \tag{2.7}$$

Chapter 3

Midair Click of Dual-Layer Haptic Button

In this chapter, an aerial interface that is assumed to be operated by a human's palm is considered. The palm is one of the possible options for the body part for us to manipulate virtual objects placed in the air. If the switch is assigned only a single function, a button operated with the palm of the hand will make sense. For example, there is a button to stop the device and a switch that detects the proximity of the hand with infrared rays.

For example, in the case of a large industrial robot or a device that may pose a danger to humans, the emergency stop button needs to be pushed with the palm immediately. The reason of this example is because this operation is considered to be completed most quickly. Interfaces that take a long time to operate limit the applications that can be applied. Therefore, this function of being able to be pressed immediately is an important factor in using the midair button in various situations.

3.1 Abstract

In this chapter, the author proposes a method to create a quasi-click sensation in midair based on two types of tactile stimulation methods that create different sensations both in the intensity and quality. Two-layers of regions in the space that forms a virtual button

Fig. 3.1: Photograph of the industrial robot emergency stop switch.

Fig. 3.2: Midair click using dual-layer haptic feedback. The intensity and quality of haptic feedback are switched according to the hand position.

is considered. A user's hand is tracked by a sensor and stimulated by the two methods according to the hand position. When the user's hand is in the upper or lower layer, the hand skin is stimulated weakly or strongly by the two methods, respectively. These two states indicate a neutral position and action completion. This midair click was enabled by a recent finding where an ultrasound focus motion on the skin produced a stronger perception than amplitude modulation given at a constant position. The author conducted experiments to confirm whether two haptic layers can be perceived. In addition, it was investigated whether a blind operation of button selection can be performed.

3.2 Dual-Layer Haptic Feedback

3.3 Mid-air Tactile Display

An ultrasound phased array produces midair haptic sensation using the radiation pressure [29] [22]. Figure 3.3 shows the arrangement of the phased array. The ultrasound focus was generated by nine units of phased arrays (Fig. 3.7) driven at 40 kHz [18] [19] [27]. The aperture size of the phased array is 576 mm (W) * 454.2 mm (H). The XY coordinates of the focus were determined by the position of the user's hand. The hand position was measured by Realsense Depth Camera SR300 (Intel).

3.4 Dual Haptic Layer

Figure 3.5 shows the configuration of the dual-layer haptic button. The user's hand position was measured, and stimulated by AM and LM [54] when the hand enters upper and lower layers, respectively. The hand position was used for only layer switching. The focal position of the AM/LM layer was fixed. The AM frequency is 150 Hz. In the LM, the LM vibration amplitude and the frequency were 4.5 mm and 50 Hz, respectively, where the LM vibration amplitude was defined as the displacement amplitude of the focal spot on the skin. The depths of the AM layer and LM layer were 50 mm and 100 mm, respectively. The output of the nine phased arrays was 144 mN with the maximum intensity. In this experiment, the driving intensities of the phased array on the AM and the LM layers were 10% and 100%, respectively.

Fig. 3.3: Prototype device. Photograph of the phased array.

Fig. 3.4: Schematic diagram of a nine-unit phased array and depth camera.

The AM and LM stimuli convey the two states of a neutral position and action completion, respectively, and produce a quasi-click sensation. To increase the contrast between the two stimuli, the author selected specific AM and LM frequencies such that the tactile feel quality and perceived strength were clearly different following the previous study [5].

Fig. 3.5: Schematic diagram of the dual-layer haptic feedback.

3.5 Experiment

In this experiment, the tactile sensations of the above-mentioned haptic button were presented and they were evaluated whether the difference can be perceived by the palm. Next, three buttons were presented in midair and it was investigated whether the buttons could be operated in a blind state. Informed consent was obtained from all individual participants included in the study.

3.5.1 Experiment 1: Identification of the tactile sensation

The experiment setup is shown in Fig. 3.6. The experimental procedure is as follows. Before the experiment, the participants were explained that the haptic button was consisted of two layers and were directed to find the upper AM layer by themselves. They were informed that the positions of the buttons were on the front side and the lower side of the initial hand position of fig. 3.7 . They wore the headphones and listened to white noise to interrupt the audible sounds from the phased array. They identified the height of the top surface of the two tactile layers by matching the center of the palm with the XY coordinates of the focal point. The hand position of the participants were guided manually by the examiner to the starting position. The participants, with their eyes closed, identified the surface position of the upper AM layer first, followed by the position of the lower LM layer. They freely moved their hands to find the button position, and held the position of their right hand and answered "yes" to inform the examiner that the search was completed. Subsequently, the examiner measured the position of the participants' hand and completed the task. No time limit was imposed for the answers. The answers were obtained from the average of three trials. There were a total of eight participants. All participants were male, aged 23-27 years.

3.5.2 Experiment 2: Tactile button operation

In this experiment, which was carried out in a manner similar to experiment 1, three haptic buttons were placed in different positions. Figure 3.8 shows the arrangement of

Fig. 3.6: Experimental setup (front view). The top-surfaces of the upper (AM) and lower (LM) layers were located at heights of 625 mm and 575 mm.

Fig. 3.7: Experimental setup (top view). The participants placed their hands at the initial position (Z = 800 mm) and started the experiment.

the haptic buttons. The experimental procedure is as follows. Before the experiment, the participants were informed that three buttons were presented side by side in the horizontal direction; however, they were not informed of the distance between the adjacent buttons. At the start of the experiment, the examiner informed the participant with letters and orally which button they must select out of the three. The participants were orally informed of the start of the experiment. With their eyes closed, they placed their right hand in the same position as that in experiment 1 and identified the position of the instructed button in the same manner as that in experiment 1. Next, they identified the

Fig. 3.8: Experimental setup (top view). Three buttons are arranged at intervals of 100 mm.

position of the top surface of the lower LM layer. The position of the button was presented randomly to them. The answers were obtained from the average of three trials.

3.6 Results

3.6.1 Experiment 1: Identification of the tactile sensation

Figure 3.9 shows the position of the haptic layer perceived by the palm. "Distance" indicates the distance from the phased array surface. The error bars indicate the standard deviation. The average of the positions of the top surface positions of the perceived AM and LM layers were 649.6 and 575.5 mm, respectively. The range of the identified top-surface heights of the upper and lower layers were 47.4 and 44.7 mm, respectively.

3.6.2 Experiment 2: Tactile button operation

Figure 3.10 shows the average values of the answers of each button position of all the participants. The average values of the perceived left, center and right button's X-axis are -95.9, 1.1 and 102.5 mm, respectively. Figure 3.11 shows the position of the tactile button perceived by the palm. The origin of the graph corresponds to the XY coordinate of the center of the phased array. Figure 3.12 shows the Z-axis value of the participants' answers. The average values of the perceived left, center and right button's Z-axis are 586.2, 584.1, and 586.0 mm, respectively. The ranges of the answered height of the button were 46.3 (left), 53.7 (center), and 31.1 mm (right), respectively.

Fig. 3.9: Perceived top surfaces of two layers. Error bars show the standard deviations of the position that the participants identified.

3.7 Discussions

3.7.1 Experiment 1: Identification of the tactile sensation

The result of Fig. 3.9 shows that the participants perceived the surface of each layer surface correctly. The surface of the LM layer was set at a position of 600 mm, while the average height perceived by the participants was 575.5 mm. This indicates that the presented button was pushed deeper than the author's assumption. However, this result still suggests that the user's hand could stop at the LM layer surface and feel the two-step feedback. As a subjective comment by the authors, the difference in stimulation between the AM and LM layers was clearly perceived. The AM layer presents a stimulus that eases the perception of the button position. The LM layer increases the resistance to the action of pushing the button compared to that in the AM layer. No repulsive force exists to push back the hand, but when moving from the AM layer to LM layer, a weak click feeling was felt by the palm.

Fig. 3.10: Three perceived focal points. The plots show the average values of all the participants.

Fig. 3.11: Three perceived focal points. The plots show the answered value of the eight participants.

Fig. 3.12: Perceived top surface of the lower layer. The average value of participants' answers for all the buttons was 586.4 mm.

3.7.2 Experiment 2: Tactile button operation

Among the 72 trials in Experiment 2, three participants answered four times in total at different positions. This may be because they could not touch the three buttons simultaneously with their palm. However, this result indicates that the participants could operate the button correctly with a probability of 94.4%, suggesting that a sufficiently practical interface can be realized by an improved button placement. The result of Fig. 3.12 shows the difference in the position of the LM layer identified by the participants. The height of the button perceived by the participants exhibited a range of 53.7 mm in the case of the center button. One of the reasons for this error is that the haptic layer was thick. In the experiment, the participants were instructed to identify the top surface of each haptic layer, but AM stimulation and LM stimulation were presented in a range of 50 mm and 100 mm, respectively. The other factor is that the participants were not restricted when identifying the position of the haptic layer as to whether to explore from the higher side or from the lower side. Nevertheless, they were confirmed that the participants could stop the button operation within the specified range after receiving the two-step feedback.

Fig. 3.13: Conceptual image of midair buttons when installed horizontally. Visual information are added for layers for explanation.

3.8 Conclusion

A dual-layer haptic button produced in midair was proposed and evaluated in this study. A user finds the button position and its surface by AM stimulation to the user's palm (Fig.3.13). The AM stimulation was provided when the user's hand was in the AM (upper) layer of thickness 50 mm. The completion of the click was conveyed by the LM stimulation provided when the user's hand was in the LM (lower) layer of thickness 100 mm. The experimental results indicated that the top surfaces of the AM and LM layers were recognized independently within the errors of 12.4 and 9.4 mm, respectively, in the standard deviation. Each haptic layer was identified without symbolic learning of tactile pattern differences. In addition, the three buttons were explored within the errors of 7.2 (center), 20.2 (left), and 12.9 mm (right) in the standard deviation, and its accuracy rate was 94.4%. The participants in the blind state could explore by hand where a specified button was located out of the three.

Chapter 4

Haptic Effect of Visuo-Tactile Display

Haptic presentation using midair ultrasound can present haptic feeling freely in real space, but its position cannot be confirmed visually. In addition, it is desired that the midair haptic sensation be used as a midair haptic object by superimposing it on the midair visual image. Several studies have been conducted assuming such applications [39] [44] .

The midair click proposing in this thesis aims to be used in such applications. In this chapter, they were described how to implement a system that superimposes a haptic sensation on a midair visual image in order to investigate the click interface. As a preliminary experiment for evaluating clicks, they were considered how the user can see the visual and haptic images presented by this system.

In this chapter, In this chapter, a visuo-tactile display using an aerial 3D display was fabricated. The autostereoscopic image was composed of multi-viewpoint images with lenticular lenses and was imaged in the air using a retroreflector. Midair haptics by ultrasound was presented according to the position of the autostereoscopic image. In the experiment, they were compared the case of presenting the midair button only with the image and the case of superimposing haptics on the image. It was confirmed that the user's finger was localized in a 14.1% narrow depth range when the haptics was superimposed on the image. In the case of a half-blind with the eyes shifted from the button, the button with superimposed haptics could keep the position of the user's finger within a narrow depth range of 18.2%.

4.1 Prototype Device

The prototype device was composed of an autostereoscopic display, depth camera, and midair tactile display. Figure 4.1 shows the appearance of the prototype system and Fig. 4.2 shows the configuration of the prototype system.

4.1.1 Autostereoscopic Display

The autostereoscopic display (Looking Glass Holoplayer One) using retro-reflector was employed. The display consists of a light source, a beam splitter, and a retro-reflector. The light from the light source is reflected by the beam splitter and then reaches the retro-reflector. Light from the retro-reflector passes through the beam splitter and generates an aerial image at 90 degrees to the light source. The cylindrical lens installed in the light

Fig. 4.1: Photograph of the prototype device.

Fig. 4.2: Schematic diagram of the prototype device.

Fig. 4.3: Visual display configuration. The aerial image is formed by a retro-reflector and a beam splitter.

source presents the image changing according to the position of the viewpoint to the user' s eye.

4.1.2 Generation of Visuo-Tactile Pattern

In this prototype system, 3D objects were presented on the 150 mm workspace in the Z direction. Midair haptics was generated using phased arrays corresponding to the position of this 3D object. The two phased arrays generate the focal point by the reflection path by the beam splitter.Since the 3D object is displayed away from the screen, it could be touched without physically touching the display. The images were controlled using the Unity 3D gaming engine. The position of the user's hand was measured by Depth Camera (Intel Realsense SR300). In this system, the fingertip was approximated as a sphere with a radius of 5 mm. The 3D objects, sensed hand data, and the focus of the phased array was plotted in 3D space corresponding to the display workspace. When the 3D object collides with the sensed finger, the focus of the ultrasound was presented to the user's fingertip.

4.1.3 Distribution of the Acoustic Radiation Pressure

Figure 4.5 shows the experimental setup to measure the focus of the ultrasound. The standard microphone(Bruel & Kjaer Type 4138-A-015) with a preamplifier (Bruel & Kjaer Type 2670) was mounted on a high-precision stage. The surface of the aerial image plane was parallel to the stage. Figure 4.6 shows the distribution of the acoustic radiation pressure of the ultrasound at the center of the display. The half-width of the acoustic radiation pressure is 10 mm. The distance from the beam splitter is 150 mm.

Fig. 4.4: Visual display configuration. The principle that the image displayed on the 2D display changes according to the user's viewpoint. This image for each viewpoint generates parallax and enables stereoscopic viewing.

Fig. 4.5: Experimental setup for the measurement of the sound pressure.

Fig. 4.6: Acoustic radiation pressure distribution.

4.2 Experiment

Experiment 1: Midair Button Operation

The experimental setup is shown in Fig. 4.7, 4.9. In this experiment, the participant touches the midair button with a finger and answers its position (Fig. 4.8). A midair button was generated by combining an autostereoscopic image and midair haptic. The midair button is a sphere with a radius of 10 mm. The participants wore the headphones and listened to white noise to interrupt the driving noise from the phased array. The experiment was started by the participants operating the keys on the keyboard with the left hand. The midair button was presented for the first time by this key operation. The participants indicate the position of the midair button with the index finger of the right hand, and the position of the button was recorded by pressing the key again with the left hand. There are five distances between the midair button and the beam splitter: 60 mm, 80 mm, 100 mm, 120 mm, and 140 mm. The position of this midair button in the Z direction was presented randomly, and presented three times at each position. All combinations were performed with and without haptics. Each answer is obtained by averaging three times. By the above combination, the procedure was repeated 30 times in total.

Experiment 2: Half-blind operation of midair button

The experimental setup is shown in fig. 4.10. In this experiment, the subjects touch the midair button with the finger without gazing at it and then answers its position. The subjects start the experiment by key operation, and the midair button was displayed at this time. The subjects first confirm the position of the midair button by visual inspection. The subjects were allowed to see the button for 2 seconds. Then, the subjects gaze at

Fig. 4.7: Experimental Setup.

Fig. 4.8: Conceptual diagram of contact between user's hand and virtual object.

Fig. 4.9: Photograph of the situation the user answers.

Fig. 4.10: Photograph of the situation the user answers. (Half-blind condition.

the marker on the wall at 45 degrees from the display with a beep signal. The subjects gaze at the marker and use the finger to answer the position of the midair button. The subjects' answer was made by key operation. The position of the finger at this time is recorded. Other procedures are the same as in Experiment 1.

4.3 Results

Experiment 1: Midair Button Operation

Figure 4.11 shows the depth position of the finger in the midair button operation. The average value of the answered position with haptics is 60.7 mm, 81.7 mm, 98.3 mm, 117.8 mm and 133.1 mm (in the order of 60 mm, 80 mm, 100 mm, 120 mm, 140 mm), and the standard deviation is 14.1 mm, 25.0 mm, 19.6 mm, 20.8 mm and 27.0 mm in the same order. The average value of the answered position without haptics is 60.65 mm, 79.0 mm, 86.3 mm, 105.5 mm and 126.1 mm, and the standard deviation is 13.0 mm, 15.6 mm, 22.1 mm, 31.5 mm and 31.4 mm in the same order.

Discussion

The standard deviation (Z = 140 mm) of the depth position of the button, which the subject answered in the experiment, is 26.9 mm in the presence of haptics and 31.4 mm in the absence of haptics. When haptics was superimposed, the accuracy of tasks specifying one point in space is 14.1% better than without tactile sensations. In this experiment, no visual feedback was presented when touching the midair button. If the haptic sensation was not superimposed, the participants answer the position of the midair button by relying only on vision. On the other hand, when there is a sense of touch, the subject can sense the feedback when the user presses the air button with touch. This feedback makes it possible to answer with more accurate finger pointing at the programmed position of the midair button.

As a subjective comment of the authors, it is difficult to perceive the depth position of the button with the operation of a vision-only midair button. This virtual 3D object allows

Fig. 4.11: Experimental result of Experiment 1.

the user to constantly receive haptic feedback and adjust the position of the finger relative to the target. Even in the case of a virtual 3D image, haptic feedback can compensate for the difficulty of the depth position of the object.

Experiment 2: Half-Blind Operation of Midair Button

Figure 4.12 shows the depth position of the finger in the midair button operation in the half-blind state (the viewpoint was tilted 45 degrees from the display). The average value of the answered position with haptics is 56.4 mm, 70.3 mm, 89.4 mm, 110.7 mm and 125.7 mm (in order of 60 mm, 80 mm, 100 mm, 120 mm, 140 mm), and the standard deviation is 26.6 mm, 26.7 mm, 30.9 mm, 31.8 mm and 34.8 mm in the same order. The average value of the answered position without haptics is 53.0 mm, 73.4 mm, 84.5 mm, 102.1 mm and 120.7 mm (in order of 60 mm, 80 mm, 100 mm, 120 mm, 140 mm), and the standard deviation is 31.5 mm, 34.8 mm, 28.5 mm, 36.8 mm and 42.5 mm in the same order.

Discussion

The standard deviation (Z = 140 mm) of the depth position of the button that the subject answered in the experiment is 34.8 mm with tactile sense and 42.5 mm without tactile sense. When haptics was superimposed, the accuracy in the task of specifying one point in space was improved by 18.2% compared to the case without haptics. In this experiment, the subject could not gaze at the button when pressing the midair button. If haptics was not superimposed on the button, the subject could not receive operation feedback. Therefore, the operation was performed based on visual memory. However, when haptics was superimposed on the button, the participants could put the finger on the position

Fig. 4.12: Experimental result of Experiment 2. (Half-blind condition.)

with haptic feedback even if the button was not seen with eyes.

The results of Experiment 2 show that the button was perceived at a deeper position than in Experiment 1 in which the participant was able to gaze at the midair button. This result was also seen when haptics was superimposed on the button. One of the reasons for this result is that the participants incorrectly answered the button position by the XY coordinate of the button. In this experiment, if the fingertips and the spheres deviate in XY coordinates, no haptics was presented to the participants.

4.4 Conclusions

In this chapter, the author fabricated a 3D display with midair haptics and confirmed the haptic effects in touch operation. The working space of the prototype device is 300 mm (W) * 162 mm (H) * 150 mm (D). In physical experiments, it was confirmed that the midair haptic presented at the position of the image was presented with a half-width of 10 mm. This haptics falls within the range of the 3D image used in the participant experiment. In psychophysical experiments, it was confirmed that the localization of the finger touching the air button improved by 14.1% when using haptics. In the half-blind test where the viewpoint was shifted from the button, it was confirmed that the localization of the finger was improved by 18.2% when using haptics. Our experimental results show that when the user touches the aerial button, the aerial tactile sense may solve the problem of finger penetration.

Chapter 5

Haptic Characteristics of Physical Switch and Its Realization by Ultrasound

An essential haptic function of the palm-sized button is that the user can easily confirm the position of the button and operate it. In the case of a virtual button operated with the palm, it is sufficient if the size is determined according to the size of the palm. When the interface is complicated by increasing the number of virtual buttons, a finger-sized button like a computer key is desired.

In this chapter, before explaining the finger-sized midair click using ultrasound, it is organized what kind of tactile information the physical button presents to the human skin. In addition, the outline of the reason why this method cannot be achieved by the midair haptic sensation using ultrasound is explained.

5.1 Haptic characteristic of physical switch

Physical switch presents the following states to the user's skin by haptics.

1. Contact state
2. Pressure changing on skin due to push down
3. Click vibration

For these elements, the characteristics of physical switches that can be reproduced by ultrasonic tactile sensation are investigated.

In previous studies, click sensations such as physical switches [60], touchpads [62], and mobile phone [8] were investigated. In this chapter, the characteristics of physical keys that need to be reproduced by ultrasound haptics will be summarized and described as preparations before implementing the midair haptic buttons.

1. Contact state

Static pressure is required to perceive that the user's skin is in contact with the object. When we keep touching a stationary object with fingers, constant pressure is perceived, not a vibration stimulus.

2. Pressure changing on skin due to push down

When the user's skin touches the button and push down, the pressure applied to the skin increases with respect to the push-down width. Here, the load required to press the key of the laptop computer is measured.

Measurement of push-down load

A measurement system consisting of a load cell, a standard microphone, and a digital oscilloscope was constructed to measure the physical profile of key pushing-down.

Figure 5.1 shows the configuration of the measuring instrument.

Fig. 5.1: Experimental setup using load cell and standard microphone.

Figure 5.2 shows the force changing measured by the load cell when the key was completely pushed down.

Hereinafter, this force is called the pressing pressure. The most important property of this result is that the pressing pressure continues to increase up to the point of the maximum value in the graph. This result shows the dynamic change of the haptic sensation by the user's operation. The haptic sensation of the click occurs at the point of the maximum value in the plot. The characteristics of this click vibration will be described in the next section. After the maximum value in the plot, the pressing pressure decreases because the key was released after the click vibration. If the key continues to be held after the vibration of the key click, the pressing pressure does not decrease. The difference between this release and the hold also shows a dynamic change in the haptic sensation to the user's operation. In this experiment, the gradient of the increasing pressure was not constant. This change in gradient indicates how large the reaction force is presented to the user before the click vibration occurs.

In the above force measurement, the sound profile of the click vibration was measured

Fig. 5.2: Normalized force that expresses physical key pressing pressure. The plot shows the change in load when a key is pressed.

simultaneously using a standard microphone. In this experiment, it was confirmed that the click vibration described later did not occur except for the inflection point, which is the peak of the force.

3. Click vibration

As described above, when the user's skin presses down a button and applies a certain amount of force, a vibration stimulus is presented as a tactile sensation to notify the completion of the operation.

Figure 5.3 shows the sand profile of the click vibration.

The measurement setup was used the same setup as the measurement of the pressure below. The plot shows that the amplitude of the physical sound representing the haptic sensation of the click converges in about 5 ms. The time axis of the plot was aligned so that the click occurred 5 ms. This result indicates that the user can perceive the click by generating at least about 5 ms of vibration. The length of this vibration is considered to be equivalent to the frequency of the haptic stimulus.

5.2 Midair Haptic Button Presentation Method

5.2.1 Physical Experiment

If these haptic information can be reproduced even in the case of ultrasound, a virtual button with a function equivalent to a physical button can be realized. One of the reasons that have not been realized until now is the weakness of the radiation force of the midair ultrasound phased array. Due to the limitation of this weak force, amplitude modulation has been used to present vibration stimuli around 200 Hz except for a few cases [24] [26]. The haptic sensation of this vibration stimulus can inform the presence of the midair interface to user by haptics [40]. Even this single haptic sensation is useful for improving

Fig. 5.3: Key click sound profile for physical key. This click signal is presented at the inflection point of the load graph.

the operability of the midair interface depending on the design method. The next stage of this haptic feedback is to reproduce the two kinds of haptic information: the contact state and the notification of the operation completion. In other words, the problem of the maximum radiation force is a problem of dynamic range. This problem makes it difficult to switch and present two or more types of textures with different qualities and intensities. For these reasons, midair haptic buttons with a click sensation have not been realized ever before.

In the above explanation, the haptic information of the physical switch which is considered to be useful when presenting the midair haptic button is described. In the above explanation, the haptic information of the physical switch which is considered to be useful when presenting the air tactile button is described. Here, the haptic presentation method in the case of midair ultrasound corresponding to these haptic information is described.

5.2.2 Static Pressure to Indicate Contact State

1. Contact state

Here, the important factor for presenting the contact haptic state is considered to be static haptic stimulation of unmodulated ultrasound. The haptic sensation of touching a physical object with a finger is static pressure. It is known that FA I and SA I receptors respond to such active movements [57]. In order to present this haptic sensation with ultrasound haptics, it is necessary to present a stimulus at a frequency that the tactile receptor cannot perceive as vibration. In this method, 40 kHz ultrasonic waves are used without modulation in order to maximize sound pressure. There is a possibility that it can be realized haptically even at frequencies lower than this frequency. However, such a control is not recommended because it will generate an audible sound when modulated

Fig. 5.4: Experimental setup of barometric pressure and sound pressure. The focal point was generated at a distance of 200 mm from the phased array surface.

below 20 kHz. It has been investigated that static haptic sensation by 40 kHz ultrasound can be perceived in a box-shaped setup surrounded by 996 transducers [24].

In present haptic presentation [6][33][22] by midair ultrasound, it is popular to use about 250 transducers. It can be considered that the number of oscillators is set as the minimum configuration that allows most users to perceive the vibration stimulus by amplitude modulation of 200 Hz on the skin. The unmodulated stimuli of 40kHz ultrasound cannot be perceived with fingertips or hands in these situations. The reason for this is that the unmodulated haptic threshold is higher than the vibratory haptic threshold.

In the following, it is described how unmodulated static stimulus by 40 kHz ultrasound can be perceived. First, the pressure at the focal point when the drive strength of the phased array is changed is investigated. Based on these results, the perception threshold when actively touching the ultrasound focal point with a finger pad is investigated.

Sound pressure distribution considering interception of opposing waves

In the case of airborne ultrasound using standing waves, the opposing waves are cut off when the user touches with the finger, and the sound pressure distribution actually presented to the finger changes. Here, the sound pressure, when the opposing wave radiated in the vertical direction is blocked by an object that assumes a finger, is investigated.

Figure 5.4 and 5.5 show the measurement setup. The prototype device consists of 1494 vibrators.

The measuring instruments are a pressure sensor (MPX5100DP, NXP Semiconductor), a digital oscilloscope (Picoscope 4423, Pico technology), 3D stage. The surface of the top and buttom phased arrays were parallel to the x-z plane of the 3D stage composed of high-precision stages (SIGMA KOKI OSMS26-300) and a stage controller (SIGMA KOKI

Fig. 5.5: Experimental setup of sound pressure measurement considering a reflecting sphere. The diameter of the styrene ball is 20 mm.

SHOT-304GS). The location determination accuracy of each stage was 15 μm. The data were acquired at every 1 mm. The ultrasound was driven with a continuous 40 kHz rectangular signal during the measurement. The driving intensity of the phased array unit is 100% except for experiments in which drive strength was changed as a parameter.

In this setup, the pressure that is applied to the finger pad when touching the focal point of the ultrasound needs to be measured excluding the ultrasound from above the fingertip. As a condition in consideration of the pressure received by the finger, a condition was set in which a styrene ball having a diameter of 20 mm was disposed immediately above the pressure sensor as Fig.5.5.

The measurement was performed in two cases: when the opposing wave had a reflecting sphere, and when the opposing wave was blocked by the reflecting sphere. During the experiment, the ultrasound wave was emitted at 40 kHz and no amplitude modulation was performed.

Figures 5.6 and 5.6 show the spatial distribution of the measured pressure along the x-y plane. Figures 5.8 and 5.9 show the spatial distribution of the measured pressure along the y plane. Figures 5.10 and 5.11 show the spatial distribution of the measured pressure along the x plane. These four sections plots were normalized to the maximum pressure value indicated by Fig. 5.9.

Fig. 5.6: Pressure distribution. A condition without a reflective sphere considering the fingertip.

Fig. 5.7: Pressure distribution. A condition with a reflective sphere considering the fingertip.

Fig. 5.8: Vertical section of acoustic radiation pressure distribution. The focal position is the 0 mm origin.

Fig. 5.9: Vertical section of acoustic radiation pressure distribution with a reflective sphere.

Fig. 5.10: Horizontal section of acoustic radiation pressure distribution without a reflective sphere.

Fig. 5.11: Horizontal section of acoustic radiation pressure distribution with a reflective sphere.

Relationship between phased array driving intensity and focal point barometricpressure

The pressure of the focal point was measured using a barometric pressure sensor (MPX5100DP, NXP Semiconductors) and a digital oscilloscope (Picoscope 4423, Pico technology). Since this pressure sensor is a differential pressure sensor with two apertures, one side was sealed and measured. Figure 5.4 shows the measurement setup.

Figure 5.12 shows the barometric pressure for the driving intensity of the phased array when using unmodulated 40 kHz ultrasound. The pressure sensor aperture is located at the center of the phased array unit. The focal point of the ultrasonic wave is generated at the center of the phased array unit, similar to this aperture. The measured values are 0 Pa when the driving intensity of the phased array is 0%.

Fig. 5.12: Barometric pressure for phased array drive strength. The plots shows the conditions with/without reflective sphere considering fingertips.

5.2.3 Psychophysical experiment

Haptic threshold of unmodulated ultrasound

In this experiment, the threshold for perceiving the focus of unmodulated ultrasound at the fingertip was investigated. As a result of preliminary experiments, the intensity of the static stimulus by the 40 kHz ultrasound was not enough for the user to fix and perceive the finger with this prototype device. Therefore, in the experiment, it was investigated whether the focus can be perceived by actively moving the finger.

The experimental setup is shown in Fig. 5.13.

Fig. 5.13: Photo of threshold experiment. The participant performs all operations in the blind state.

The participant's viewpoint during the experiment is shown in Fig. 5.14.

The experimental procedure is shown as follows. The experimental procedure is based on the method of limits. The driving intensity of the phased array is varied in the range of 0-100%. The presentation stimulus is changed in 20 steps of 5%. The driving intensity of the phased array is controlled by changing the duty ratio of the PWM. The focus is fixed at the center of the phased array unit as shown in Fig. 5.4. The focal distance from the upper and lower phased arrays is 200 mm. Ultrasound is emitted at a frequency of 40 kHz without amplitude modulation. The participant places their right hand palm on the stage. The stage consists of a horizontal sliding stage and a metal plate for placing the palm. The participant places the finger pad of the right hand at the focal point. The horizontal position of the focal point is indicated by a laser marker. The height of the focal point is indicated by a thread placed behind the finger position. Based on these information, the participant learns the focus position visually with the palm placed on the stage. The participant places his left hand on the keypad for answer operation. The participant wears a headphone and listens to white noise. The reason for interrupting the

Fig. 5.14: Participant's viewpoint. The participant moves the hand horizontally and touches the focus actively.

environmental sound is to prevent the participant from getting a clue to the operation of the cooling fan. The participant closes his eyes and touches the focus with his right index finger during the experiment. The participant is allowed to move his hand on the sliding stage horizontally when touching the focus. The participant responds about the tactile sensation at the fingertip.

Participants are allowed an alternative answer of Yes or No. There is no time limit for responses. The experimental procedure includes an ascending series and a descending series. These two series are each tried three times. The experiment starts with an ascending sequence and is presented in order from the smallest stimulus. The descending series is presented in order from the largest stimulus. The participant's absolute threshold is calculated as the average of the two series. The total number of trials for one participant is 120. The experiment was performed on seven participants. All participants were male and their average age was 24.9 ± 1.46 years.

The experimental result of the threshold is shown in Fig. 5.15.

The plot includes an average of the thresholds of the ascending and descending series. The error bars are the average of the ascending series and the descending series. "Pressure" was obtained from the driving intensity of the phased array. The average threshold for all participants is 46.4%. This result indicates that the focus can be presented at a pressure of 1095.5 Pa.

Discussions

As a result of the psychophysical experiment, the participant's average threshold was 46.4% in the driving intensity of the phased array. This result indicates that the minimum condition is that the focus can be presented at a pressure of 1095.5 Pa. This is the result of careful search by the user, and there are individual differences, so it is desirable to present higher pressure in the actual interface. The results also show that the pressure has a dynamic range in the region higher than the threshold. This means that the change in pressure can be perceived when the distance between the center of the focal point and

Fig. 5.15: Experimental results of threshold of unmodulated ultrasound. The pressure value is the value in the state without reflective object.

the finger is changed. This is perceived as a repulsive force to pressing a button like a key weight.

Fig. 5.16: Vertical section of the integrated pressure distribution. The plot shows the sum in the range of finger pad (10 mm).

5.2.4 Change in repulsive force to push down

The strength of the stimulus can be inferred from the applied pressure, but there is actually a process of human perception of skin displacement[51]. After this displacement, the corresponding tactile receptors are stimulated[15]. Figure 5.12 shows the dynamic range of barometric pressure that can be presented by a phased array. In the experiment described below, the haptic threshold when the static unmodulated ultrasound wave is touched by a human fingertip is investigated. This threshold was 46.4% on average for the driving intensity of the phased array. These results indicate that the prototype phased array unit presents a higher pressure than the haptic threshold pressure.

Here, the width of the region exceeding the tactile threshold is investigated. The finger pad is regarded as a disk with a diameter of 10 mm, and the integrated value of the one-dimensional horizontal pressure received in this area can be obtained from fig. 5.7.

The plot shows a vertical section of the horizontal pressure received by the finger pad. The haptic threshold at the driving intensity of the phased array was 46.4%.

This distribution (Fig.5.16) indicates that there is a peak of the pressure distribution exceeding the threshold with a width of 19 mm (-19 to 0 mm), and the pressure that changes in this range is presented to the user.

These results show that the pressure distribution generated by the unmodulated focal point can present the repulsive force against finger push-down while dynamically changing it according to the user's movement.

Presentation of click vibration stimulus

As mentioned with the description of the palm-sized midair button, LM stimulation is an effective method to expand the dynamic range of stimuli of midair ultrasound haptic displays[54]. The stimulus of the click vibration of the physical key converged in 5 ms as described above. In the case of a physical key, a click is perceived because the intensity of the vibration stimulus is sufficient to be perceived by the finger. In the case of ultrasound, the force that can be presented is lower than that of a physical key, so it is important to increase the stimulus intensity as much as possible. Click vibration in the case of airborne ultrasound can be perceived even with AM stimulation. However, it is effective to use the LM stimulus with a lower threshold to ensure that the short-term vibration stimulus is perceived.

Figure 5.17 shows the driving signal waveform measured at the transducer terminals.

Fig. 5.17: Driving voltage waveform of ultrasound transducer. The drive signal was measured directly from the transducer terminals.

Figure 5.18 shows the time average of the sound pressure distribution at the two LM focal points. Previous studies [ref LM] have shown that a stimulus with a lower perceptual threshold than AM can be presented when the LM vibration amplitude is 9 mm p-p. Even when the LM vibration amplitude is 9mm p-p, it is possible to fit the entire acoustic radiation pressure distribution in the fingerpad by adjusting the focus moving direction of the LM to the long side direction of the fingertip.

5.2.5 Conclusions

In this chapter, the haptic characteristics of physical keys operated by fingers were investigated, and the factors for designing the haptic sensation with ultrasound were described. The following factors were investigated as tactile characteristics of physical keys.

1. Contact state
2. Pressure changing due to push down
3. Click vibration

Fig. 5.18: Time average distribution of LM focal sound pressure. The LM vibration amplitude is 9 mm p-p. Time average distribution of LM focal sound pressure. The measurement surface was determined by the peak value of the sound pressure when the finger pad touched the focus.

In the case of a physical key, the vibration stimulus is not presented when presenting the contact state and the repulsive force at the time of pressing down. This is different from the conventional midair haptic sensation using vibration stimuli as haptic stimuli.

In order to resolve this difference, a method of presenting unmodulated static haptic stimuli was described. It was investigated by threshold experiments that this unmodulated static haptic sensation could be perceived reliably. This stimulus is not strong enough to be perceived while the finger is stationary, but can be perceived by actively moving and touching the finger.

In the experiment, the range in which the unmodulated stimulus could be perceived above the threshold was investigated in the prototype device. This result indicates that a dynamically changing repulsive force can be presented within a range of 19 mm, considering the results of sound pressure distribution due to reflection.

In addition, the sound profile of physical key vibration was investigated. The presentation of this click stimulus is completed in about 5 ms. Numerical experiments have shown that LM stimuli can be presented in the area of the fingertip as an element for presenting this vibration stimulus. In addition, it was shown by the vibrator drive pattern that this LM stimulation can expand the tactile dynamic range not only in the case of the palm investigated in the past but also in the case of the fingertip.

This LM stimulation may be able to stimulate meissner corpuscle located on the surface rather than pacinian deep in the skin. This enables perception in a narrow receptive field (12.6 mm^2). In order for meissner corpuscle to respond, low-frequency stimulation below 40 Hz is required. The temporal integration effect [ref], which increases the perceived amount of the vibration stimulation pulse, is also a factor that determines the click

Fig. 5.19: Sectional view of time-average distribution of LM focal sound pressure.

vibration time.

This chapter does not conduct experiments on the perception of actual clicks, but this evaluation will be performed in the next chapter.

Chapter 6

Midair Click Produced by Standing Haptic Image and Vibration

In chapter 4, a method to realize a palm-sized midair haptic button was shown. This chapter describes the click presentation method assuming button operation with a human fingertip based on the haptic presentation method described in Chapter 5. For example, when considering a group of buttons with input functions, such as a computer numeric keypad, it is desirable that these buttons be downsized to the size of the fingertip. This method has a past performance in history so far, from the typewriter to the touchpad keys.

In this chapter, the author proposes a method for presenting a click sensation to the fingertip in midair based on two types of contrastful haptic sensations. The virtual button is formed with two regions in the space. One is a standing haptic image region which has high acoustic energy density with no temporal modulation. The user can find the region by the reaction force in the active finger motion. The other one is a vibratory region placed inside the standing haptic image region. The finger receives vibratory stimulation when it enters the vibratory region. The standing haptic image region notifies the neutral position of the finger and vibratory region notifies the completion of the click action, which forms a midair haptic button. The experiments were conducted to examine the performance of the midair click. The author investigated whether a blind operation was possible and evaluated the efficiency with the operation time and the accuracy rate.

6.1 Dual-Layer Haptic Feedback

6.1.1 Midair Haptic Button

Figure 6.2 shows the configuration of the midair haptic button. The user's finger perceives the two kinds of haptic stimulation. One is an unmodulated haptic sensation perceived by active touch, and the other is a vibrotactile sensation using LM [54].

These haptic sensations were presented by the following procedure. First, an unmodulated standing haptic image [24] [26]was generated when the finger enters the determination area for button presentation. This presentation determination was always executed when buttons are placed at multiple locations in the space. In order to maximize the radi-

Fig. 6.1: Midair click using standing haptic image and lateral modulation.

Fig. 6.2: Schematic diagram of the midair haptic button. Outer region presents the contact feeling by a standing haptic image. Inner region indicates the detection area of the action completion feedback. R_{ST} was set to the same value as the half-width of the sound pressure distribution. R_{LM} is set to 1 mm and indicates the LM presentation position.

ation force presented to the fingertip, this system instantaneously generates the standing haptic image that is a single ultrasound focus. The user can actively touch this standing haptic image and perceive a spherical focus from the reaction force in the motion. In this system, when the user's finger pad moves inside and touches the inner region, a vibrotactile sensation is presented as the second haptic sensation. This vibrotactile sensation was presented by LM and notified the user of the action completion. AM is also available as the vibrotactile stimulation, but LM was adopted to produce a stronger haptic sensation. This haptic button was presented in the following procedure.

Require: $R_{ST}, R_{LM}, p_{finger}(x,y,z), p_{button}(x,y,z)$
Ensure: $p = \sqrt{p_{finger}^2 + p_{button}^2}$
if $p < |R_{ST}|$
  generate static haptic image

if $p < |R_{LM}|$ {
  destroy static haptic image
  for timer 0 **to** T_{LM} **do**
    generate LM vibration pattern
  generate static haptic image
}

6.1.2 Haptic Feedback Timing

Figure 6.3 shows the timing of LM stimulus presentation according to the finger position. The LM vibration amplitude and frequency are 4.5 mm and 200 Hz, respectively. In this system, the position of the user's fingertip is measured with a depth camera. The fingertip was assumed to be a 10 mm diameter sphere due to sensing limitations. The standing haptic image is perceived by the user's exploratory motion. At this time the system takes no action. The LM is presented when the user's fingertip touches the inner region. As a result of preliminary experiments, the LM presentation period was set to 40 msec in order to obtain a quasi-click sensation. During this period, no standing haptic image is presented. Even if the user's fingertip continues to touch the inner region, the standing haptic image was presented after the LM immediately.

Fig. 6.3: Example of haptic feedback according to finger position. Distance indicates the distance between the finger position and the center of the haptic button. Top: Phased array driving pattern, Middle and Bottom: Finger position relative to the outer region and the inner region.

Fig. 6.4: Relationship between two haptic positions and a user' s finger. Top: Haptic button. Bottom: Visual image. (a) Perception of standing haptics. (b) Perception of LM.

6.1.3 Combination of the Haptic Button and Vsual Image

Figure 6.4 shows the correspondence between the haptic button and visual image. This button was presented as a switch that is pushed vertically with the fingertip. The center of the haptic button was set to the position where the visual button was pushed down 5mm. The size of the image was determined based on a 40 kHz ultrasound wavelength of 8.5 mm, that defines the size of the standing haptic image.

6.1.4 Visual Display

A system that superimposes 3D images on midair haptic sensation was constructed in order to compare the operation efficiency of haptic buttons in blind state and the conditions with visual assistance. The 3D display was composed of 2560 * 1600 px resolution display, lenticular lens, retro-reflector and beam splitter.

6.1.5 Midair Tactile Display

Figure 6.5 shows the layout of the ultrasound phased array in the experiments. The ultrasound focus is generated by six phased arrays driven at a frequency of 40 kHz [14] [15]. The size of one phased array is 192 * 151.4 mm. The six phased arrays have 1492 transducers, and the output of maximum radiation force is 96 mN. The XY coordinate of the focal point was determined by the position of the user's finger. The finger position was measured by Realsense Depth Camera SR300 (Intel). Figure 6.6 shows the appearance of the device from the user's viewpoint.

Fig. 6.5: Schematic diagram of prototype device. (Front view)

Fig. 6.6: Schematic diagram of prototype device. (Side view)

6.1.6 Image and Haptic Calibration

The phased array and the 3D display were arranged considering the viewing angle of the depth sensor and the acoustic path of the ultrasound. The distance of the space expressed by the depth sensor and the 3D display was scaled to the physical distance of the workspace of the phased array unit. In this system, each device was controlled using Unity gaming engine.

6.2 Experiment

In this experiment, we evaluate the speed of the user' s midair button operation. The author also evaluate the user's finger position when the two kinds of haptic sensations were perceived by the fingertip. Next, the author evaluate whether the user could search and operate the haptic buttons when the presentation position has changed in the horizontal direction. Finally, the author evaluate whether the indicated button can be operated from the three buttons presented simultaneously. All tests are conducted in two ways: visual and haptic conditions and blind conditions. Informed consent was obtained from all individual participants included in the study.

6.2.1 Experiment 1: Single Touch and Continuous Touch

Figure 6.7 shows the experimental setup. Figure 6.8 shows the experimental procedure presented to the participants. Before the experiment, the experimenter explained that the midair button had two types of haptic sensations in the vertical direction and that the haptic stimulus indicating the action completion was given when the button was pushed down with the index finger. The participant is allowed to confirm these haptic sensations before the experiment by operating the midair button. The participant places their finger at the start position 40 mm away from the button in the vertical direction. The participant starts the experiment by pressing a computer key with their left hand. These procedures are common to the following two tasks. The participants were 8 males with an average age of 25.4 years and a standard deviation of 2.1 years. One of the participant is a left-hander. One of the participant has no experience of ultrasound haptics.

(a) Single Touch

The participant is instructed to immediately push the button down and vertically from the starting position after "Push" appears on display. The participant perceives the LM and immediately returns their finger to the start position. The time from when "Push" is displayed until the haptic sensation is presented to the participants is measured. Then, within 2 seconds, the computer automatically displays instructions to the participant, and the participant repeats a series of sequences. Participant's response is an average of 10 times.

(b) Continuous Touch

First, the participant lowers their finger from the start position, and places the finger on the action completion position of the midair button. The measurement of the experiment

Fig. 6.7: Photograph of the experimental environment.

Fig. 6.8: Experimental procedure. Top: In the case of a single touch, the time from the start position to the completion of the operation is measured. Bottom: In the case of continuous touch, the time between the completion of the current operation and the completion of the next operation is measured.

starts at this time. The participant returns the finger to the upper contact position and confirms the standing haptic image with the finger pad. After that, the participant lowered the finger to the lower action completion position and immediately returns the finger to the upper contact position when a change in haptic sensation is felt. The participant is instructed to perform this procedure continuously. Participant's answer is the average of 10 times.

6.2.2 Experiment 2: Identification of the Haptic Sensation

The experimental procedure is as follows. In addition, the participant explained that the midair button was placed at the lower-left position from the start position of the experiment, as shown in fig. 6.9. In this experiment, only the center button is presented.

(a) At the start of the experiment, the participant places the index finger of the right hand at the position where the text (Start) appears in the upper right of the display, as shown in Fig. 6.9. The experiment starts when the participant presses "1" of the numeric keys on the computer. The numeric keypad is operated with the participant's left hand. At this time, a measuring timer is started.

(b) The participant moves their finger from the start position and aligns their finger pad with the contact position above the button. The position is answered by pressing "2" on the numeric keypad.

(c) The participant places their finger on the action completion position at the bottom of the button and presses "3" on the numeric keypad to answer that position. At this time, the time required for the participant's operation is recorded, and the timer is reset. After that, the participant moves their finger to the start position, and the next measurement starts.

The participant operates the button shown 10 times, according to the above procedure. First, an experiment in the case of presenting a visual image is performed, next an experiment in a blind state only haptics is performed. During the experiment, participant wears headphones and listen to white noise to prevent the driving sound of the phased array. There is no time limit for answers.

6.2.3 Experiment 3: Randomly arranged single buttons

In this experiment, a single button is randomly presented at three positions. The experimental procedure is the same as in Experiment 2. Figure 6.9 shows the button layout. Before the experiment, the experimenter explains that the haptic button is presented without the visual image at one of the three points arranged on a horizontal line. The participant explorers the button position with their finger and answers the position. Buttons are presented three times at each position.

6.2.4 Experiment 4: Multi-buttons placed simultaneously

In this experiment, three buttons are presented simultaneously, and the participant operates the button at the position indicated by the text message. The participant indicates the button position to be operated with text such as "Left", "Center", and Right". The position is indicated randomly, and the buttons are presented three times at each

Fig. 6.9: Users view of the prototype display. x = 20 mm. The text area shows "Start", "End" and "Message indicating button position".

position.

Fig. 6.10: Response time for blind condition. Operation time of the single touch. The average value is 2.92 sec.

6.3 Results

6.3.1 Experiment 1: Single Touch and Continuous Touch

Figure 6.10 and 6.11 show the operating time of single touch and continuous touch in the blind state. The error bar indicates the standard deviation. The author conducted T-tests corresponding to the operation time of each participant. The p-value for this condition was 0.0038 or less. Figure 6.12 and 6.13 show the operating operating time of visual and haptic condition.

6.3.2 Experiment 2: Identification of the Haptic Sensation

Figure 6.14 and 6.15 show the positions of two types of haptic sensations perceived by the participant. "Distance" indicates the distance from the origin of the phased array unit. The error bar indicates the standard deviation.

(a)The average values of the contact position and action completion position are 11.5 mm and -1.4 mm, respectively. The average standard deviation of all participants is 1.84 mm.

(b)The average values of the contact position and action completion position are 11.9 mm and -3.2 mm, respectively. The average standard deviation of all participants is 3.40 mm.

Fig. 6.11: Response time for blind condition. Operation time of the continuous touch. The average value is 1.20 sec.

Fig. 6.12: Response time for visual and haptic condition. Operation time of the single touch. The average value is 3.44 sec.

Fig. 6.13: Response time for visual and haptic condition. Operation time of the continuous touch. The average value is 1.60 sec.

Figure 6.16 and 6.17 show the operation time for each participant. Error bars indicate standard deviation. The response time for the blind condition increased by 2.7% compared to the visual and haptic condition.

6.3.3 Experiment 3: Randomly arranged single buttons

Figure 6.18 and 6.19 show the operation time for each participant. The response time for the blind condition increased by 8.1% compared to the visual and haptic condition.

6.3.4 Experiment 4: Multi-buttons placed simultaneously

Figure 6.20 and 6.21 show the operation time for each participant. The response time for the blind condition increased by 45.4% compared to the visual and haptic condition.

Figure 6.22 shows the accuracy rate and selectivity of each button.

Fig. 6.14: Answer position by a fingertip in the depth direction of the button. (Visual and haptic condition) The average standard deviations of all participants in the horizontal direction is 4.10 mm.

Fig. 6.15: Answer position by a fingertip in the depth direction of the button. (Blind condition) The average standard deviations of all participants in the horizontal direction is 2.18 mm.

Fig. 6.16: Required time to move the finger from the start position to the action completion position. (Visual and haptic condition) Experiment 2. The average operation time is 8.94 sec.

Fig. 6.17: Required time to move the finger from the start position to the action completion position. (Blind condition)) Experiment 2. The average operation time is 9.18 sec.

Fig. 6.18: Required time to move the finger from the start position to the action completion position. (Visual and haptic condition) Experiment 3. The average operation time is 8.01 sec.

Fig. 6.19: Required time to move the finger from the start position to the action completion position. (Blind condition) Experiment 3. The average operation time is 8.66 sec.

Fig. 6.20: Required time to move the finger from the start position to the action completion position. (Visual and haptic conditi on) Experiment 4. The average operation time is 8.31 sec.

Fig. 6.21: Required time to move the finger from the start position to the action completion position. (Right: Blind condition) Experiment 4. The average operation time is 12.08 sec.

Fig. 6.22: Accuracy rate of multi-button and selectivity of each position. 100% indicates the number of button presentations at each position. The accuracy rate of Left, Center and Right are 95.8, 58.3, and 75.0%. The selectivity of Left, Center and Right are 145.8, 66.6, 83.3%.

Fig. 6.23: Result of Likert Scale Questionnaires.

6.3.5 Likert Scale Questionnaires

The author conducted a Likert scale questionnaire to examine the participants' opinions about the midair button. Evaluation is performed by 7-Point Likert Scale. The participant answers the following questions.

Q1. Did you perceive that you pressed the button?
Q2. Did you perceive a click sensation when you pressed the button?

1. Strongly disagree
2. Disagree
3. Somewhat disagree
4. Neither agree nor disagree
5. Somewhat agree
6. Agree
7. Strongly agree

Figure 6.23 shows the results of the Likert scale questionnaire. The error bar indicates the standard deviation. In Question 1, all participants answered 7.

6.4 Discussions

6.4.1 Experiment 1: Single Touch and Continuous Touch

This result of fig. 6.10 and 6.11 are thought to be because the user could perceive two points in the space by presenting two haptic sensations. Single touch is not an impossible operation even with a single conventional AM stimulus. This operation was made possible by presenting two types of haptic sensations according to the operation timing. The user can perform both single-touch and continuous-touch conditions with the fingertips with the wrist almost fixed. Under these conditions, it is possible to memorize and manipulate haptic positions without visual guidance. As a result, in the blind state, the average operation time is 17.5% and 33.3% shorter for single touch and continuous touch, respectively.

6.4.2 Experiment 2: Identification of the Haptic Sensation

The result of Fig. 6.14 and 6.15 show that the participant was able to perceive two types of haptic sensations accurately. The LM focal plane answered at the height of 11.3 mm when the image was presented and 8.86 mm when under blind conditions.

This result shows that the button operation is deeper under blind conditions. However, participants still feel LM stimulation and can perceive two-step haptic feedback. As an author's subjective comment, the LM focal plane has an area that has a width in the height direction. The LM stimulation is performed in a short time by contact between the virtual fingertip and the LM Region, but the perceived focus has a width of at least 40 kHz ultrasound wavelength of 8.5 mm. In this width range, the stimulus is felt even if the fingertip has pushed the button deeply.

One of the reasons that the answered positions have horizontal variations is that the button edges cannot be reproduced. In the case of a computer keyboard, there is a clear edge between the keys that can be perceived by the fingertip, allowing the user to be close to the finger is off the center of the button. A slight bump toward the center of the key has the effect of guiding the finger pad to the center of the key. Such haptic sensation has not been reproduced in the current midair haptic button.

There are two possible reasons why the operation takes about 10 seconds. One is that midair ultrasound cannot reproduce a strong repulsive force. The other is that we need to press while holding our hands and fingers in the air. If the haptic sensation is sufficient to stop the finger when the operation is completed, the operation will be faster. Despite these limitations, this midair haptic button allows the user to perceive the button position with a smooth haptic sensation without vibration and presents a quasi-click sensation with a short vibration.

6.4.3 Experiment 3: Randomly arranged single buttons

The response speed in the blind condition increased by 24.6% compared to the visual and haptic condition. Nevertheless, the accuracy rate for participants with this condition is 100%. The participant can search and operate a single midair haptic button in the blind

state.

6.4.4 Experiment 4: Multi-buttons placed simultaneously

The results in Fig. 6.22 show that the participant cannot always press the button at the indicated position. Each button is correctly operated with a probability of over 58%, but in other cases, the user lost the finger position for the three buttons. The correct answer rate with visual assistance is 100%.

The center button has the lowest correct answer rate. This is probably because "Left" and "Right" are the buttons that touch for the first time when searching with a finger from a non-haptic area. These two edge positions are correctly answered if the user can perceive that the haptic sensation has changed from OFF to ON without having to remember the current finger position. On the other hand, in the case of the center, it is necessary to operate at the position where the same haptic sensation as the target haptic sensation is felt next to it. At this time, the user is required to search by moving the finger beyond the maximum distance between the Left and Right buttons and to memorize the positions of the three buttons temporarily. If either of these conditions is not satisfied, the user should operate Center, but will operate Left and Right.

In setting up this experiment, the author conducted a preliminary blind experiment with nine buttons arranged in a 3x3 layout assuming a numeric keypad like a numeric keypad. At this time, the button spacing is the same as Experiments 3 and 4. In this case, it takes a long time and a wide space search compared to the case of three buttons, and the above search and memory becomes difficult, so the author limited the number of buttons to three and conducted experiments.

6.5 Couclusions

In this study, a midair haptic button using two-step feedback was proposed and evaluated. A user can actively search for the button position with the fingertip and hold the contact state. The standing haptic sensation was presented continuously when the user's finger is in contact with the outer region with a diameter of 20 mm. Action completion was indicated when the user's finger is in contact with the 1 mm diameter inner region. The user' s fingertip could move to the inner region and return to the button surface in 1.20 sec in average. The experimental result of blind single button shows standing haptic image and LM stimuli are perceived independently with standard deviation errors of 2.08 mm (Width) and 3.14 mm (Height), respectively. Each haptic sensation can be identified in a single trial without symbolic learning of the haptic difference. Participants were able to select and operate three buttons arranged at 20 mm intervals in a blind state, and the average correct answer rate of the button position selection was 95.8, 58.3, 75.0%. As the conclusion, identifying the neutral position and action completion was intuitive and the time to return after clicking was as short as 1.2 sec. The clicking for a single button was very easy but blind selection task from three buttons were not very easy for 2 cm button interval.

Chapter 7

Conclusions

In this thesis, the methods to realize a clickable midair haptic interface was indicated and the practical methods were discussed. In Chapter 1, the significance of using haptic sensation is shown based on applications, and the necessity for future haptic research is shown as an example of supporting human behavior. Here, the author explains the function of the haptic sensation that the author uses without being conscious of daily life and discusses how to reproduce it artificially.

Chapter 2 explain the principles of human haptic sensation that are currently being interpreted. Here, a limited explanation is given of the skin sensation that enables humans to perceive haptic sensations with their hands. These findings show the spatio-temporal characteristics of haptics perceived by skin mechanoreceptors. Next, the current state of haptic presentation is introduced. Haptic presentation devices are reviewed by classifying them into installation type, wearing type, and skin stimulation type. Here, the author shows that there are a wide variety of methods for presenting haptic sensations to humans, and the issue of this thesis is a representative example of midair haptics that is skin-stimulated. The research of haptic presentation is carried out according to the specific use that humans feel haptic sensation, and it is important that it is very difficult to develop a general-purpose haptic presentation method. Next, a method for generating acoustic radiation pressure using ultrasound waves is described. The physical explanation of acoustic radiation pressure is given, and the principle of a phased array composed of ultrasound transducers is described. The fundamental method of ultrasound phased array in this thesis was constructed by Iwamoto et al. And developed to the current system by the extension of Hoshi, Hasegawa, Inoue, et al. Here, distance attenuation, focus diameter, and directivity that determine the performance of a phased array, which are important in terms of haptic presentation were explained. Distance attenuation indicates the workspace for using a phased array. The focus diameter numerically expresses the half-value width of the acoustic radiation pressure distribution and indicates the resolution of haptic presentation. Directivity, as distance attenuation, is a factor that determines the phased array workspace and affects the acoustic radiation pressure distribution at the focal point. From these explanations, the performance of an actual device that presents a midair haptic sensation using ultrasound is shown, and the basic performance of the haptic application to be realized in the following chapters is clarified.

In Chapter 3, the author discusses a virtual midair haptic button operated with the palm of the ultrasound phased array described above. Midair haptic sensation is generated

by nine phased array units. The phased array unit is installed on the floor, and the application is determined on the assumption that it would be used on the desk when the user sat down. This palm-sized haptic button consists of two haptic layers in midair. The upper layer presents the AM vibration stimulus used conventionally, and the lower layer presents the LM stimulus presenting a stronger haptic sensation. The design concept of this palm-sized button is that when pressed down, it presents a strong haptic sensation with LM, and the user can stop the hand at the LM position. In the experiment, it is clarified that the user can perceive two haptic layers and that the user can perceive the LM stimulus with strong haptic sensation when the button operation is completed. Besides, it is clarified that the user can operate the palm-sized buttons arranged with a 10 cm interval with the eyes closed.

In Chapter 4, the author discusses the method of presenting the above-mentioned midair haptic buttons superimposed on the midair visual image. An aerial image is generated by changing the projection direction of a two-dimensional display image with a lenticular lens. By switching the image, the user stereoscopically views using binocular parallax. The presentation surface of the image with parallax is imaged in the air using a retro-reflector and a beam splitter. As a result, the user perceives a 3D image in midair. This visual image space is calibrated with the haptic image space of six phased array units, and the user can touch the virtual object with the virtual finger tracked by the depth camera. In the experiment, it is clarified how the virtual object is perceived by the user who moves the hand by the calibrated visual image and the haptic image.

In Chapter 5, the haptic characteristics of physical buttons were investigated in order to reproduce the virtual buttons operated by fingers with the midair haptic sensation. In addition, a presentation method of ultrasound haptics to reproduce these haptic characteristics with midair haptics was described. The investigated haptic characteristics of the physical buttons were contact state, repulsive force, and click vibration. Contact state and repulsive force were measured using a load cell as "force". As a means to present this haptics by ultrasound, a method of presenting unmodulated static stimuli without using vibration was described. It was confirmed that the haptic threshold of unmodulated stimulation by 40 kHz ultrasound was equivalent to 46.2% driving strength in a setup using 1492 transducers. Click vibration was measured using a standard microphone. It was confirmed that the click vibration stimulus converged in 5 ms. As a method of presenting this stimulus by aerial tactile sensation, the sound pressure distribution of the LM focal point of the same order as the finger pad size was confirmed by simulation.

In Chapter 6, the author discusses midair haptic buttons operated by the user's finger. This button is designed with a size of 20 mm in consideration of the size of the fingertip and the current ultrasonic focus size (8.5 mm). This method uses the standing wave of the sound wave to present the touch feeling of the button with a smooth touch without audible sound while maintaining the resonance frequency (40 kHz) of the ultrasound transducer. With the buttons based on the standing haptic image, the user can perform active haptic movements and feel the repulsive force due to the acoustic radiation pressure. This button presents the pulsatile LM vibrotactile sensation when the user presses it down with a finger. The temporal switching between the standing haptic image and the LM vibration haptic sensation presented the user with a haptic sensation that changes dynamically at one point in space, enabling a new midair ultrasound haptic sensation that has never been touched before. It was clarified that the midair button designed here can be searched by

hand and clicked even when the user cannot visually see the button.

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