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A Fingernail-Mounted Tactile Display for Augmented Reality Systems

Hideyuki Ando,[1,2] Junji Watanabe,[3] Masahiko Inami,[4] Maki Sugimito,[1,2,*] and Taro Maeda[1,2]

[1]NTT Communication Science Laboratories, NTT Corporation, Atsugi, 243-0198 Japan

[2]Japan Science and Technology Agency, Kawaguchi, 332-0012 Japan

[3]Graduate School of Information Science and Technology, The University of Tokyo, Tokyo, 113-8656 Japan

[4]Mechanical Engineering and Intelligent Systems, The University of Electro-Communications, Chofu, 182-8285 Japan

SUMMARY

There have been many efforts to present skin tactile information to the fingertips. In these studies, however, the tactile stimulus has been presented to the pad side of the finger. In that approach, it is difficult to superimpose virtual tactile information on the tactile information of the real world. Consequently, this paper proposes a tactile display device in which vibration is applied to the fingernail side, not to the pad side of the finger, so that a virtual undulating sensation can be superimposed on the real-world sensations obtained during the scanning action of the finger. The proposed device is based on the phenomenon that when a vibration is applied while the finger is scanning an object, a perception of undulation rather than of vibration is produced. This study measures the pressure change produced on the pad side of the finger in such a scanning operation and investigates the mechanism that causes the perception. The vibration timing required to present an arbitrary virtual convex width is determined by a psychophysical experiment. Electron Comm Jpn Pt 2, 90(4): 56–65, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ecjb.20355

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*Now affiliated with the Electrical Communications Research Laboratory, Graduate School, University of Electro-Communications.

1. Introduction

In studies of virtual reality, there have been efforts to reproduce artificially such skin sensations as the undulating sensation of the finger when touching an object. Skin tactile presentation is generally considered different from force presentation [1], since the frequency range of the stimulus is different. The skin tactile presentations hitherto proposed include methods of faithfully reproducing physical information, such as a method of presenting an undulating sensation by reproducing the shear stress in the perpendicular direction with an electrostatic actuator [2], a method of deforming the contact surface shape using pins moving vertically [3]. There are also methods of directly stimulating nerves or tactile receptors by surface acoustic waves [4], electrical stimulation, [5] and ultrasonic stimulation [6].

Furthermore, when a human tries to sense the surface shape of a motionless object by tactile sensation, the finger is moved actively in most cases, as in the scanning action, and the surface shape is inferred from the stimulus applied to the fingertip accompanying the motion [7]. There are also

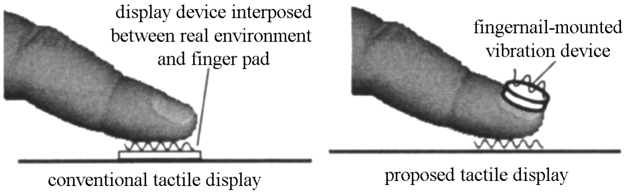


Fig. 1. Proposed method to give tactile sensation.

studies in which the tactile sensation is presented in an effort to reproduce such vibrations generated at the fingertip during the scanning action by using vertical vibrating bars [8] and pins [9], and also with a polymer gel actuator [10].

These methods of tactile sensation presentation are utilized not only in the virtual space, but also in augmented reality (AR) [11], where artificial sensation is superimposed on the real environment. In AR, the virtual information is added to information from the real environment, and AR must be achieved without degrading the sensation of the real environment [12–14].

The problem then arises that all of the tactile presentation methods apply the stimulus to the pad side of the finger. Consequently, the device is interposed between the real environment and the finger pad, as in the left part of Fig. 1, thus blocking tactile sensations from the real environment. Kajimoto and colleagues [14] proposed a method in their AR study in which the tactile sensations of the real environment and artificial tactile sensations can be acquired at the same time by covering the finger pads with a very thin film to provide electrical stimulation. In this method too, tactile sensation of the real environment is lost, since the device is mounted on the pad side of the finger.

Consequently, this paper proposes the following method. As shown in the right panel of Fig. 1, an adequate vibration stimulus is applied from above the nail to generate the virtual sensation of undulation, so that the virtual undulation sensation can be superimposed on the sensations of the real environment.

Below, Section 2 describes the principle of generating an undulation sensation from above the fingernail, which is verified in Sections 3 and 4. Section 5 presents a psychophysical experiment to investigate the properties of the undulating sensation perceived in the proposed method. Section 6 proposes a method in which the nail-mounted tactile display is effectively utilized in an AR system, based on the experimental results.

2. Principle of Proposed Method for Presentation of Undulating Sensation

In the proposed method, a vibration stimulus is applied from above to the fingernail during the scanning of an object, so that undulation edges are perceived as a result of an adequate impulse stimulus to the finger pad.

When a human tries to sense the surface shape of a motionless object, the scanning action is performed in most cases, and the surface shape is inferred from the motion of the fingertips and the accompanying stimulus produced at the fingertips [7]. It is known in particular that the impulse vibration component perpendicular to the finger surface which is produced by the undulation edge is important in the perception of the undulating sensation [8]. Consequently, it is important in the presentation of the undulating sensation that the stimulus with an impulse component be presented appropriately, so that it is aligned to the scanning action.

In the method proposed in this paper, the impulse stimulus is applied to the fingernail from above, so that tactile information from the real environment is not blocked. When a vibration is applied to the nail as in the right panel of Fig. 1, a stress is indirectly produced on the finger pad and the contact surface by the driving force. Since the tactile receptors are concentrated in the finger pads [15], it is expected that the vibration sensation will be produced more strongly in the finger pads in contact with the object than on the nail side. Thus, a virtual undulating sensation will be superimposed when a vibrational impulse component perpendicular to the finger surface is applied to the fingernail during scanning action. An experiment which indicates that an impulse component is generated in the finger pad by the vibration stimulus to the fingernail is presented in the next section.

3. Impulse Stimulus to Finger Pad by Vibration Stimulus to Fingernail

This section considers the scanning of an undulating surface, which is one of the basic textures in real environments. The pressure change (such as the impulse component) produced in the finger pad is determined, and a method of experimentally generating a stimulus simulating the real environment in the finger pad is tested. In the experiment, the dynamical stress at a local point on the finger pad is measured in the cases of a real environment with undulation and the virtual environment produced by a vibration stimulus from above the fingernail. The pressure changes in the two cases are compared.

3.1. Experiment A: Pressure change of finger pad in scanning an edge in a real environment

To observe experimentally the pressure change in a real environment, a real environment with undulation is scanned in one dimension. The displacement and the pressure on the finger pad are measured [Fig. 2(A)]. The purpose is to observe the vibration on the finger pad surface in contact with the environment, when the object is scanned by the fingers. A film-type pressure distribution sensor (I-SCAN10 × 10, Nitta Co.) was attached to the finger pad. It was a pressured distribution sensor in which measuring points with a size of 0.52 mm × 0.52 mm were arranged in a 10 × 10 grid with a 1.27-mm spacing. In the standard specification, a measurement time of approximately 10 ms is required for this sensor to scan all points. It was modified in the experiment to perform the measurement in less than 1 ms so that the vibration frequency of the actuator could be effectively observed.

In order to achieve noncontact measurement of the distance moved, a laser distance meter (LK-500, Keyence Co.) was used to determine the relation between the distance moved and the pressure. The sensor was fixed to the finger pad so that the center of the sensor agrees with the center of the contact region in the scanning action, and the pressure at that point was measured with a precision of 0.01 N/cm^2 (see pressure sensor in Fig. 3).

The area of measurement by this pressure sensor is a square of size 0.52 mm × 0.52 mm. The laser distance meter measures the distance from the origin to the measurement point of the pressure distribution sensor with a resolution of approximately 0.05 mm. These data were sampled at a rate of 1 kHz by a PC. A real undulation environment was provided by cementing Kent paper 0.25 mm thick with gaps of 10 mm on an acrylic plate.

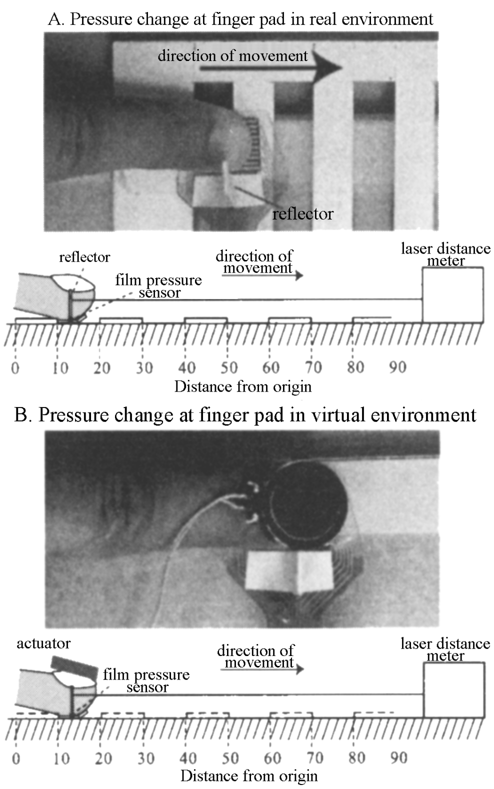


Fig. 2. Composition of experimental system.

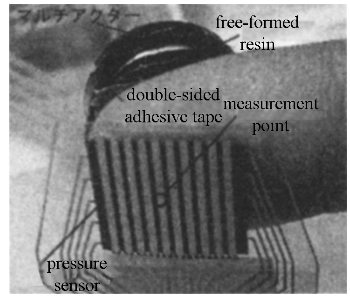


Fig. 3. Installation of experimental device.

In this experimental environment, the scanning action was performed from the origin to approximately 100 mm. The distance from the origin and the pressure on the finger pad were measured. The speed of movement of the finger was set as approximately 70 mm/s, and scanning was performed by applying a stationary force of approximately 0.50 N or 1.00 N to the whole contact region of the finger pad. The subject was trained beforehand to achieve the required moving speed and force.

3.2. Experiment B: Pressure change on finger pad due to vibration stimulus to fingernail

In realizing the virtual environment, the device must be of small scale and light weight in order to be mounted on the nail. The general means of realizing a small-scale vibration device is to use a vibration motor. However, considering that only vibration in the direction perpendicular to the finger surface with a fast response, such as the impulse component, is required, a structure for recursive motion in a single direction, such as the voice coil of a speaker, seems suitable.

Consequently, a multiactor (Type 33, NEC Tokin Co.) was used in this study as the vibration device. This vibration sensor is composed of a mass and a voice coil. The resonant frequency of vibration was approximately 132 Hz. Since the vibration output was extremely low except for this frequency, the driving frequency was set as the resonant frequency. When the impulse vibration (burst waveform vibration with impulse-shaped envelope) excited this vibration device, approximately 20 ms was required for the amplitude to settle to a constant value.

In this experiment, the actuator was driven at approximately 90% of the rated output. Figures 2(B) and 3 show the installation state. The vibration device was fixed firmly on the nail by means of nail-shaped formed adaptor. The equivalent edges were set at the same positions as in the previous experiment. Based on the distance information from the distance meter, the device was vibrated for 20 ms when crossing the virtual edge; this was the narrowest pulse that could be output from the device.

Under these conditions, scanning action was performed on a smooth acrylic plate, and the distance from the origin, and also the force generated on the finger pad, were measured. In this experiment too, the speed of movement of the finger is set as approximately 70 mm/s, and a stationary force of approximately 0.50 N or 1.00 N was applied to the contact area of the finger pad. The subjects performed the trials after training.

3.3. Measurements of pressure change

Figure 4 shows the force at the central point of the pressure distribution sensor in experiment A, converted to pressure. It is evident from the figure that an impulsive force is generated when the finger arrives at the edge. The impulse is observed in the progress from both a concave to a convex surface, and a convex to a concave surface.

It is evident that the greatest pressure is observed when a small area of measurement at the center of the contact region of the film sensor, which deforms in accordance with the shape of the finger pad, passes over an edge with a concave/convex change of shape [such as (a) 10 ms and (b) 20 ms in Fig. 4]. This is attributed to the state in which the point on the finger pad (measurement region of the sensor) arrives at the edge, receiving an impulsive force.

Figure 5 shows the weight of the central point of the pressure distribution sensor in experiment B, converted to pressure. It can be seen that a fast vibration (burst waveform) is generated at the instant when the point passes over the equivalent edge.

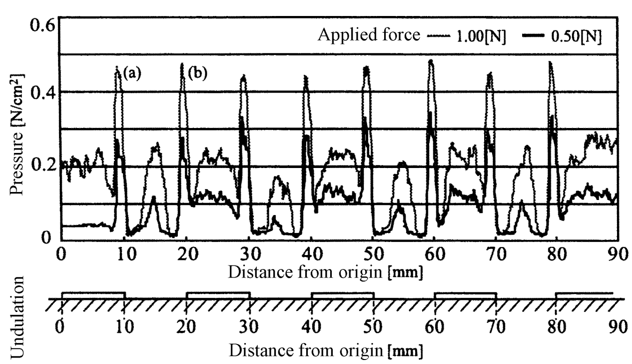


Fig. 4. Force characteristic to finger under real environment.

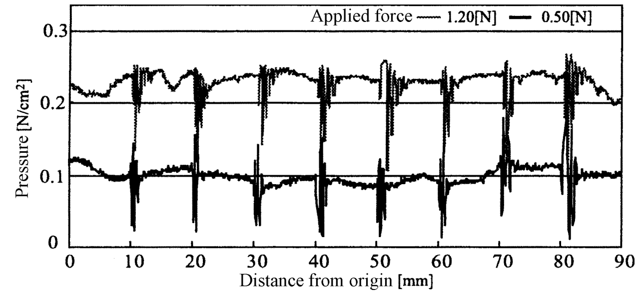
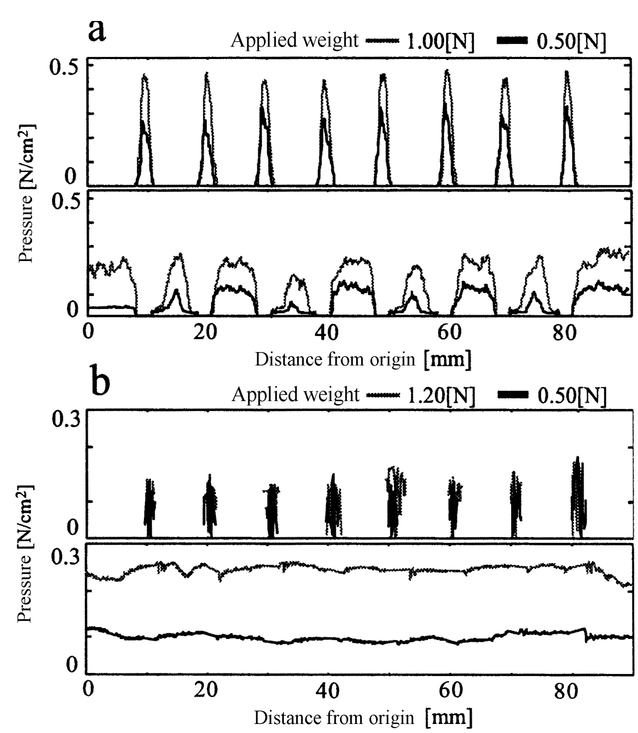


Fig. 5. Force characteristic to finger under virtual environment.

In order to compare clearly the force characteristics in the real environment (experiment A) and the virtual environment (experiment B), the waveform is separated into the impulse component at the edge and other components. For the waveform in Fig. 4, the edge impulse component is shown in the upper part of Fig. 6(a), and the other components are shown in the lower part of Fig. 6(a). Similarly, the force in Fig. 5 is separated as in Fig. 6(b). Comparing Figs. 6(a) and 6(b), it can be seen that a force with a



a upper. Impulse component at edge of Fig. 4
a lower. Component other than impulse at edge of Fig. 4
b upper. Impulse component at edge in Fig. 5
b lower. Component other than impulse at edge in Fig. 5

Fig. 6. Element separation of edge part force.

burst waveform (considered equivalent to an impulsive stimulus) is produced at the same position and with the same timing.

It can be seen from the upper part of Fig. 6(a) that the impulsive force at the edge increases in proportion to the applied stationary force. On the other hand, it is evident from the upper part of Fig. 6(b) that the impulsive force at the edge changes little with the stationary applied force. In the lower part of Fig. 6(a), there is a pressure variation due to the undulation (thickness), but no such pressure change is observed in the lower part of Fig. 6(b), since the surface is smooth.

3.4. Discussion of experiment on pressure change measurement

In a real environment, the impulsive force is generated at edges. In the virtual environment, on the other hand, fast vibration (burst waveform) is presented to the finger pad by a vibration stimulus from above the nail. The duration of vibration of the burst waveform is short, namely, 20 ms. It is inferred that, as pointed out in Refs. 7 and 15, the rapid rise is strongly perceived and the perception of vibration is faint. That is, a perception similar to the case of a stimulus with an impulsive rise is obtained.

In the real environment, the amplitude of the impulsive pressure at the edge increases with the applied stationary pressure [upper part of Fig. 6(a)]. In the virtual environment, on the other hand, the waveform changes little when the applied stationary applied force is increased [upper part of Fig. 6(b)]. It is inferred that the impulsive force increases in the real environment in proportion to the applied force, while the impulsive force in the virtual environment is affected only by the amplitude of the vibrator output and is independent of the applied force.

4. Tactile Presentation by Nail-Side Vibration Stimulus

A device was constructed on the basis of the results of this study (Fig. 7), and its operation was displayed [16]. The content of the display is as follows. A sheet of paper with a printed black and white pattern was set below the acrylic plate. The border between white and black was detected by a reflection photosensor attached to the nail. The same vibration device as in the previous experiment was attached to the nail, and a vibration of 20 ms was produced when the sensor crossed the boundary.

The subject was required to scan the finger on the stripe pattern shown in Fig. 7 from the upper end to the lower end in the direction perpendicular to the stripe. Then the subject was asked to select one of the following three answers.

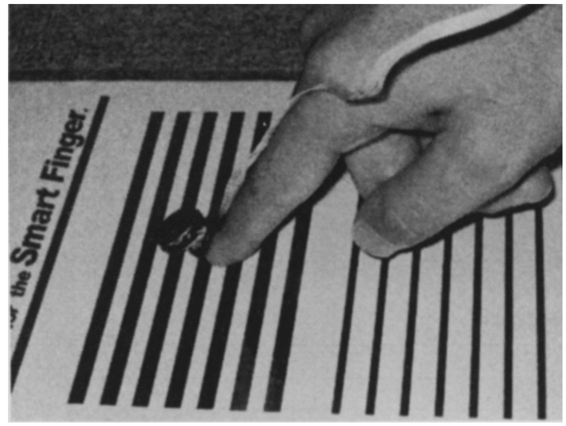


Fig. 7. Nail-mounted tactile display.

(a) The stimulus was sensed as vibration.

(b) A certain undulation (nonflat texture) was sensed on the scanned plane.

(c) Nothing was felt (or could not tell).

In 300 subjects, answers (a) and (c) comprised less than 5% of the total.

As another trigger for vibration generation, instead of the black and white border, an invisible stripe environment was also provided. The material, which is excited by ultraviolet radiation and produces emissions, was applied in the same stripe pattern on the sheet as in Fig. 7. The sheet was set under the transparent acrylic plate. The setup was visible as a white paper to the subject. The same experiment was performed and the same sensation was reported. Thus, the subject was not sensing the written line visually as an edge.

The responses of the subjects verified the following property. When the vibration stimulus is presented in synchrony with the finger motion, burst vibrations of short duration, such as 20 ms, are not sensed as vibration, but are sensed virtually as a tactile sensation of undulation. It was also noted by the subjects that although the stimulus was applied to the whole region of contact of the finger pad with the environment, the difference in width could be recognized for undulation widths narrower than the width of the contact region.

There was also a comment that the subject sensed the undulations but could not decide in the course of scanning whether the surface scanned at each instant was concave or convex. In the experiment in a real environment described in Section 3, it was possible to determine whether the finger was progressing onto a convex surface or a concave surface.

On the other hand, it was impossible to distinguish these two cases in the virtual environment. This is interpreted as follows. In the real environment, differences in height can be recognized as pressure differences under a stationary applied pressure other than the impulse component [lower parts of Fig. 6(a) and 6(b)]. But in the equivalent environment, no such difference exists, making concave/convex discrimination impossible. There were also many comments that the sensation of a broad edge rather than sharp edge undulation was obtained.

Thus, it is verified that an undulating sensation can be presented by the proposed method. The next section discusses what vibration stimulus should be provided in order to present undulations of the specified magnitude.

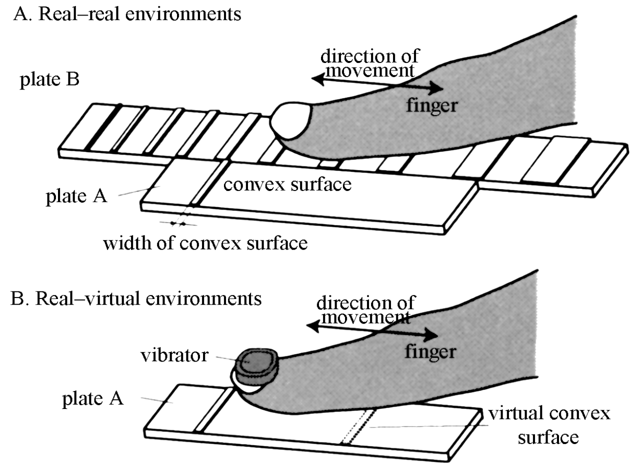


Fig. 8. Perception experiment of convex width.

5. Properties of Undulating Sensation Perceived by Nail-Side Vibration Stimulus

It was shown in the previous section that a virtual undulation surface could be presented by applying a vibration stimulus to the fingernail during the scanning action. According to comments by the subjects, the presented edge sensation differs from the sensation in the real environment. This section describes a psychophysical experiment to investigate the perceived convex surface width, in order to determine the differences between the properties of the undulating sensations produced in the real environment and the virtual environment.

5.1. Measurement of perceived convex surface width

A psychophysical experiment was performed to investigate the difference in the perception characteristics when the convex surface width is varied in the real and virtual environments. As the real environment, 10 plates A (20×80 mm) with a convex surface of height 0.25 mm and width 1 to 10 mm were prepared as shown in Fig. 8. In order to investigate the characteristics of human perception of convex surface widths in a real environment, a plate B (20×160 mm) with all of the above convex surfaces (1 to 10 mm) was prepared.

The subject was asked to state which of the convex surfaces of plate B had the same width as the convex surface of plate A. In order to prevent perception of the width from visual information, the subject performed the scanning action through a blurring filter composed of frosted glass. The position of the finger could be roughly recognized through the filter, but the width of the convex surface cannot be viewed. Ten plates A were selected at random each time, avoiding the same width, and the trials and answers for all 10 plates were defined as a set. The subject was not informed of the exact width. Each of five subjects performed three sets, giving 30 trials in all.

The scanning action is performed using the index finger of the right hand (Table 1 shows the length to the first joint of the index finger). The force to be applied by the finger to the plate is set as approximately 1.00 N, and the subject is trained beforehand to apply this force. The scanning speed is arbitrary. The subject is free to touch the undulations for approximately 30 s, and is then asked to answer.

Next, two equivalent edges are presented below plate A without the convex surface (lower part of Fig. 8). Based on the distance information from the distance meter, vibration is presented at the physically equivalent timing when the finger crosses the equivalent edge (vibration of 20-ms duration when arriving at and departing from the edge). The vibration device is firmly fixed on the fingernail in the same way as in the previous experiment.

Under these conditions, the subject adjusts the equivalent edge width so that it is perceived to be the same as that of the convex surfaces on plate A. The adjustment is performed by using two switches indicated as + and –. Each

Table 1. Result of straight-line regression analysis

Subject (age-sex-length to first joint, mm)	Real environment		Virtual environment	
	Segment [mm]	Slope	Segment [mm]	Slope
A (26–male–25)	0.29	0.94	3.29	1.09
B (27–male–26)	0.31	0.94	4.11	0.92
C (30–male30)	1.44	0.80	3.71	0.85
D (26–female–25)	0.62	0.91	4.32	0.79
E (28–male–26)	0.31	0.94	3.58	1.05
Average	0.60	0.91	3.80	0.94

time a switch is operated, the edge width is varied by 0.5 mm. The subject is not informed of the true edge width. The scanning speed is arbitrary. The subject is free to touch the surface for approximately 30 s, and the final width after adjustment is defined as the measured value. The force that the finger applies to the plate is set as approximately 1.00 N, and the subject is trained before the experiment. As in the previous experiment, the subject observes the scanning action through the filter. Ten plates A are selected at random, each once. The adjustment for all 10 plates is defined as a set. Each subject performs 3 experiment sets, or 30 trials in all.

5.2. Results of perception experiment

Figure 9 shows the mean and standard deviation of the perceived convex surface width for 5 subjects as a function of the convex surface width on plate A. Straight-line regression analysis is applied to the perceived convex surface width for each subject, and also for the mean. Table 1 shows the segment and the slope.

It can be seen by comparison of the real and virtual environments (Fig. 9) that the straight line function of the convex surface width in the real environment has the same slope but different segment length. That is, a stationary deviation is revealed. The existence of the deviation is also verified from the segment of the straight-line regression analysis (Table 1). Thus, the segment is perceived in the virtual environment as approximately 3.8 mm longer than in the real environment. Since the slope in Table 1 is close to 1, we see that the above property does not depend on the convex surface width. In the comparison of the real environments in Fig. 9, the standard deviation is approximately 1 mm. In contrast, the standard deviation in the comparison of the real and virtual environments is approximately 3 mm. This tendency is the same for all subjects.

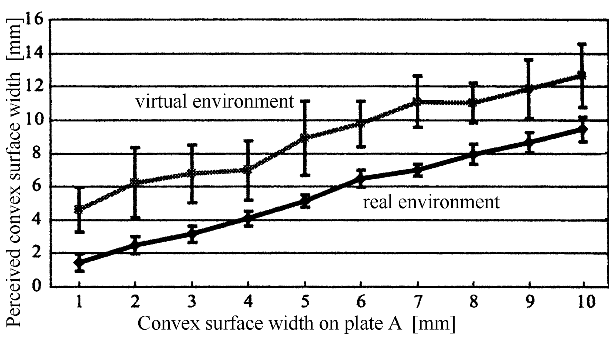


Fig. 9. Spatial resolution of real and virtual environment.

The properties of the comparison between the real and virtual environments which were recognized in this experiment are summarized as follows.

(1) Comparing the convex surface widths in the real–real and real–virtual environments, the relation can be approximated by straight lines with the same slope, but in the real–virtual environments, the perception is always approximately 3.8 mm longer in the latter.

(2) The standard deviation in the comparison of the convex surface width between real–real environments is approximately 1 mm, and the standard deviation in the comparison of the convex surface width between real–virtual environments is approximately 3 mm.

5.3. Discussion of perception experiment

Property 1, that the convex surface width is always perceived as longer in the virtual environment, seems due to the fact that the vibration is applied to the whole contact region. In the experiment, the impulsive stimulus is given when the central point of the contact region arrives at the equivalent convex surface, and similarly, the impulsive stimulus is given when the point leaves the convex surface. However, the contact region is not a point but has an area. Consequently, the perception will occur that the stimulus is given before arriving at the equivalent convex surface, and after leaving the surface. This is the reason that the convex surface width is perceived as longer (Fig. 10). However, the deviation in the longer perception is approximately constant, and it will be possible to realize the same perception of the convex surface width as in the real environment if the convex surface width in the virtual environment is set shorter by an amount equal to the standard deviation (approximately 3.8 mm).

The standard deviation in property 2 is next considered. When a human senses the width of a convex surface,

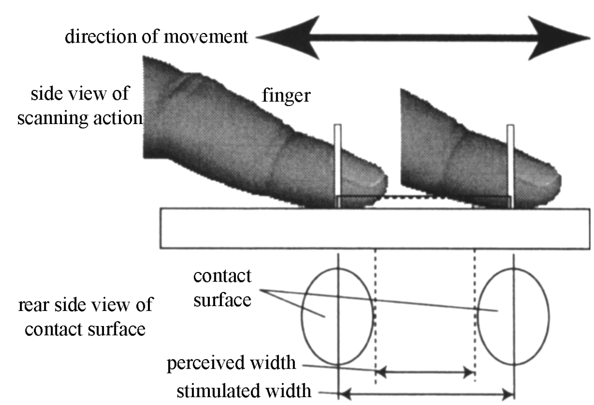


Fig. 10. Perception gap of convex width.

the information from a large number of tactile receptors distributed on the finger pad is integrated. The standard deviation of approximately 1 mm obtained in the real environment seems reasonable considering that the receptors on the fingers are uniformly distributed with a density of approximately 100/cm^2, that is, with a spacing of approximately 1 mm [15].

On the other hand, the standard deviation in the virtual environment is approximately 3 mm. This is interpreted as follows. The contact region between the finger pad and the environment in this experiment is a circle with a diameter of approximately 8 mm. When the stimulus is given from above the fingernail, all tactile receptors in the contact region will be stimulated, and a width less than the contact width should not be perceived. In spite of this fact, the standard deviation is approximately 3 mm. This result seems to suggest that spatial texture information is converted to temporal information through the scanning action, and that the spatial resolution is improved.

In this experiment too, the subjects reported that the edge sensation (sharpness) was poorer in the virtual environment than in the real environment, as in Section 4. The decrease in the edge sensation is considered as a factor increasing the standard deviation. The edge sensation in the real environment is produced not only by the impulsive force, but also by the change of the contact area and the change of the pressure distribution due to undulations within the contact region. In the proposed device, these factors are not reproduced, which is considered to be the reason for the increased standard deviation.

Consequently, the following three points are considered for improvement of the edge sensation.

(1) Improvement of the temporal performance of the device
(2) Stimulation of multiple receptors
(3) Adjustment of presentation according to the pressure

In the device used in this study, the vibration frequency was approximately 130 Hz. From the viewpoint of frequency, the sensory receptors under the skin that can fire are considered as FA-II (Pacinian) and SA-I (Merkel).

(1) FA-II has the spatial additive property in terms of the contact area. Since the proposed device has a wide contact area, this type of receptor will have the dominant effect. Since the FA-II receptor responds to frequencies higher than the presently applied frequency, it is expected that the temporal characteristics, and also the edge sensation, will be improved by using an actuator with higher-frequency and higher-output performance.

(2) When the finger is stationary, SA-I has an important role in detecting small edges [19]. Since this receptor works as a differential filter in terms of the spatial frequency, it fires less when the vibration stimulus is applied to the whole contact area, as in this system. This seems to be the reason for the decreased sharpness of edge sensation. It is expected that the edge sensation will be improved by forming the spatial distribution of pressure by a method such as the generation of surface acoustic waves on the contact surface by multiple vibrators [4].

(3) Reference 8 notes the importance of adjusting the presentation according to the pressure. In the upper part of Fig. 6(a) in Section 3, we see that the amplitude of the impulsive stimulus changes according to the applied static force in the real environment. But there is no change in the upper part of Fig. 6(b). Thus, the information needed to adjust the presentation according to the pressure is missing in the proposed method. In order to supply this information, it will be reasonable to control the amplitude of the finger-mounted device according to the pressure. This will be achieved by utilizing force measurement on the finger pad from above the fingernail [17, 18].

6. Application to Augmented Reality

In the application of the proposed method to the augmented reality, the following functions must be realized from the fingernail side in the scanning action.

(1) Detection of position to be presented
(2) Detection of finger movement
(3) Vibration stimulus

The proposed method produces tactile sensation through the scanning action, and is not suited to applications such as Braille, where the information is acquired by pressing the whole finger pad against the object. On the other hand, the device is similar to a fingernail-mounted device in the sense that the motion is not disturbed. It can be contained in a device the size of a wristwatch, including the power supply and the control circuit, and there are few spatial constraints. Thus, tactile sensation can be realized over a wide range accompanying the motion of the whole arm. For example, it will be possible to add tactile sensation to the contour of a picture drawn on a poster, and to provide interaction through tactile sensation in combination with a large-scale monitor, such as a plasma display. The proposed device will also be applied to problems such as improvement of operability by adding click sensations to a touch panel [22]. It will be possible to include the method in shape presentation systems in VR [20, 21], in order to add tactile sensation to the surface and to improve realism.

7. Conclusions

This paper has proposed a new tactile sensation device which can superimpose tactile sensation onto real environments by providing the vibration from the fingernail side while leaving the finger-pad side free. The vibration (change of force) on the finger pad when the scanning action is performed by using the device is measured, and the result is compared to the case of scanning action in a real environment. An experiment was performed to compare the widths of the convex surface in the virtual and real environments, and the presentation performance of the device was investigated. A nail-mounted tactile display combining a set of small sensors is discussed, aiming at effective application to augmented reality systems.

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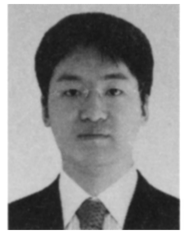
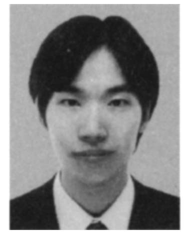
AUTHORS (from left to right)




Hideyuki Ando (member) received his B.E. and M.E. degrees in electronic engineering, Aichi Institute of Technology, in 1997 and 1999. From 2000 to 2001, he was a Junior Research Associate at the Bio-mimetic Control Research Center, RIKEN, where he researched control theory and robotics. From 2001 to 2002, he was a researcher with the Japan Science and Technology Agency, and also with the University of Tokyo, where he researched virtual reality and communication devices with applied perception. Since 2002, he has been with NTT Communication Science Laboratories. His studies have been presented in international conferences such as Siggraph2002, 2004, 2005.

Junji Watanabe received his Ph.D. degree in information science and technology from the University of Tokyo in 2005. He is currently a PRESTO researcher at the Japan Science and Technology Agency in residence with NTT Communication Science Laboratories. His research area is cognitive science and communication devices using applied perception. His researches have been presented not only in conferences (e.g., CHI, Siggraph) but also in art festivals such as Ars Electronica.

Masahiko Inami is a professor in the Department of Mechanical Engineering and Intelligent Systems at the University of Electro-Communications. He directs the Human Interface research group. His research interests include augmented reality and tele-existence. He received his B.E. and M.S. degrees in bioengineering from Tokyo Institute of Technology and completed his Ph.D. degree in engineering from the University of Tokyo in 1999. He joined the Faculty of Engineering of the University of Tokyo in 1999, and moved to the University of Electro-Communications in 2003.

Maki Sugimoto received his B.S. and M.S. degrees in engineering from Chiba Institute of Technology in 2000 and 2002. From 2002 to 2003, he was with the Graduate School of Interdisciplinary Information Studies at the University of Tokyo, and at NTT Communication Science Laboratories as a group member of the Japan Science and Technology Corporation, and was engaged in Parasitic Humanoid studies. He is currently a graduate student (mechanical and control engineering) at the University of Electro-Communications.

Taro Maeda (member) received his B.S. degree from the Department of Mathematical Engineering and Instrumentation Physics, University of Tokyo, in 1987 and joined the Mechanical Technology Research Laboratory, Ministry of International Trade and Industry. He became a research associate at the Advanced Technology Research Center in 1992, a research associate in 1994, a lecturer at the Graduate School of Engineering in 1997, and a lecturer at the Graduate School of Information Science, University of Tokyo, in 2000. Since 2002, he has been a lead researcher at NTT Communication Science Laboratories. He is engaged in research on human perception characteristics, modeling of neural circuits, and tele-existence. He received a Paper Award and a Science Encouragement Award from SICE, and a Technology Award from the Robotics Society of Japan.