

Hybrid Display of Roughness, Softness and Friction Senses of Haptics

Yuta Shiokawa

Keio University

4-1-1 Hiyoshi, Kouhoku, Yokohama, 223-8526

Japan

blinkslip@a7.keio.jp

Masashi Konyo

Tohoku University

Aramaki Aza Aoba 6-6-01, Aoba, Sendai,

980-8579 Japan

konyo@rm.is.tohoku.ac.jp

Atsushi Tazo

Keio University

4-1-1 Hiyoshi, Kouhoku, Yokohama, 223-8526

Japan

at0419@gmail.com

Takashi Maeno

Keio University

4-1-1 Hiyoshi, Kouhoku, Yokohama, 223-8526

Japan

maeno@sdm.keio.ac.jp

Abstract

A hybrid tactile displaying method of roughness, softness and friction senses is realized by use of ultrasonic vibrator and force display. Various realistic tactile senses are displayed by controlling multiple factors. First, a tactile display system was constructed for displaying roughness, softness and friction senses, simultaneously, by compensating the interference among multiple parameters of ultrasonic vibration and force feedback on multiple tactile senses. Second, the relationship between each control parameter and the tactile senses were quantified by conducting several sensory evaluation experiments. Finally, to verify the constructed system, tactile senses of six real materials were recreated, and reality and variety of the artificial senses were compared with the tactile senses of original materials. As a result, it was verified that the correlation coefficients between real materials and hybrid artificial tactile senses displayed using our system were quite large in the evaluation items on roughness, softness and friction sense.

1. Introduction

Technology to display realistic tactile sensation is expected to create various applications, especially in the field of tele-robotics and virtual reality. Tactile sensation is the sense caused when skin interact objects mechanically or thermally. Generally, tactile sensation is divided into deep sensation and skin sensation. The former one is detected by receptors at the muscles and the latter one is detected at the skin. In this study, the word tactile sense is used to refer to skin sensation. Displaying method for deep sensation has almost been established whereas displaying method for skin

sensation has been in progress. First, to display roughness, various methods are proposed for creating vibration at the surface of fingers. Konyo developed a tactile display by use of ICPF (Ionic Conducting Polymer gel Film) actuator array [1]. Watanabe utilized ultrasonic vibration for creating tactile stimuli [2]. Yamamoto utilized electrostatic actuator for displaying surface roughness [3]. Second, to display softness perceived as skin sensation, Ikeda proposed a method for changing pressure distribution at the surface of finger using pneumatic actuator [4]. To display friction, method for changing friction coefficient between display area and human finger by use of squeeze film caused due to ultrasonic vibration is proposed [2]. As stated above, numbers of methods are proposed for displaying single tactile factor by recreating single stimulus of multiple stimuli caused depending on physical property of objects. However, variety and reality of tactile senses could be displayed only by recreating multiple tactile factors simultaneously. Although several trials to realize hybrid display of tactile sense has been made [1][5][6], quantitative hybrid display of tactile sense has not been successfully realized in the previous study. This is because the effect of multiple stimuli on multiple tactile factors has not quantitatively been considered in the past studies. Difficulty is caused by the following relationship between multiple stimuli parameters and tactile factors. One stimulus parameter affects multiple tactile factors. In other words, multiple stimulus parameters affect one tactile factor. This means that realistic tactile senses cannot be displayed only by simple integration of existing tactile displaying methods. So it was necessary first to clarify quantitatively the relationship among multiple stimuli parameters and multiple factors. It was also necessary to create a method for displaying desired realistic tactile sense by use of the obtained relationship among multiple stimuli parameters and multiple factors.

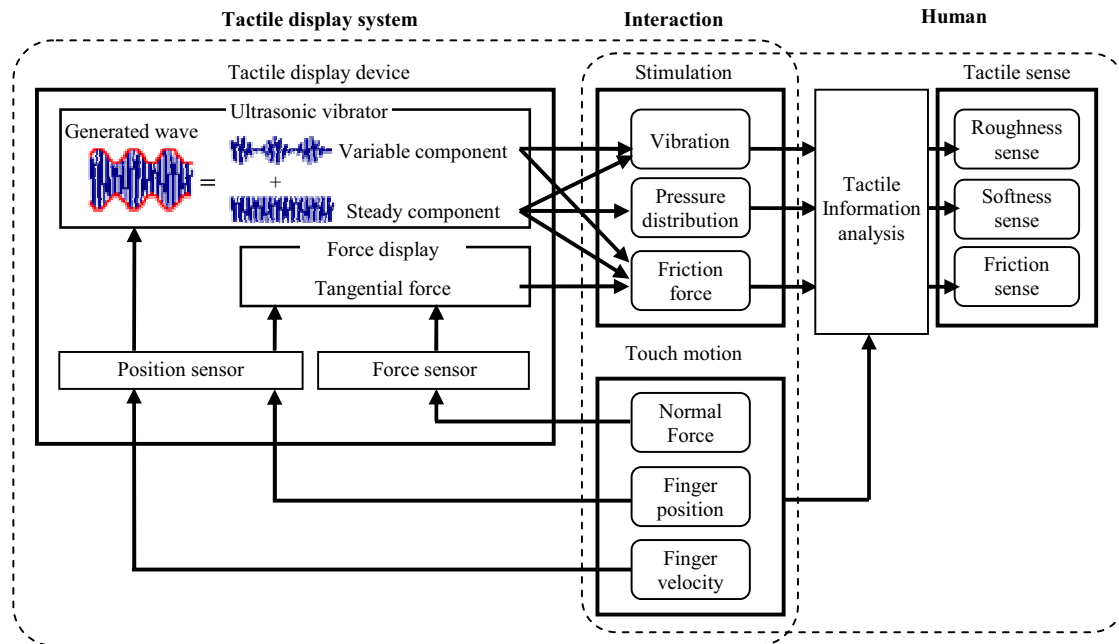


Fig. 1 Outline of tactile display system and recognition of human

The goal of the present study is to display roughness, softness and friction senses quantitatively. To achieve the goal, we construct a tactile display system using ultrasonic vibrator and force display possible to display hybrid tactile senses, simultaneously, by utilizing relationship among tactile factors that we have clarified. Then, we quantify the effect of multiple control parameters of the system on each tactile factor. Finally, we verify the variety and reality of displayed tactile senses by conducting sensory evaluation experiments.

2. Proposed Method

2.1. Outline of Tactile Displaying Method

As stated in the previous chapter, it is necessary to recreate multiple tactile stimuli caused depending on physical property of objects in order to recreate various realistic tactile senses like real materials. Especially, surface texture, elasticity, friction characteristic and heat transfer characteristic are known to have significant effect on tactile senses [7][8]. In this study, we establish method for recreating mechanical stimulus perceived as skin sensation -- vibration patterns caused inside skins depending on surface texture, pressure distribution patterns caused at the surface of skins depending on elasticity, and friction force patterns depending on friction characteristic of objects for the first step of hybrid tactile display. We have shown in our previous study that roughness, softness and friction sense are assumed to be displayed by recreating those mechanical

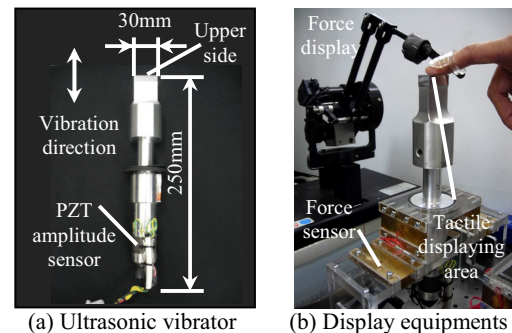


Fig. 2 Tactile display devices

stimuli patterns [7]. In this study, each tactile sense is defined referring to our previous study as follows; roughness sense is the tactile sense such as rough or flat perceived mainly due to surface texture of objects, softness sense is the tactile sense such as soft or hard perceived mainly due to elasticity of objects, and friction sense is the tactile sense such as slippery or non-slippery perceived mainly due to friction characteristic of objects. As a result of factor analysis, it is confirmed that roughness and softness senses are orthogonal [7]. In a strict sense, friction sense is not orthogonal to roughness and softness senses. However, it is also confirmed that friction characteristic is an important physical property for tactile sense [9]. Hence, friction sense is selected as one of the target tactile senses to be displayed in this study.

Fig. 1 shows outline of the proposed tactile display system and human's recognition of tactile sense. As shown

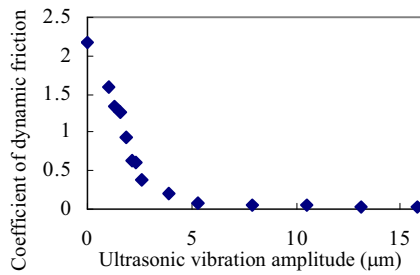


Fig. 3 Relationship between amplitude of ultrasonic vibration and coefficient of dynamic friction of touch area

in Fig. 1, roughness, softness and friction sense are displayed by controlling the parameters of ultrasonic vibration and force display, simultaneously. As an ultrasonic vibrator, Langevin-type ultrasonic vibrator is used as shown in Fig. 2 (a). Driving frequency is close to 28.2 kHz. It is the natural frequency of primary longitudinal vibration mode. In this case, the vibrator vibrates in the direction as shown in Fig. 2 (a) to create maximum amplitude of 20 μm . As shown in Fig. 2 (b), upper side of the vibrator having flat metal surface is used as tactile displaying area. Therefore, the vibration is normal to human finger pad. In this case, squeeze film effect occurs between finger and displaying area. The squeeze film effect is phenomenon to create pressure in fluid between two flat plates occurs when the two plates approach rapidly. Due to squeeze film effect, friction characteristic of vibrator surface changes depending on amplitude of ultrasonic vibration. Fig. 3 shows relationship between amplitude of ultrasonic vibration and coefficient of dynamic friction of the vibrator surface obtained by tracing tactile displaying area of the vibrator with finger pad. The displaying area measures 30 mm in width and 15 mm in depth. In addition, as shown in Fig. 2 (a), PZT amplitude sensor is placed in the vibrator. Voltage of sensor output is proportional to the vibration amplitude. Hence, monitoring and control of vibration amplitude is available by use of sensor output. In this system, intended vibration amplitude can be obtained in spite of an operator's suppress strength by the control system built using FPGA (Field Programmable Gate Array) [10]. It is confirmed that vibration amplitude can be controlled with an uncertainty of 1 % using the system when load is under 10 N. Normal force sensor is placed under the ultrasonic vibrator, as shown in Fig. 2 (b), which enables to measure normal force applied by finger to the vibrator. As a force display, PHANToM Premium 1.0 by SensAble Technologies is used as shown in Fig. 2 (b). Force display and velocity measurement of Three DOF (degree of freedom) is available by use of PHANToM. In this system, stimuli are generated in response to touch motion of human finger (velocity, position and direction) measured using PHANToM. Fig. 4 shows closeup view of an operator's finger and tactile displaying area. As shown in Fig. 4, finger

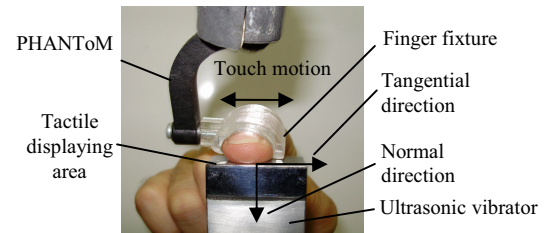


Fig. 4 Closeup view of finger and tactile displaying area

fixture made in this study does not bind the operator's finger pad. Hence, stimuli generated by ultrasonic vibrator and PHANToM can be displayed at the same time.

In the proposed system, variable and steady component of amplitude modulated wave generated by ultrasonic vibrator and force tangential to human finger surface obtained by PHANToM are used for control parameters. As shown in the center of Fig. 1, each parameter affects multiple stimuli. Hence, it is necessary to quantify relationship among multiple control parameters and multiple stimuli, and compensate the interferences. In the following section, principals of displaying each tactile sense are described in detail as well as interferences among multiple parameters on multiple tactile senses.

2.2. Method for Displaying Roughness Sense

Roughness sense is displayed by use of amplitude modulation (AM) of ultrasonic vibration [11]. When amplitude of ultrasonic vibration is modulated, AM wave, shown in the upper left of Fig. 1, is generated. By tracing the AM wave, bump equivalent to approximately 100 times as much height as the amplitude of ultrasonic vibration is displayed due to vibration inside the finger arose from the change in friction of the vibrator surface [12]. In the present study, high-frequency noise and irregular patterns of the real materials' surface is recreated by utilizing waveform of real materials' surface as the variable component of AM wave [13].

2.3. Method for Displaying Softness Sense

We confirmed that steady component of AM wave affects softness sense [14]. It is considered that squeeze film between displaying area and human finger changes the space-time distribution of pressure caused at the surface of the finger. Hence, by controlling the amplitude of AM wave correlated to the amount of change in pressure distribution at the surface of the finger, intended softness sense can be displayed. In addition, by controlling the amplitude of only the steady component of AM wave, softness sense can be displayed in combination with roughness sense. However, the amplitude of the steady component has effect on roughness sense. So the effect is compensated by adjusting the ratio of variable component amplitude to steady

component amplitude.

2.4. Method for Displaying Friction Sense

As squeeze film has effect of decreasing friction, friction sense cannot be controlled while keeping certain roughness or softness sense only by the control of ultrasonic vibration. Hence, we propose a method for displaying friction sense by compensating the change in friction of the ultrasonic vibrator by displaying tangential force equivalent to friction force to the side of a human finger using force display. The point of the proposed method is that tangential force is displayed not to the finger pad but to the side of a human finger. Different from vibratory stimulation perceived as skin sensation, friction force is perceived as deep sensation. Hence, natural friction sense can be displayed even if tangential force was displayed to the side of finger. In addition, as tangential force is not displayed to finger pad, the proposed method can be used in combination with the method to display roughness and softness.

Tangential force is displayed in response to the position and the velocity of human hand measured using PHANToM and normal force applied by finger to the ultrasonic vibrator measured by normal force sensor. First, right after human finger contacts the ultrasonic vibrator, static friction force proportional to the displacement from default contact position is displayed to the operator. When the ratio between tangential and normal force exceeds the coefficient of static friction, dynamic friction force is displayed to the operator. Coefficient of static friction of material to be displayed, μ_s , where μ_{sf} and μ_{st} are coefficient of static friction displayed by force display and ultrasonic vibrator, respectively, is assumed to be expressed by

$$\mu_s = \mu_{sf} + \mu_{st} \quad (1)$$

Similarly, Coefficient of dynamic friction of material to be displayed, μ_d , where μ_{df} and μ_{dt} are coefficient of dynamic friction displayed by force display and ultrasonic vibrator, respectively, is assumed to be expressed by

$$\mu_d = \mu_{df} + \mu_{dt} \quad (2)$$

By calculating μ_{sf} and μ_{df} according to equations (1) and (2), respectively, it is expected that intended friction sense can be displayed in spite of the change in friction of the ultrasonic vibrator.

3. Analysis of Relationship among Control Parameters and Tactile Senses

In this chapter, effects of each control parameter on roughness, softness and friction sense are quantified. The sensory evaluation experiments were conducted by eight examinees, who were males in their twenties with visual and auditory information masked. Suppress strength and touch velocity of examinees were told to be under 1 N and 100

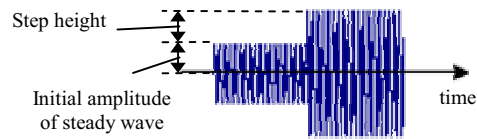


Fig. 5 Step input of steady amplitude

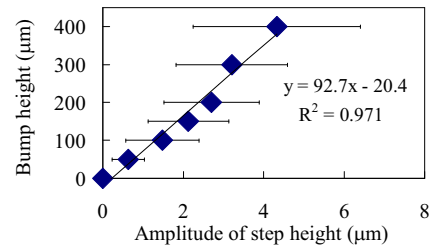


Fig. 6 Relationship between amplitude of step height and bump height

mm/s, respectively. Only index finger cleaned using ethanol was used for the experiments.

3.1. Effect of Variable Component of AM wave on Tactile Senses

First, a sensory evaluation experiment was conducted to quantify the relationship between height of step change in vibration amplitude and height of displayed bump. As shown in Fig.5, artificial bumps were displayed by using step voltage to increase amplitude of the steady component to a certain value. In this case, the amount of increased amplitude, step height, corresponds to the amplitude of variable component. The initial amplitude was zero in this experiment. Effects of initial amplitude will be stated in the next section. The task for examinees was to compare samples having difference in height of bumps and artificial tactile sense, and then adjust the amplitude of the step height until it is felt that perceived bump became equal. Six acrylic resins were used as the sample in the experiment. Each sample had a bump with height of 50 μm to 400 μm processed at the center of the plate. Fig. 6 shows the relationship between bump height and averages of adjusted amplitude of step height. From Fig. 6, we can say that relationship between amplitude of step height and displayed bump height is almost proportional. In addition, under conditions of this study, it was found that displayed bump is equivalent to approximately 90 times as much height as the amplitude of step height. However, the value of step height varies considerably when bump height is large. This is because the larger a bump height is, the more clearly tactile sense of the bump becomes. Hence, the difference between real bump and artificial bump gets clearer. In conclusion, we can say that this method to utilize AM is suitable for displaying fine roughness.

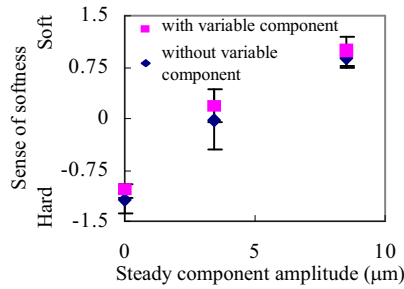


Fig. 7 Relationship between steady component amplitude and average value of evaluated softness sense

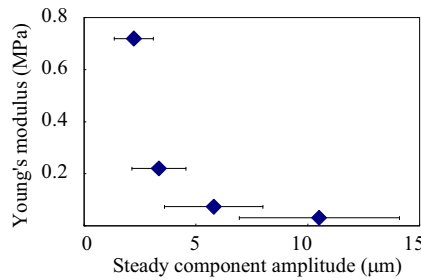


Fig. 8 Relationship between steady component amplitude and Young's modulus

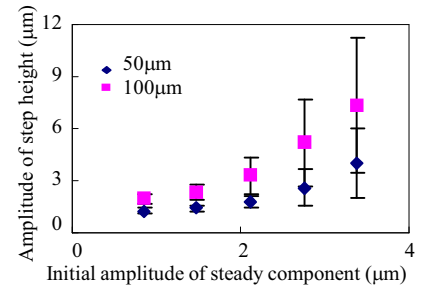


Fig. 9 Effect of initial amplitude on roughness sense

Second, effect of variable component on softness sense was surveyed. The examinees were asked to evaluate three different artificial tactile senses whose amplitude of steady component were 0 μm , 3.4 μm and 8.5 μm , respectively, on a 7-point scale using items related to softness sense. Each artificial sense was displayed in two ways, with variable component and without variable component. Sine curve was used for waveform of the variable component and frequency f was calculated by

$$f = \frac{v}{\lambda} \quad (3)$$

where v was touch velocity and λ was wavelength. Amplitude and λ of the variable component were 2 μm and 1 mm, respectively. Fig. 7 shows averages and standard deviations of the evaluation for each artificial tactile sense, where horizontal and longitudinal axes are the amplitude of the steady component and the evaluation value of the softness sense, respectively. The averages were calculated after normalizing the evaluation values of each examinee against each evaluation item to relieve effects of individual difference. As shown in Fig. 7, presence or absence of variable component does not affect softness sense while amplitude of steady component has much effect on it. By conducting analysis of variance, it was found that the effectiveness of variable component was not significant in softness sense, whereas amplitude of steady component was significant in it in 99 % confidence interval. In conclusion, it was confirmed that different softness senses can be displayed without being affected by variable component of AM wave.

3.2. Effect of Steady Component of AM wave on Tactile Senses

First, relationship between amplitude of steady component and displayed softness sense was quantified. The task in this sensory evaluation experiment was to compare samples having difference in Young's modulus and artificial tactile sense, and then adjust the amplitude of the steady component until perceived softness sense is felt

to be equal. The samples used in the experiment were rubbers with Young's modulus of 0.72, 0.22, 0.07, 0.03 MPa, respectively. Fig. 8 shows the relationship between Young's modulus of the samples and averages of adjusted amplitude of steady component. As shown in Fig. 8, the larger steady component amplitude becomes, the more considerable the adjusted value varies. This shows the limitation in ability to display softness sense only by the control of steady component amplitude. It will be the future task to display wider range of softness sense by displaying reaction force simultaneously.

Second, the effect of the steady component amplitude on roughness sense was quantified by conducting a sensory evaluation experiment. The task for examinees was similar to the first experiment conducted in the previous section except the initial amplitude of the artificial bumps displayed in this experiment were under five different conditions. Two samples were used in the experiment having bumps with height of 50 μm and 100 μm , respectively. Fig. 9 shows the relationship between initial amplitude of steady component and step height. As shown in Fig. 9, it was found that the amplitude of the step height necessary to display a certain bump increases when the initial amplitude of the steady component increases. This is because stimulation arose mainly from drastic change in friction decreases by the increase of initial amplitude as shown in Fig. 3. By determining the amplitude of the variable component utilizing Fig. 9, we can compensate the effects of the amplitude of the steady component on roughness sense.

3.3. Effect of Tangential Force on Tactile Senses

First, proposed method for displaying friction sense was verified by conducting a sensory evaluation experiment. The examinees were asked to evaluate six different artificial tactile senses a, b, c, d, e and f on a 7-point scale using items related to roughness and friction sense. The amplitude of the variable component in a, b and c were 0 μm whereas the amplitude, wavelength and the frequency of the variable component in d, e and f were the same as those displayed in the second experiment conducted in section 3.1. Static and

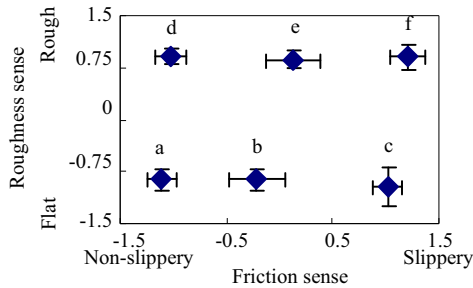


Fig. 10 Relationship between average values of evaluated roughness and friction sense

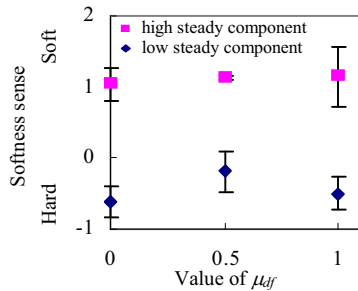


Fig. 11 Relationship between tangential force and softness sense

dynamic coefficient of friction μ_{sf} and μ_{df} displayed by force display was set 1.2 and 1.0 in a, d, 0.7 and 0.5 in b, e and 0 in c, f, respectively. Fig. 10 shows averages and standard deviations of the evaluation for each artificial tactile sense where horizontal and longitudinal axes are the evaluation value of friction sense and roughness sense, respectively. The averages were calculated after normalizing the evaluation values of each examinee against each evaluation item to relieve effects of individual difference. From Fig. 10, we can say that the examinees evaluate the artificial tactile senses more non-slippery when μ_{sf} and μ_{df} are larger. In fact, all the examinees state that they felt natural friction senses even if tangential force was displayed to the side of their finger. In addition, it was found that tangential force does not affect roughness sense. By conducting analysis of variance, it was found that the effectiveness of μ_{sf} and μ_{df} was significant in friction sense, whereas it was not significant in roughness sense in 99 % confidence interval. In addition, effect of tangential force on softness sense was surveyed. The task for the examinees were similar to the previous experiment except steady component amplitude of artificial sense d, e, f were 3.4 mm. Fig. 11 shows averages and standard deviations of the evaluation for each artificial tactile sense where horizontal and longitudinal axes are the value of μ_{df} and the evaluation value of roughness sense, respectively. The averages were calculated after normalizing the evaluation values of each

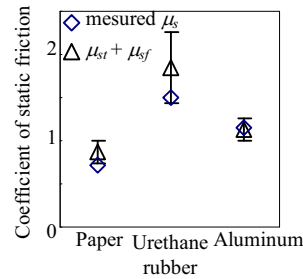


Fig. 12 Coefficient of static friction

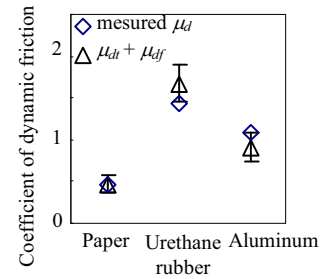


Fig. 13 Coefficient of dynamic friction

examinee against each evaluation item to relieve effects of individual difference. By conducting analysis of variance, it was found that the effectiveness of μ_{sf} and μ_{df} were not significant in softness sense in 99 % confidence interval. As stated above, it was confirmed that we can display friction sense without affecting roughness or softness sense by displaying tangential force to the side of human finger.

Second, a sensory evaluation experiment was conducted to confirm validity of calculating μ_{sf} and μ_{df} using equations (1) and (2), respectively. The examinees were asked to compare samples having difference in friction and artificial tactile senses, and then adjust μ_{sf} and μ_{df} until perceived friction sense is felt to be equal. The samples used in the experiment were paper, aluminum and urethane rubber. The static and dynamic coefficients of friction μ_s and μ_d of each sample were measured in advance when they were traced with human finger. Fig. 12 and 13 show the results of the experiment to adjust μ_{sf} and μ_{df} , respectively, when friction of ultrasonic vibrator is at a certain condition. As shown in Fig. 12 and 13, it was confirmed that the sum of μ_{sf} and μ_{df} that examinees adjusted and μ_{st} and μ_{dt} of ultrasonic vibrator almost corresponds with the measured μ_s and μ_d . Maximum error rate were 23.6 % in the experiment to adjust coefficient of static friction and 16.1 % in the experiment to adjust coefficient of dynamic friction. The former error rate was larger because of the difficulty of the experiment to adjust maximum static friction arising only for a moment. Especially, it was difficult to evaluate the moment of change from static to dynamic friction when the sample was urethane rubber because difference between coefficient static and dynamic friction of urethane rubber was very small. On the other hand, error rate of adjusting static friction was only 2.1 % when the sample was aluminium, whose difference between coefficient of static and dynamic friction was quite large. It means that friction sense can be displayed by using equations (1) and (2).

Table 1 Values of physical parameters of real materials

Material	Young's Modulus (MPa)	μ_s	μ_d
Silk	11.4	0.71	0.36
Felt	2.29	0.63	0.34
Silicone rubber	0.05	1.05	0.96
Cloth gum tape	Rigid body	1.60	1.28
Cardboard	Rigid body	0.70	0.31
Acrylic resin	Rigid body	2.04	1.56

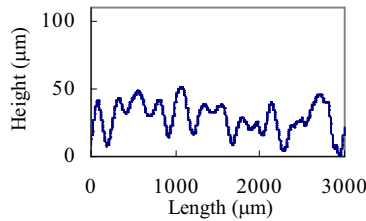


Fig. 14 Surface geometry of silk

Table 2 Values of control parameters of artificial tactile senses

Material	Max various component amplitude (μm)	steady component amplitude (μm)	μ_{sf}	μ_{df}
Silk	2.0	2.1	0.3	0
Felt	3.3	3.8	0.6	0.3
Silicone rubber	2.3	8.5	1.1	1.0
Cloth gum tape	3.2	1.2	0.3	0
Cardboard	3.4	1.9	0.4	0
Acrylic resin	0.5	0	0	0

Table 3 Percentage of questions answered correctly [%]

Displaying method	Silk	Felt	Silicone rubber	Cloth gum tape	Cardboard	Acrylic resin
Roughness	100.0	62.5	50.0	62.5	100.0	50.0
Hybrid	100.0	87.5	100	87.5	100.0	100

4. Verification Experiment

4.1. Outline of verification

In this chapter, hybrid texture of roughness, softness and friction sense of real materials are displayed simultaneously. Hybrid tactile senses were generated using method stated in the following section, and reality and variety of the artificial senses were evaluated by conducting two sensory evaluation experiments stated in section 4.3 and 4.4, respectively. In addition, artificial tactile senses reproducing only roughness of the materials were displayed for comparison. The sensory evaluation experiments were conducted by eight examinees. Experimental conditions were similar to those of chapter 3.

4.2. Generation method of hybrid tactile senses

Hybrid tactile senses of six materials shown in Table 1 were generated because they had various characteristics in surface texture, elasticity and friction characteristic. Table 1 shows Young's modulus and coefficient of static and dynamic friction of each material measured in advance. Cloth gum tape, cardboard and acrylic resin were assumed to be rigid as they had sufficiently larger Young's modulus compared to the other three materials. Table 2 shows the values of control parameters of the tactile display system. These values were determined by utilizing physical properties of each material and the relationships quantified in the preceding chapter. Surface geometry of each material was used for the waveform of each variable component. As an example, surface geometry of silk is shown in Fig. 14.

Steady component amplitude of the artificial senses recreating rigid materials were supposed to be 0. However, coefficient of friction of the vibrator surface is considerably large when ultrasonic vibration is not excited. Hence, steady component amplitude was adjusted to decrease the coefficient of friction. As the effect of steady component to softness sense was confirmed to be sufficiently small within the setup value, matching of friction was prioritized.

4.3. Material Discrimination Experiment

Material discrimination experiment was conducted to verify whether the artificial tactile senses could display the difference in texture of real materials. The task for examinees was to compare the artificial senses and answer which one correspond to original material, respectively.

Table 3 shows the percentage of questions answered correctly. As shown in Table 3, correct ratio had variance when only roughness sense was displayed. It is shown that examinees couldn't discriminate the tactile senses whose roughness were similar. On the other hand, correct ratio was larger than 87.5 % in all the cases when hybrid tactile senses were displayed. Especially, although the roughness of silicone rubber and acrylic resin was similar, correct ratio was 100 %. It is proved that the softness and friction sense of silicone rubber and acrylic were displayed using the proposed hybrid displaying method. In conclusion, multiple materials were discriminated with high accuracy using our system compared with the case when only roughness sense was displayed.

4.4. Evaluation using Adjectives

A sensory evaluation experiment using adjectives were

Table 4 Correlation coefficients to real materials

Evaluation item	Displaying method	
	roughness	hybrid
Bumpy / Flat	0.93	0.86
Rough / Fine	0.79	0.73
Soft / Hard	-0.16	0.84
Downy / Non-downy	0.12	0.75
Slippery / Non-Slippery	0.52	0.77
Warm / Cool	0.41	-0.06

conducted to evaluate the similarity of artificial senses and tactile senses of real materials quantitatively. The examinees were asked to evaluate hybrid artificial tactile senses and tactile senses of real materials on a 7-point scale using items shown in Table 4.

Coefficient of correlation between artificial tactile senses and tactile senses of real materials are shown in Table 4 where horizontal and longitudinal axes are the evaluation values of artificial senses and real materials, respectively. Evaluation values of each examinee were normalized against each evaluation item to relieve effects of individual difference. The items that had larger correlation coefficient than 0.7 and were significant in 99 % confidence interval are colored in gray. As shown in Table 4, when only roughness sense was displayed, items relating to roughness sense had large correlation coefficient, whereas items relating to the other senses had small correlation coefficient. On the other hand, when hybrid tactile senses were displayed, items relating to roughness, softness and friction senses had large correlation coefficient. Hence, we can conclude that variety and reality like real materials are successfully displayed using our system.

5. Conclusion

We proposed the method for displaying roughness, softness and friction sense, simultaneously, by compensating the interference among multiple parameters of ultrasonic vibration and force feedback on multiple tactile senses. First, relationship among three parameters, variable and steady component of amplitude modulated wave of ultrasonic vibration and force tangential to the side of human finger displayed using force display, and tactile senses were quantified by conducting several sensory evaluation experiments. Then tactile display system for realizing hybrid display of roughness, softness and friction senses was constructed based on the obtained knowledge. Finally, different from numbers of previous tactile displays, our tactile display system could successfully display various realistic tactile senses very close to the real texture of material surface. Integrating method for displaying thermal and reaction information with our present system and

generating distributed stimulation will be future studies for realizing more realistic and various tactile senses.

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