Third Joint Eurohaptics Conference and Symposium on Haptic Interfaces
for Virtual Environment and Teleoperator Systems
Salt Lake City, UT, USA, March 18-20, 2009

Virtual Active Touch: Perceived Roughness Through a Pointing-Stick-Type Tactile Interface

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ABSTRACT

For realizing a tactile display for a handheld device, active touch movement should be represented on a small interface. We propose the addition of a tactile feedback mechanism for a pointing-stick-type (PS) input device. In this study, we describe a method for enabling virtual active touch with a cursor on the screen operated by the PS-type tactile interface without actual touch movement. First, to validate our concept, we compared tactile detection capabilities of roughness information represented by the PS-type tactile interface and the interface with actual touch movement. The experimental results showed that the PS-type tactile interface exhibited almost the same ability as the interface involving actual touch movement. We also found that the force-to-velocity scaling factor of the cursor movement had a significant influence on the roughness detection capability of the interface. In addition, to apply our method to devices having small screens, such as mobile phones, we tried to restrict the cursor velocity in proportion to the object size that appears on the screen. The experimental results showed that the PS-type tactile interface can represent almost the same roughness information as the original object size.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; H.1.2 [Information Systems]: User/Machine Systems—Human factors

1 INTRODUCTION

Many handheld devices such as mobile phones, PDAs, and portable media players have become popular in our life. The addition of display functions to handheld devices is expected to enhance their usability and make them enjoyable in terms of enabling physical interaction with virtual objects. This study describes the development of a compact input device using a tactile display method, in order to obtain rich tactile information from handheld devices.

A touch panel with vibratory tactile feedback mechanism is a possible solution for enhancing the usability of handheld devices. For example, the touch panels of several commercial mobile phones have been installed with tactile feedback. Immersion Corp. has developed tactile feedback technologies for touch screens [1]. Poupyrev *et al.* have developed "TouchEngine" that can generate a variety of tactile sensations such as clicking of switches by causing vibration the body case of a handheld device to vibrate [2]. However, the vibration of the touch panel or the body case has some limitations in their actuation to provide rich tactile information, which requires a large part of the body to vibrate. On the other hand, Luk *et al.* [3] have developed a handheld tactile display using a compact tactile stimulator known as "STReSS2" [4], which enables lateral skin stretch. The compact stimulator was mounted on a slider-type controller on the side of a handheld device and actuated in response to the movement of a finger placed on the controller. The objectives of their study were to present symbolic information as a haptic icon and enhance the usability of handheld devices.

The objective of this study is to display rich tactile information such as perceived texture on handheld devices. The authors have focused on the following two important key technologies to describe various tactile sensations 1) skin stimulation methods and 2) relationships between skin stimulation and active touch movement. Konyo *et al.* have developed stimulation methods to generate multiple tactile sensations by combining vibratory stimulations in different frequency ranges [5]. These stimulations were based on the frequency response characteristics of the human tactile receptors. They have also developed a wearable tactile display to enable an active touch interaction using high polymer gel actuators. By creating a relationship between stimulations and touch movement, they could display complex textures feelings like clothes. Konyo *et al.* have also proposed a friction display method using high frequency vibratory stimulations based on stick-to-slip contact transitions in response to touch movement [6]. Their developed tactile displays also showed that natural tactile sensation could be produced by generating uniformly distributed vibrations in the skin contact area. This implies that even a single vibrator can produce a tactile sensation if it is actuated in response to the touch movement. However, in the case of a handheld tactile display, one critical problem is how to enable touch movement on a small body. For example, the touch screen of mobile phones lacks sufficient area to enable touch movement. Therefore, this small area causes a lack of immersive sensation on the screen.

This study proposes an approach to use cursor movement on the screen as moving a fingertip on the screen, without actual performing touch movement. We define this approach as "virtual active touch". The cursor is operated by a pointing-stick-type (PS) input device, which is a force-input type pointing device located on a fixed point such as an arrow pad. A vibrator is mounted on the PS and is actuated in response to the cursor operation to provide tactile feedback. This approach solves the problem of physically touching the handheld device, because a direct touch is not required. In addition, the virtual active touch approach is more flexible than the touch panel approach in terms of changing the screen or objects size, because the virtual active touch can be controlled by adjusting the cursor movement. For example, in the case of a small screen, the cursor movement can be restricted.

Campbell et al. have introduced tactile feedbacks into a PS-type interface. They have shown that providing tactile feedbacks could improve the effectiveness of pointing tasks by appropriately superposing visual stimuli on the screens [7]. However, they have not discussed the perceived textures, whereas our study focuses on how to equalize the textures displayed by the PS-type tactile interfaces with those displayed in response to actual touch movement. One probable problem is how to convert the PS input to the cursor movement. We investigate the influence of the force-to-velocity scaling factor of the cursor movement on the perceived texture. In addition, to extend the applicability of our method to small screens, we examined the effect that a restricted cursor movement exerts on texture sensations. we examined whether the virtual active touch functions

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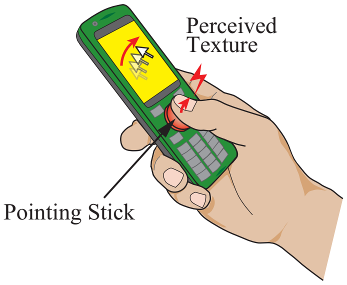

Figure 1: Image of the developed tactile interface

or not. Note that the objective of this study is to propose a virtual active touch mechanism and confirm of its validity. Therefore, we give more importance to the performance of the experimental equipments than miniaturization of a handheld device. We use a sufficiently large vibrator to generate stimulations and a sufficiently precise force sensor to perform pointing operation. We evaluate perceived roughness of the textures, because perceived roughness is a fundamental sensation used for determining the texture and has a relatively clear relationship between touch movement and tactile stimulation.

2 CONCEPTS OF VIRTUAL ACTIVE TOUCH

2.1 Proposal

Virtual active touch enables the users of mobile interfaces to interact with an object on the screen through cursor movement used as a virtual fingertip. This study proposes the addition of tactile feedback mechanism in a PS-type input device to enable virtual active touch. A pointing stick is a force input type interface and enables the operations of the cursor on the screen with the application of a requisite amount of pushing force in a desired direction. Figure 1 shows an example of a tactile interface to clarify our concept. The white arrow represents the cursor on the monitor. A vibrator is mounted on the PS-type interface of the mobile phone and tactile feedback is provided corresponding to the cursor operation performed using the fingertip. The generation of vibration in response to virtual active touch is likely to produce various texture sensations, using our proposed method [5, 6].

Advantages of the PS-type tactile interface are summarized as follows.

(1) Production of rich tactile sensation

The proposed PS-type tactile interface can be compact because the size of the tactile display is sufficient enough to cover an area corresponding to one fingertip on the pointing stick. A pointing stick has good compatibility with handheld devices, because it is commonly used with them.

The PS-type interface has an advantage in that it displays richer tactile sensation as compared to that produce by the vibration of the touch panel. In the case of the touch-panel-type interface, the entire touch screen must vibrate. It is difficult to covert the vibration of the entire screen to complex wave forms due to the limitation of the actuation response. On the other hand, the PS-type interface can arrange smaller actuators locally. This ability to arrange smaller actuators is advantageous for generating complex wave forms, in order to produce rich tactile sensations.

In practice, we need to develop a compact vibrator that is mountable on the pointing stick and generates vibrations in the wide frequency range with sufficient amplitude. The authors have proposed an ultrasonic vibrator that can be mounted on the joystick of a game controller [8]. This vibrator is expected to be used for the PS-type tactile interface, although the generated force is not sufficient enough to produce rich tactile sensation at present.

(2) Adaptability for the screen size

The PS-type tactile interface has little restriction on the size of stroking area because the cursor movement does not require the actual hand movement. For example, if the touch-panel-type tactile display is used for the small screen, it is not possible to stroke against the object in the small area on the screen. This small stroke causes a lack of immersive sensation in the screen. On the other hand, the PS-type interface can adjust the cursor movement corresponding to the screen size. In the case of a small screen, the cursor movement can be restricted by reducing the force scaling factor. By using this adjustment, it is expected that the users of mobile interfaces can touch the compressed or enlarged objects on the screen and experience the textures of those scaled objects.

2.2 Questions

Many problems should be solved in order to realize the PS-type tactile interface. The objective of this study is to answer the following questions. The sections related to each experiment are also described.

(1) Can the PS-type tactile interface convey texture sensation?

First, we should know whether the virtual active touch with PS-type interface can induce equal texture sensations in response to the actual touch. We compare roughness sensations represented through the PS-type tactile interface and those represented though by an actual-movement-type tactile interface using psychophysical methods of adjustment under the condition that identical tactile stimulators are used for both types of interfaces (Section 5.1–5.2).

(2) Does the conversion from force input to cursor movement influence texture sensation?

It is important to develop a process for converting the PS input into cursor movement for the virtual active touch. It is expected that the force-to-velocity scaling factor of the cursor movement has some influence on the texture perceived in response to virtual active touch. In this study, we use a linear force-to-velocity conversion as the simplest approach to avoid an unexpected influence. We investigate the influence of the force-to-velocity scaling factor on roughness sensation (Section 5.1 - 5.2). Finally, we evaluate an optimum value of scaling factor to perceive the same roughness in response to the actual touch, from the results of the above experiments (Section 5.3).

(3) Is the proposed method applicable to compressed objects?

As mentioned in subsection 2.1, the PS-type tactile interface is adaptive to a change in the size of the screen due to adjusting the force-to-velocity scaling factor of the cursor movement. In these cases, still there is a question remaining, which is whether the users experience the perceived textures correctly even if the object size on the screen is compressed. We examine this question using three different-sized images and corresponding scaling factors (Section 6).

3 VISUAL AND TACTILE STIMULI

3.1 Tactile stimuli

Virtual roughness textures are used as tactile stimuli,. Virtual texture has sinusoidal displacements on the surface of a virtual object. When the finger of an operator traverses the virtual texture, sinusoidal displacements are applied to the finger skin. The displacements applied to the finger skin are expressed as

$$y(t) = A(\sin(2\pi\frac{x(t)}{\lambda}) + 1), \tag{1}$$

where x(t) and λ are the position of the finger along the virtual texture and the spatial wavelength of the surface of the virtual texture,

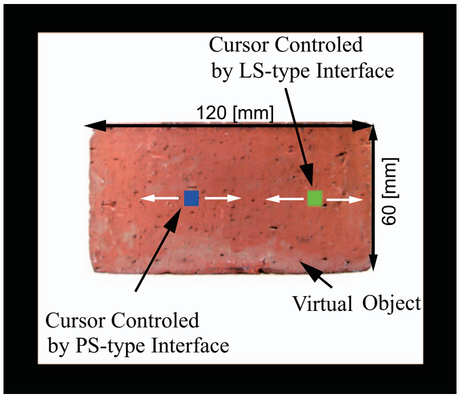

Figure 2: Virtual information displayed to participants

respectively. A vibratory actuator is used as the tactile stimulator, and voltage supplied the actuator is expressed by (1), where A is the amplitude of the voltage. When the instantaneous velocity of the finger is $v(t)$, the frequency of the vibratory stimuli subjected to the operator is $f(t) = v(t)/\lambda$; this affects the perceived roughness of the virtual textures. The control frequency required for updating the supplied voltage is 5 kHz.

When a human explores a rough texture, the perceived roughness depends on the physical properties of the texture, such as groove widths or spatial wavelengths of grating scales [9, 10]. It should be noted that the vibratory stimuli depends only on the vibratory frequency, and it is independent of the other factors of perceived roughness. Therefore, the roughness perceived in response to the above stimuli differs from that perceived in response to real tactile exploration.

3.2 Visual stimuli

The image of target object that is used as the visual stimuli in the experiments should be a familiar thing such that the every experimental subject can imagine its actual dimensions. Otherwise, the objects would not consider tactile stimuli as natural stimuli. In our experiments, we consider the image of a brick as that shown in fig. 2. Its dimensions as observed on a computer screen are 120 mm × 60 mm. The cursor that is manipulated by the interface is a 6-mm-square. When the cursor slides on the brick, vibratory stimuli are displayed through the tactile interfaces.

4 EXPERIMENTAL SETUP

Two types of tactile interfaces have been developed. One interface is a PS-type tactile interface used for virtual active touch. The other interface is a linear-slider-type (LS) tactile interface used for tactile exploration with touch movement. Roughness stimuli presented through these two types of interfaces are compared, and then the hypothesis of virtual active touch is examined.

4.1 PS-type tactile interface

The developed pointing-stick-type tactile interface is shown in figs. 3 and 4. When an operator applies tangential forces with a finger to the x-axis, the cursor on a computer screen moves according to the applied force. In addition, according to the speed of the cursor, vibratory stimuli are presented to the finger of the operator. Vibratory stimuli are substituted for roughness stimuli.

A contact shoe is installed on top of the vibrator for securing an adequate contact area between the finger and the vibrator. The shoe is circular in shape and its diameter and thickness are 20 mm and 10 mm, respectively. A six-axial force sensor (BL-AUTOTECH, MINI2-10) is installed beneath the vibrator for measuring the tangential force along x-axis applied to the vibrator.

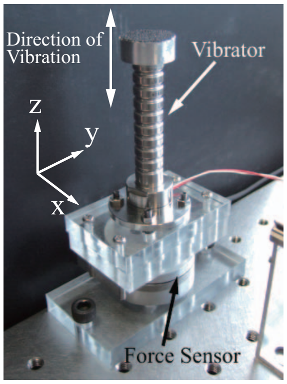

Figure 3: PS-type tactile interface

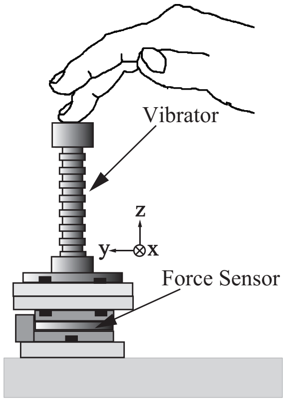

Figure 4: Contact between the finger and the PS-type interface

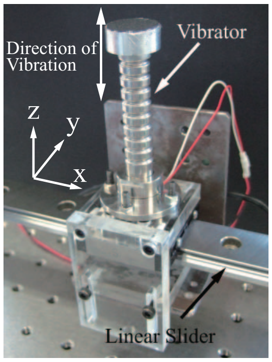

Figure 5: LS-type tactile interface

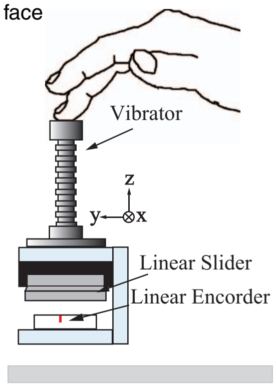

Figure 6: Contact between the finger and the LS-type tactile interface

For commonly used pointing devices such as a mouse or a touch pad, the transformation between the applied force and the cursor velocity is not linear; this is partly because the objective of these devices is to improve manipulability of small workspaces and translate the applied force with ease in large workspaces. However, thus for, for the display of perceived textures, dexterous manipulation of the cursor has not been necessary. In order to simplify the analysis of the effect of the transformation equation, we employ a linear transformation between the applied force$F(t)$ and the cursor velocity$v(t)$. The transformation equation is expressed as

$$v(t) = \alpha F(t), \tag{2}$$

where α is the gain. The computation frequency required for calculating the cursor velocity is 1 kHz.

4.2 LS-type tactile interface

The developed LS-type tactile interface is shown in figs. 5 and 6. When the operator places his finger on the vibrator and moves his hand along with the linear guide, the cursor on the computer screen moves and the tactile stimuli are presented to the operator's finger on the basis of the cursor velocity. The vibration actuator is installed on top of the linear slider, and it is moved along the x-axis with touch movement. The linear guide slides along the x-axis. Its movable length on the slider is approximately 200 mm. The position of the vibrator on the slider is measured by an optical encoder whose spatial resolution is 0.4 μm.

The velocity of the cursor controlled by the LS-type interface is equal to the actual hand velocity measured by the encoder. The computation frequency required for calculating the cursor velocity is 1 kHz.

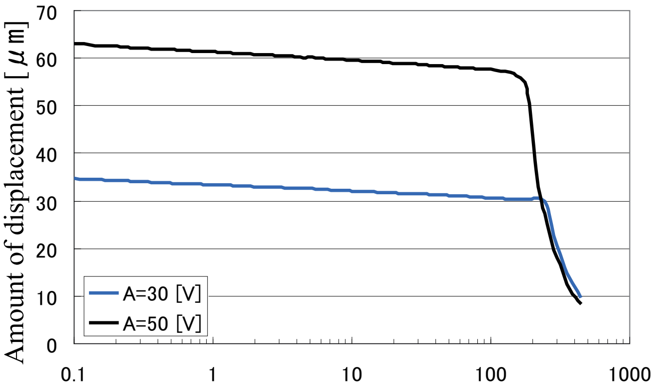

Figure 7: Amplitude-frequency response of the vibrator

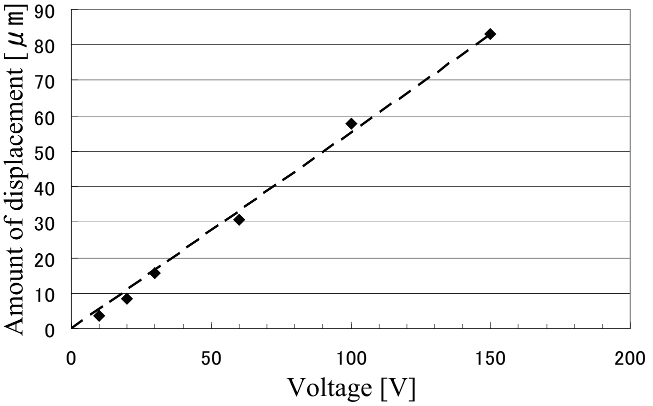

Figure 8: Amplitude-frequency response at 100 [Hz]

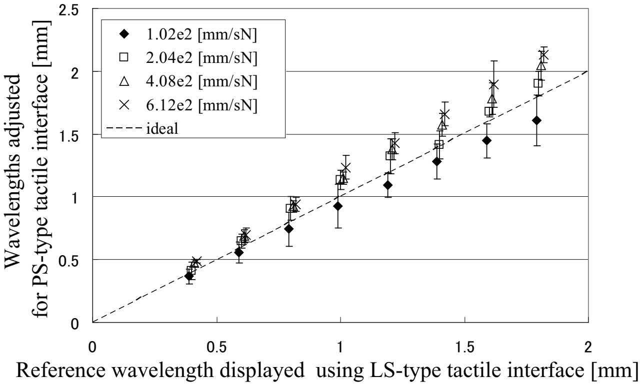

Figure 9: Relationship between the adjusted spatial wavelength and the reference spatial wavelength in terms of α

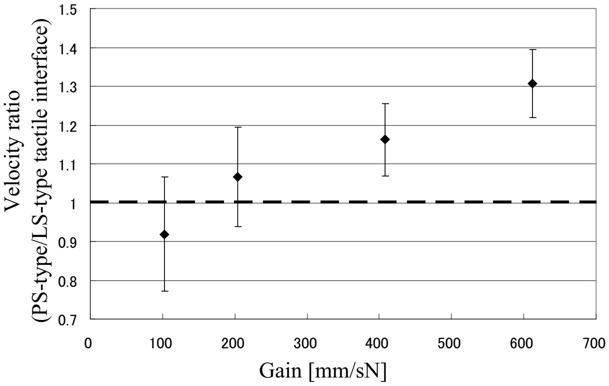

Figure 10: Relationship between α and velocity ratio

4.3 Vibrator

Vibratory actuators are piezostacked actuators (NEC/TOKIN, AHB800C801FPOLF). The amplitude-frequency response of the vibrator is shown in fig. 7; this response is obtained when the amplitudes of the voltage applied to the vibrator are 30 V and 50 V. The response curves are relatively flat for low frequencies, while the amplitudes of the displacement decrease with an increase in frequencies. However, it was confirmed that vibrations were sufficient enough to allow the participants to receive tactile sensations in response to vibratory stimuli with frequencies as high as 200 Hz or more. The relationships between the applied voltage and the displacement of the vibrator is linear, as shown in fig. 8. The figure shows the voltage-displacement plot of the vibrator, when it is actuated with a frequency of 100 Hz.

5 VERIFICATION OF VIRTUAL ACTIVE TOUCH

If the perceived textures displayed by the PS-type tactile interface are found to be same as those displayed by the LS-type tactile interface, the hypothesis of virtual active touch is proved. An experiment is performed in order to prove this hypothesis. In the experiment, participants compare the textures perceived by both the PS-type and LS-type interfaces. The effect of α expressed in equation (2), is unknown. In order to examine the effect of α on the perceived textures, α is varied.

5.1 Experimental condition

The experiment was performed using the psychophysical method of adjustment. The reference and comparison stimulus were displayed by the LS-type and the PS-type tactile interfaces, respectively. The participants adjusted the spatial wavelength of the comparison stimulus such that the textures displayed by the PS-type interface became close to those obtained in response to the reference stimuli.

Eight reference stimuli whose wavelengths varied from 0.4 to 1.8 mm by 0.2 mm were used. Four trials were conducted for each reference stimulus. The following four gains were employed; 1.02×10^2, 2.04×10^2, 4.08×10^2, and 6.12×10^2 mm/sN. For each gain, 32 trials (eight reference stimuli × four trials) were conducted. In total, 128 trials were conducted for each participant.

The participants adjusted the wavelength of the comparison stimulus by using a keyboard. In order to increase and decrease the wavelength, the key of for letters ”a” and ”s” were pressed, respectively. The wavelength changed by 0.05 mm by pressing either of the keys just once. Due to the limitation of the electric amplifiers used for the vibrators, A defined in equation (2) was set to 30 V when the reference wavelengths were 0.4–0.8 mm. In addition, A was set to 50 V when the reference wavelengths were 1.0–1.8 mm.

The duration of one trial was limited to 30 s. If the participant did not complete the trial within 30 s, the trial was retried after all of the completion of all the remaining trials. Prior to performing the experiment, the participants practiced manipulating the cursors using both the PS-type and LS-type tactile interfaces. Furthermore, they were instructed to practice matching the cursor velocity of the PS-type interface with that of the LS-type interface. The participants could practice until they were comfortable with the tasks. They wore ear plugs to avoid hearing the sounds generated by the vibrator and headphones through which pink noise was audible. 5 participants performed the tasks.

5.2 Experimental result

The experimental result is shown in fig. 9. This figure shows the relationships between the adjusted spatial wavelength and the reference spatial wavelengths in terms of α. The error bars indicate standard deviations among the participants. The dashed line denotes the ideal line on which the adjusted wavelengths are completely identical to the reference wavelengths. It can be observed from the figure that the adjusted wavelengths increased with the reference wavelengths for any α. However, differences between the adjusted wavelengths at different values of α were observed. Analysis of covariance was applied to the experimental results, with the covariant being the reference wavelength and the group factor being the gain. The results of the analysis showed that there was a significant difference between the slopes of the regression lines at different values of $\alpha(F(3,152)=14.09,\ p<0.001)$. With the smaller gains, the adjusted wavelengths were smaller than those for the higher gains.

The reason for an increase in the adjusted wavelengths with α is probably attributed to the effect of the cursor velocity. The cursor velocities are probably affected by α. In order to examine the effect of α on the cursor velocities, the average cursor velocities were compared at different values of α. The average was estimated for velocities greater than 5 mm/s.

The ratio of the average cursor velocities for the PS-type tactile interface to those of the LS-type tactile interface is shown in fig. 10, where the horizontal axis represents the magnitude of α. The error bars indicate the standard deviations among the participants. The cursor velocities of the PS-type tactile interface increased with α. At the smallest gain of 1.02×10^2 mm/sN, the ratio went below 1.0, which implied that the cursor of the PS-type tactile interface was slower than that of the cursor of the LS-type tactile interface. This result is consistent with the experimental results of the adjusted wavelengths. The adjusted wavelengths were also smaller than the reference wavelengths presented by the LS-type tactile interface, only if α was 1.02×10^2 mm/sN.

5.3 Optimal gain

From the experimental data, we estimate the optimal gain $\alpha_{optimal}$. The optimal gain is defined as the gain at which the adjusted wavelengths are equal to the reference wavelengths. The value of $\alpha_{optimal}$ is estimated by performing regression analysis of the experimental results.

From the regression analysis, we obtain the following approximation equation:

$$\lambda = 5.41 \times 10^{-4}\alpha + 1.05\lambda_r - 0.152, \tag{3}$$

where λ and λ_r are the adjusted and reference wavelengths, respectively. $\alpha_{optimal}$ is defined as

$$\arg\min_{\alpha} \int_{0.4}^{1.8} (\lambda - \lambda_r)^2 d\lambda_r. \tag{4}$$

From this equation, we obtain $\alpha_{optimal} = 1.74 \times 10^2$ mm/sN. The task described in 5.2 was performed by the same participants using this value of $\alpha_{optimal}$. Its experimental results are shown in fig. 11. The adjusted wavelengths of the PS-type tactile interface were almost similar to the reference wavelengths displayed by the LS-type tactile interface ($R^2 = 0.995$).

It was confirmed that the PS-type tactile interface with a tuned gain could display identical perceived textures as those displayed by the LS-type tactile interface. In other words, the PS-type and LS-type tactile interfaces perceive identical textures.

6 TACTILE DISPLAY METHOD FOR SCALED OBJECTS AND ITS EXPERIMENTAL VALIDATION

Large-sized objects need to be compressed so that they are recognizable on the screens of mobile phones. In order to accurately identify these scaled objects, the display method has to take account the scale of the compressed objects. In this section, the method for displaying scaled objects on the PS-type tactile interface is proposed and experimentally validated.

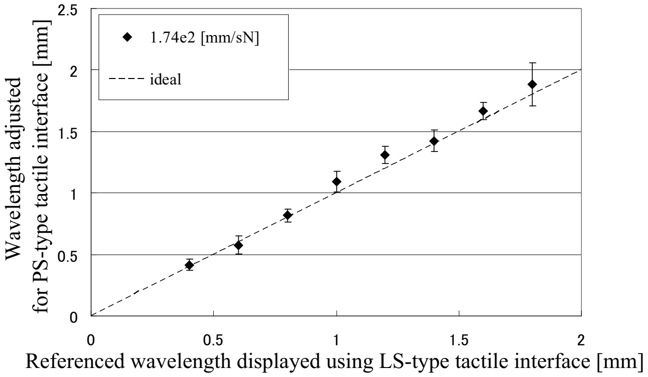

Figure 11: Relationship between the adjusted spatial wavelength and the reference wavelength in terms of $\alpha_{optimal}$

6.1 Method for displaying scaled objects

In the proposed method, roughness sensations depend on the vibration frequency f of the stimuli. Before and after the objects are scaled, f are maintained constant. In order to maintain a constant value of these frequencies, irrespective of the scaling values, the cursor velocity v and the spatial wavelength of the texture λ are also scaled at the same rate as are the visual dimensions of the object. As long as v and λ are scaled at an equal rate, f is not affected by the scaling, because f is the ratio of v and λ.

In summary, when an object is scaled, the cursor velocity, the size of the cursor, and the spatial wavelengths are also scaled at an equal rate. Then, tactile stimuli can be presented with no regard to scaling.

6.2 Experimental conditions and tasks

If the same textures are perceived through the PS-type tactile interface before and after the object is scaled, the proposed display method is considered to be effective. In the experiments, the participants compare the textures of the scaled- and nonscaled objects and match their perceived roughnesses.

The experiment was performed using the psychophysical method of adjustment. The reference stimulus was a nonscaled object. The comparison stimulus was an object whose size, spatial wavelength, and cursor velocities were scaled at an equal rate. The participants adjusted the wavelength of comparison stimulus in order to perceive the close textures before and after the object was scaled.

The reference stimulus included the nonscaled object, as shown in fig. 12. The dimensions of this object, as observed on the screen, were 120 mm × 60 mm. The wavelength of the reference stimulus varied from 0.6 mm to 1.4 mm by 0.2 mm. The value of α was set to 2.04×10^2 mm/sN.

Three comparison stimuli were used. Their scaling values were 0.25, 0.5 and 1.0 (nonscaled), respectively. The visual stimuli of these scaled objects are shown in figs. 13 and 14. For each of the five reference wavelengths and the three comparison stimuli, three trials were conducted. In total, 45 trials were conducted for individual participants. The display order of the stimuli was random.

Participants analyzed the reference and comparison stimuli alternatively. They switched between the reference and comparison stimuli by pressing the key for letter ”z”. They increased and decreased the wavelength of the comparison stimuli by pressing the key for ”a” and ”s,” respectively; the wavelengths were increased and decreased in the same way in the previous experiment. The

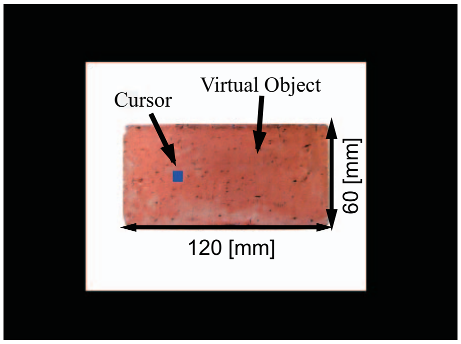

Figure 12: Fundamental scale size of the virtual object

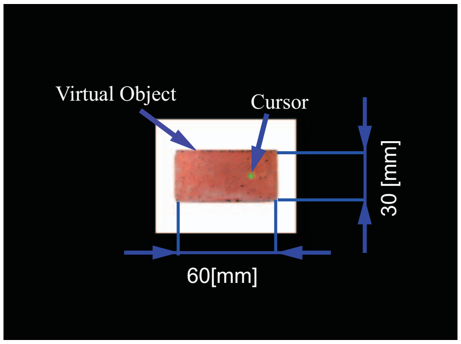

Figure 13: Half-scale size of the virtual object

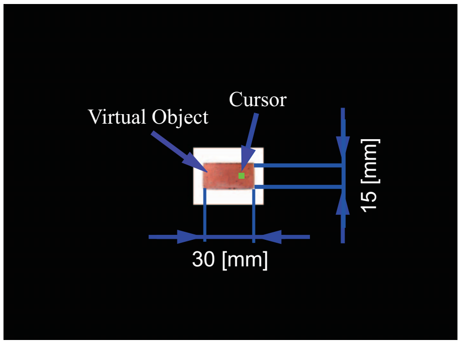

Figure 14: Quarter-scale size of the virtual object

duration of one trial was limited to 30 s. If the participants did not complete the trial within 30 s, the trial was retried after the completion of the remaining trials. The participants wore headphones through which pink noise was audible. They practiced the above-mentioned tasks prior to performing the experiments until they were comfortable with the tasks. 5 participants performed these tasks.

6.3 Experimental result

Fig. 15 shows the experimental results. The averages of adjusted wavelengths are shown in the figure for every scaling value. The error bars indicate the standard deviations among the participants.

In order to examine the effects of the scaling values, one-way ANOVA was applied to the adjusted wavelengths, where the factor was one of the scaling values. The result of the statistic test did not show a significant difference between the adjusted wavelengths at different scaling values ($F(2, 72)=1.287$, $p=0.282$). The result indicates that the participants could compare the textures before and after the object was scaled. The participants perceived the same textures for every scaling value. It was confirmed that the proposed method for displaying the scaled textures was effective.

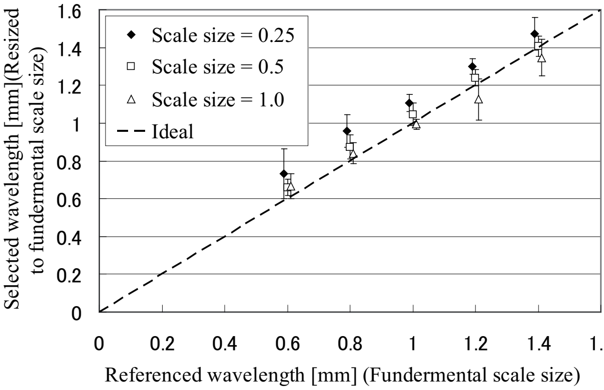

Figure 15: Relationship between the adjusted spatial wavelength and the reference wavelength at different scale values

7 CONCLUSION

In this study, the concept of virtual active touch was introduced for the PS-type tactile interface of mobile terminals. The result of the psychophysical experiments confirmed that the PS-type tactile interface displayed identical perceived roughness as that displayed by the tactile interfaces involving active touch. The results of the experiments also revealed that the gain factor required to linearly transform the force applied to the pointing stick into cursor velocities significantly affects the perceived textures.

In the case of compressed objects that were displayed on the screen of mobile terminals, a method to clearly display these objects so that they are recognizable was developed. The results of the experiments confirmed that the developed method accurately displayed the perceived roughness, even when the objects were scaled.

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ACKNOWLEDGEMENTS

This work was supported in part by a grant from the Ministry of Internal Affairs and Communications SCOPE (082102006).