2段階触覚フィードバックを用いた空中クリック

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Midair Click Using Two-State Haptic Feedback

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本研究では，我々は強度と質の異なる2種類の触感に基づいて，空中で擬似クリック感を提示する方法を提案する．空中触覚ボタンは，空間中の2層の触覚領域により提示される．ユーザの手はセンサーにより追跡され，手の位置に応じて2つの方法で刺激される．ユーザの手が上層にあるとき手の皮膚に弱い触覚が提示され，下層にあるとき強い触覚が提示される．これらの2つの状態は，ニュートラルな接触と操作完了を示す．この空中クリックは，皮膚における超音波の焦点の空間変調が，固定された位置の振幅変調よりも強く知覚される近年の発見により可能になった．我々は，2つの触覚層を知覚できるかを確認する実験を行ない，さらにブラインド状態でのボタン選択操作が可能かどうか調査した．この空中クリックは，視覚や聴覚フィードバックを必要としない空中インタフェースに応用できると考えられる．

In this study, we propose a method to present a non-contact tactile click sensation using airborne ultrasound. This midair click sensation is generated based on two types of tactile sensations having different intensity and quality. We consider two-layers of regions in the space that forms a virtual button. A user's hand is tracked by a sensor and stimulated by the two methods according to the hand position. Within the two tactile layers, a weak or strong tactile sensation is presented on the hand skin when the user's hand is in the upper or lower layer, respectively. These two tactile sensations correspond a contact and action completion. This midair click was enabled by the recent finding that an ultrasound focus motion on the skin produces a stronger perception than amplitude modulation given at a constant position. We conducted experiments to confirm whether two haptic layers can be perceived. In addition, we investigated whether a blind operation of button selection can be performed. This midair click can be applied to midair interfaces where no visual or auditory feedback.

Key words 空中触覚，クリック感，空中超音波，音響放射圧
midair haptics, click sensation, airborne ultrasound, acoustic radiation pressure

1 Introduction

An important tactile function of mechanical input devices, such as a keyboard or a mouse, is to provide users with two sensations corresponding to two states, one indicating a neutral position and the other an action completion position. When a user operates a mouse, the user can hold their finger in the neutral position by perceiving the tactile sensation of the static contact between the finger and the device. Owing to this neutral position, the user can quickly click and convey an input intention to the computer. With this click feedback, a user can reliably perceive action completion by touch.

Such haptic feedback is an effective technique for performing reliable operations in midair haptics. This feedback informs the user's skin of a contact sensation between the virtual object and the hand positioned in a midair gesture.

Midair haptic feedback can be provided by an air vortex[1)], an air jet[2)], and ultrasound[3)~5)]. Midair haptics using ultrasound can generate a localized pressure distribution on the skin and present a sufficiently perceptible tactile sensation by vibrational stimulation using amplitude modulation.

With this feedback, the user can quickly and comfortably operate an aerial virtual button even in a blind state. This operation requires a slight tactile sensation indicating contact between the skin and the device and a tactile sensation indicating operation completion that can be clearly distinguished from the contact sensation. However, it has been difficult to provide such haptic feedback because the force of the ultrasound stimulus is weak and it cannot clearly generate two distinguishable states with different qualities and intensity in haptic stimulus.

In this paper, we propose a method to generate a quasi-click sensation in the air using unidirectional lateral modulation (LM), which is one of the recently discovered spatial modulation methods[6)7)]. Using vibration stimulation is effective for efficiently stimulating human skin[8)] on devices such as midair tactile displays. Amplitude modulation (AM) has been used as a method for inducing a vibration stimulus in a user. LM can present a tactile sensation that is 10 dB or more stronger than AM. AM mainly stimulates the pacini corpuscle, tactile mechanoreceptors. In contrast, LM stimulates the mechanoreceptors on the surface of the skin, so that in addition to a difference in tactile intensity, LM can cause a tactile sensation different in quality from AM.

The concept of the quasi-click is shown in Fig. 1. Here, we consider a two-layer region in space. The position of the user's hand is tracked with a depth camera, and AM and LM stimuli are presented depending on whether the hand is on the upper layer (AM layer) or the lower layer (LM layer). The user can confirm the position of the virtual button with the sensation of AM and perceive the completion of the button operation with a perception of LM. These two types of haptic feedback present two states: contact, such as a mouse click, and action completion. In addition, this technique can be applied as an aerial version of full/half press, such as a shutter button on a camera, or as a pressure-sensitive touch on a touchpad.

The rest of this paper is organized as follows. First, the implementation of this two-layer tactile button is described. An experiment was performed to see if two tactile layers could be perceived. Next, it was investigated whether blind operation of the button selection can be performed.

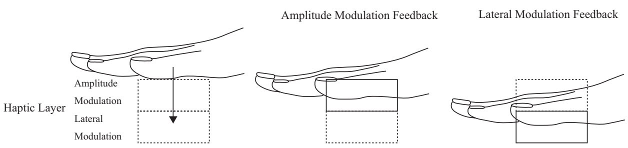

Fig. 1　Midair click using dual-layer haptic feedback. The intensity and quality of haptic feedback are switched according to the hand position.

2 Principle of Midair Tactile Display

Acoustic Radiation Pressure

The relation between sound pressure and radiation pressure[9)10)] is summarized below for the readability of the manuscript. The acoustic radiation pressure P [Pa] is proportional to the sound energy density given by

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

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 between 1 and 2 depend on the reflection properties of the object surface. When ultrasound propagates through 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, we can control the radiation pressure P by controlling the ultrasound pressure p.

Ultrasound Phased Array

Figure 2 shows the appearance of a phased array. The ultrasound focus was generated using nine units of phased arrays driven at 40 kHz[11)~13)]. The device was composed of 2241 transducers. The focal point could be moved freely by controlling the phase of the ultrasound wave emitted from each transducer. The aperture of the phased array was 576 mm (W) × 454.2 mm (H).

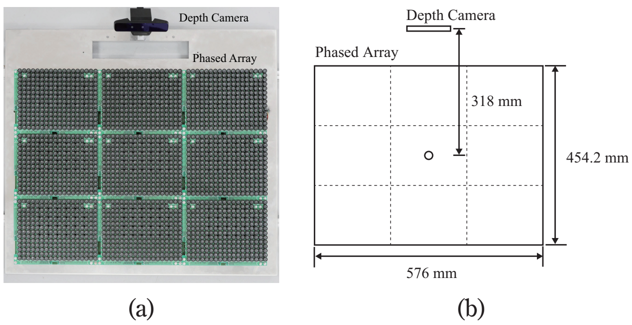

Fig. 2　Prototype device. (a) Photograph of the phased arrays. (b) Schematic diagram of a nine-unit phased array and depth camera.

3 Dual-Layer Haptic Button

Lateral Modulation

The LM modulates the focal point of the ultrasonic wave in one direction using two parameters, the LM vibration amplitude and the LM frequency. The LM oscillation amplitude indicates the spatial movement width of the focal point. The LM frequency indicates the moving speed of the focal point.

The instantaneous values of the sound pressure at AM and LM are as follows.

$$\begin{aligned} p_{AM}(t) &= p_0 \sin(\omega_c t)\sin(\omega_m t), \\ p_{LM}(t) &= p_0 \sin(\omega_c t) \end{aligned} \tag{2}$$

Here, the radiation pressure is proportional to the acoustic energy density and is as follows.

$$P_{AM}(t) = \alpha \frac{\overline{p_{AM}^2}}{\rho c^2}$$
$$P_{LM}(t) = \alpha \frac{\overline{p_{LM}^2}}{\rho c^2} \quad (3)$$

where α is a constant. Assuming that $\overline{p_{AM}^2}$, $\overline{p_{LM}^2}$ indicates a time average, the relationship of $P_{LM} = 2P_{AM}$ holds. LM can generate twice the radiation power of AM on skin over an average long enough for the modulation frequency of AM.

Dual Haptic Layer

Figure 3 shows the configuration of the dual-layer haptic button. The user's hand position was measured, and stimulated by AM and LM when the hand enters upper and lower layers, respectively. The hand position was used only for layer switching. The focal position of the AM/LM layer was fixed. The AM frequency was 150 Hz. In LM, the LM vibration amplitude and the frequency were 4.5 mm and 50 Hz, respectively, and 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 at maximum intensity. In this experiment, the driving intensities of the phased arrays in the AM and LM layers were 10% and 100%, respectively.

The AM and LM stimuli conveyed two states - a neutral position and action completion, respectively, and produced a quasi-click sensation. To increase the contrast between the two stimuli, we selected specific AM and LM frequencies, such that the tactile feel quality and perceived strength were clearly different following the previous study[7].

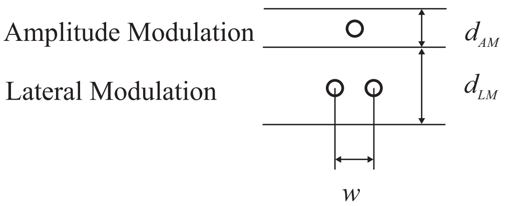

Fig. 3　Schematic diagram of the dual-layer haptic button. The depth d of each layer indicates the region where the AM or LM stimulus is presented. w indicates a value twice that of the LM vibration amplitude.

Acoustic Radiation Pressure Distribution

In this section, the acoustic radiation pressure distributions for the tactile presentations are shown. Figure 4 and 5 are the acoustic radiation pressure distribution shown by the AM and LM layers of the haptic button in Fig. 3, respectively. The focal length is 600 mm, which will be used in the next user study experiment.

Figure 5 shows the time average of the instantaneous sound pressure distribution of the two focal points of the LM stimulus for a sufficiently long period.

Figure 6 shows the sound pressure distribution in the x-z plane for a single focus.

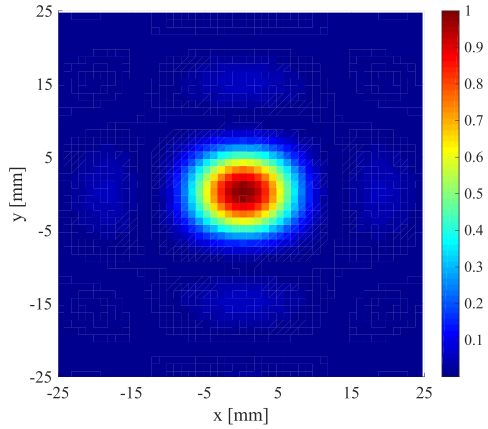

Fig. 4　Simulated normalized acoustic radiation pressure distribution. (AM Layer, Focal distance = 600 mm) The width of the zero points in horizontal section of this distribution is 26 mm.

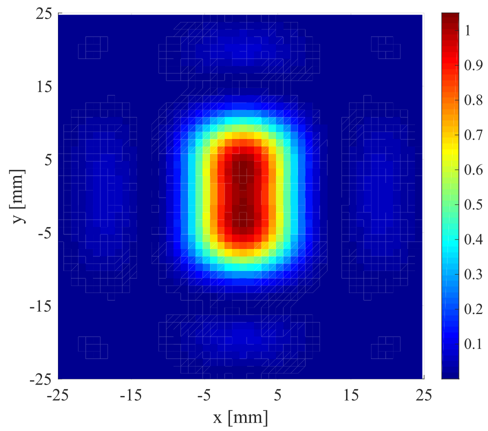

Fig. 5　Simulated normalized acoustic radiation pressure distribution. (LM Layer)

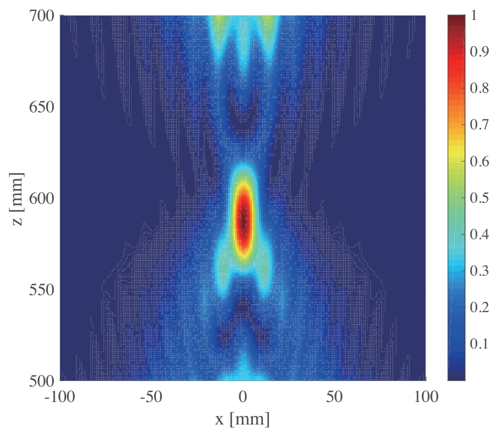

Fig. 6　Simulated normalized acoustic radiation pressure distribution. (AM Layer, x-z plane, Focal distance = 600 mm)

4 Experiment

In this experiment, we presented the tactile sensations of the above-mentioned haptic button and evaluated whether the difference could be perceived by the palm. We presented three buttons in space and investigated whether the buttons could be operated in a blind state. Informed consent was obtained individually from all participants included in the study.

Figure 2 shows the experimental device. The XY coordinates of the focus were determined by the position of the user's hand. The hand position was measured using a Realsense Depth Camera SR300 (Intel).

A. Experiment 1: Identification of the tactile sensation

The experiment setup is shown in Fig. 7. The experimental procedure was as follows. Before the experiment, it was explained to the participants that the haptic button consisted of two layers and they were then 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, as shown in Fig. 8. They wore headphones and listened to white noise to block 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 positions of the participants were guided manually to the starting position by the examiner. 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 then 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. No time limit was imposed. The answers were obtained from an average of three trials. There were a total of eight participants. All participants were male, aged 23–27 years.

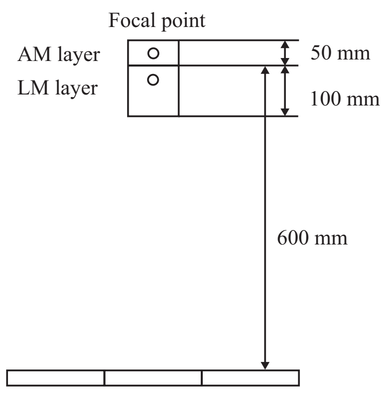

Fig. 7 Experimental setup (front view). The top-surfaces of the upper (AM) and lower (LM) layers were located at heights of 625 mm and 575 mm.

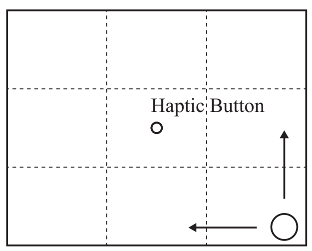

Fig. 8 Experimental setup (top view). The participants placed their hands in the initial position (Z = 800 mm) and started the experiment.

B. 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 9 shows the arrangement of the haptic buttons. The experimental procedure was as follows. Before the experiment, the participants were informed that three buttons were located 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 using letters and orally, which button out of the three they should select. With their eyes closed, they placed their right hand in the same position as in experiment 1 and identified the position of the instructed button in the same manner as in experiment 1. Next, they identified the 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.

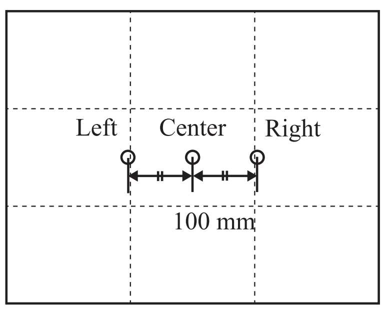

Fig. 9 Experimental setup (top view). Three buttons are arranged at intervals of 100 mm.

5 Results

A. Experiment 1

Figure 10 shows the position of the haptic layer as 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.

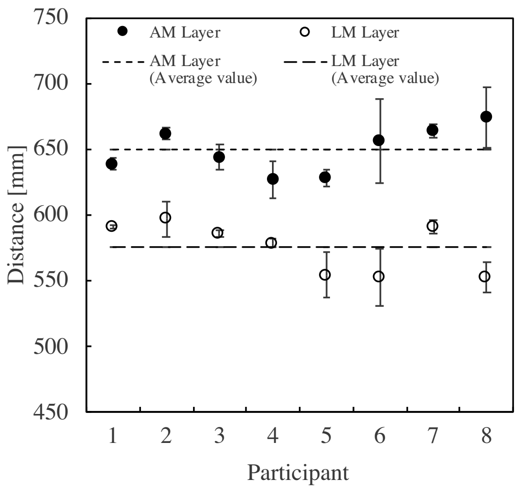

Fig. 10 Perceived top surfaces of two layers. Error bars show the standard deviations in the position that the participants identified.

B. Experiment 2

Figure 11 shows the average values of the answers for each button position of all participants. The average values of the perceived left, center and right button’s X-axis were −95.9, 1.1 and 102.5 mm, respectively.

Figure 12 shows the position of the tactile button as perceived by the palm. The origin of the graph corresponds to the X-, Y-coordinates of the center of the phased array.

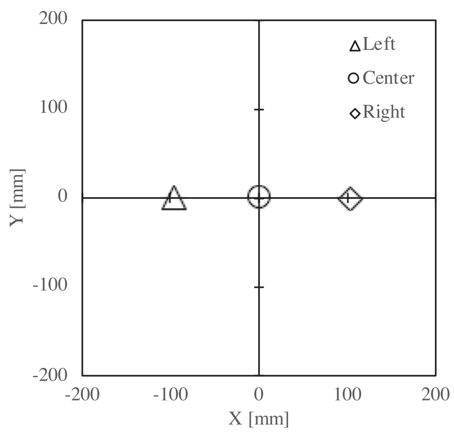

Fig. 11 Three perceived focal points. The plots show the average values of all the participants.

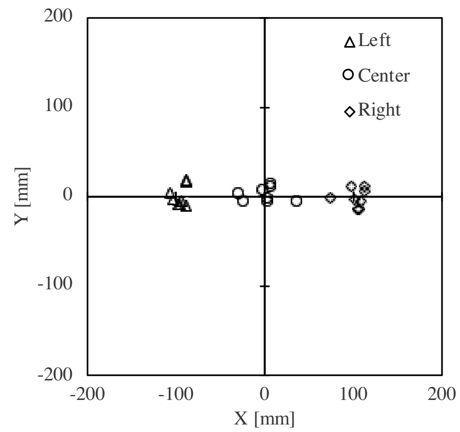

Fig. 12 Three perceived focal points. The plots show the answered value of the eight participants.

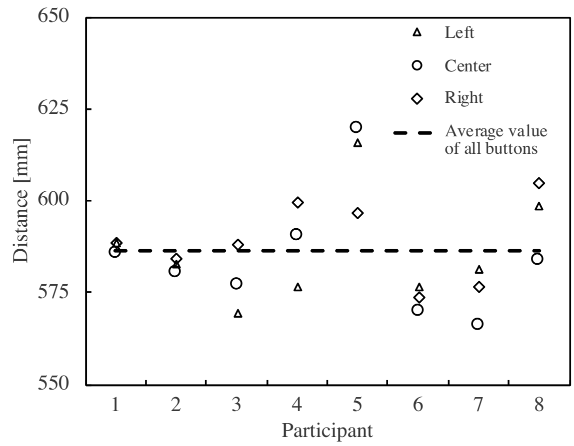

Fig. 13 Perceived top surface of the lower layer. The average value of participants’ answers for all buttons was 586.4 mm.

Figure 13 shows the Z-axis value of the participants’ answers. The average values of the perceived left, center and right button’s Z-axes were 586.2, 584.1, and 586.0 mm, respectively. The ranges in the answers regarding the heights of the buttons were 46.3 (left), 53.7 (center), and 31.1 mm (right), respectively.

6 Discussions

Experiment 1:

The results depicted in Fig. 7 show that the participants perceived the surface of each layer surface correctly. The surface of the LM layer was set to a position of 600 mm, while the average height perceived by the participants was 575.5 mm. This indicates that the perceived button was felt at a lower height than the author’s assumption. However, this result still suggests that the user’s hand stopped at the

LM layer surface and felt a two-step feedback. This indicates that the differences in stimulation between the AM and LM layers could be 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 a button compared with the perception in the AM layer. No repulsive force exists to push the hand back, but when moving from the AM layer to the LM layer, a weak click feeling could be felt by the palm.

Experiment 2:

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 all 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 with an improved button placement.

The result of Fig. 10 shows the differences in the position of the LM layer as 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, we confirmed that the participants could stop the button operation within the specified range after receiving two-step feedback.

7 Conclusions

A dual-layer haptic button placed in midair was proposed and evaluated in this study. A user finds the button position and its surface by AM stimulation of the user's palm. AM stimulation was provided when the user's hand was in the AM (upper) layer of a thickness of 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 a thickness of 100 mm.

The experimental results indicated that the top surfaces of the AM and LM layers could be recognized separately, within the errors of 12.4 and 9.4 mm, respectively, in the standard deviation. Each haptic layer could be identified without symbolic learning of tactile pattern differences. In addition, three buttons were explored within errors of 7.2 (center), 20.2 (left), and 12.9 mm (right) in the standard deviation, and the accuracy rate was 94.4%. The participants in the blind state could explore by hand where a specified button out of three was located.

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