2009 IEEE International Conference on Robotics and Automation
Kobe International Conference Center
Kobe, Japan, May 12-17, 2009

Transmission of Tactile Roughness through Master-slave Systems

Shogo Okamoto, Masashi Konyo, Takashi Maeno and Satoshi Tadokoro

Abstract— **In this study, a tactile-roughness transmission system applicable to master-slave systems with a communication time delay is developed. The master-side system constructs a local model of target objects placed in the slave-side environment. Tactile feedbacks presented to an operator at the master side are produced by combining the physical properties of target objects in the local model and the kinetic information of the operator. The time delay between the operator's motion and the tactile feedback is cancelled because the stimuli are synchronized with the exploratory motions.**

The proposed system is applied to the transmission of tactile-roughness. The tactile stimuli presented to the operator are vibratory stimuli whose amplitude and frequency are controlled. These stimuli are locally synthesized by combining the surface wavelength of target objects and the operator's hand velocity. Using the developed tactile-roughness transmission system, an experiment for transmitting the perceived roughness of grating scales was conducted. As a result, the roughness perceived by the operators was found to highly correlate with the roughness of the scales in the slave-side environment with a coefficient of 0.83.

I. INTRODUCTION

The transmission of tactile sensations is a technology that enables human operators to perceive textures being touched by robots. This technology provides the operators with benefits such as the facilitation of texture recognition, an improvement in the reality of perception, and providing a stable grasp by preventing slippage.

For the majority of tactile transmission systems, tactile stimuli are presented to the operator on the basis of the information sensed by tactile sensors. In related studies, various tactile transmission systems have been developed. For instance, palpation systems for minimal invasive surgery [1][2], tactile transmission to aid robotic manipulation for master-slave systems [3–5], transmission of perceived textures [6], or presentation of tactile sensations for prosthetic arms [7] have been reported. However, none of the studies addressed the problem of a communication time-delay between the tactile-display-side and tactile-sensor-side systems.

For tactile transmission systems, a communication time delay between the master and the slave side systems impairs tactile exploration. One of the problems induced by the time delay is a temporal gap between the exploratory motions of the operators and the corresponding tactile feedbacks presented to them. The allowable time delay is approximately 40–60 ms. When the time delay is significant, the operators do not perceive the textures accurately, or the validity of the system is deteriorated [8].

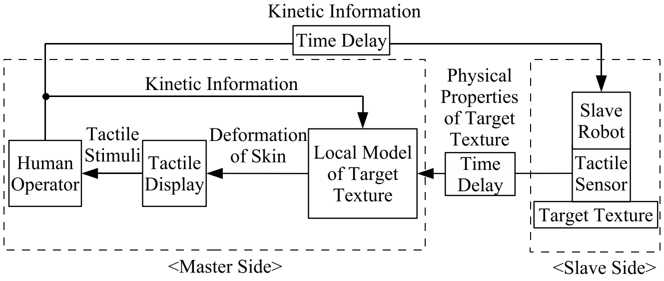

Fig. 1. Block Diagram of the Proposed Tactile Telepresence System

The objective of this study is to develop a system for the transmission of tactile roughness using a master-slave system with a communication time delay. The system cancels the temporal gap between the exploratory motions and the tactile stimuli. In order to cancel the gap, a tactile telepresence system based on the physical parameters has been proposed [9]. However, the previous system transmitted only vibratory frequencies as roughness stimuli and could not achieve the transmission of perceived roughness. In this study, the transmission of vibratory amplitudes as well as frequencies for realizing the transmission of tactile roughness is achieved.

II. PROPOSED TACTILE TELEPRESENCE SYSTEM

A. Stimuli Generation in Synchronization with Exploratory Motions at Master Side

Figure 1 illustrates a block diagram of the proposed system. The proposed tactile transmission system does not directly transfer the information sensed by a tactile sensor at the slave side to the operator at the master side. This is because the transmitted information includes a time delay. Instead, the master-side system constructs a local model of the target objects placed in the slave-side environment. The tactile feedbacks are generated by combining the exploratory motions of the operators and the physical properties in the local model. The temporal gap between the motions and the stimuli due to the communication time delay does not occur because the stimuli are synchronized with the motions.

The slave-side system estimates the physical parameters of the target textures and transmits them to the master side system. The slave-side system continues to estimate and transmit the parameters in order to renew the model at the master-side. A delay in the renewal of the model cannot be avoided due to the communication time delay or the delay in tactile sensing; however, this problem is relieved by sensing the physical parameters in real time.

S. Okamoto, M. Konyo and S. Tadokoro are with the Graduate School of Information Sciences, Tohoku University, Japan, okamoto, konyo, tadokoro@rm.is.tohoku.ac.jp

T. Maeno is with the Graduate School of System Design and Management, Keio University, Japan

978-1-4244-2789-5/09/$25.00 ©2009 IEEE

Though, the proposed system cancels the delay between the operator's motions and the tactile feedbacks presented to them, the transmission of the physical properties of target textures still includes a delay. Therefore, the proposed method does not accurately transmit the tactile sensations of uneven textures whose surface property frequently changes. However, the method is effective for the texture that is even or smoothly changes.

B. Application to Tactile Roughness

We apply the proposed system to the transmission of tactile roughness.

We determine the physical parameters and the types of exploratory movements that affect roughness perception from literature on psychophysics. The perceived roughness of grating scales used in this study strongly depends on the spatial wavelengths or the groove widths of the scales [11–13]. The vibratory frequencies of cutaneous deformations that are determined by the hand speeds affect perceived roughness [13][14]. Therefore, we focus on the surface wavelength of textures λ and the hand velocity $v(t)$.

The developed system employs vibrotactile stimuli for presenting tactile stimuli to the operators. The frequency and amplitude of vibrotactile stimuli are known to affect the subjective magnitude of stimuli [15][16]. By varying the frequency and amplitude of vibratory stimuli, the system controls the perceived roughness that is presented to the operators. In other words, the magnitude and speed of cutaneous deformations are controlled.

III. ROUGHNESS-TRANSMISSION SYSTEM

A. Master-side

1) Generation of Tactile Stimuli Via Vibration: A method for generating tactile stimuli at the master-side system is described. When a human finger explores a roughness specimen with a surface wavelength λ at a velocity v, a vibration with a fundamental frequency $f = v/\lambda$ is perceived by the human finger. As a substitute for this stimulus, sinusoidal deformations with frequency f are applied to the finger via a vibrator. The voltage applied to the vibrator is

$$y = A \sin(2\pi f t) + B, \tag{1}$$

where A and B are the amplitude and bias, respectively. The bias was 75 V, which was half of the maximal voltage applied to the vibrator.

2) Tactile Display System: The vibrator is a piezo-stack-type actuator (NEC/TOKIN ASB510C801P0). The maximal deformation generated by the vibrator is approximately 55 μm for $A = 75$ V. The deformation changed linearly with the applied voltage. As to the frequency characteristics of the vibrator, the gain reached -3 dB at approximately 310 Hz. The characteristic was relatively flat within the range of frequencies used for the tactile stimuli. The output force of vibrator is 800 N, i.e., large enough so that the vibration does not attenuate due to the finger force of the operator.

A block diagram of the tactile display system [8] is shown in fig. 2. The vibrator is installed on a linear slider whose position on a linear guide is measured using an optical encoder. A control computer receives the position of the slider and generates the value of the electric voltage to be applied to the vibrator. The control frequency of the computer was 5 kHz.

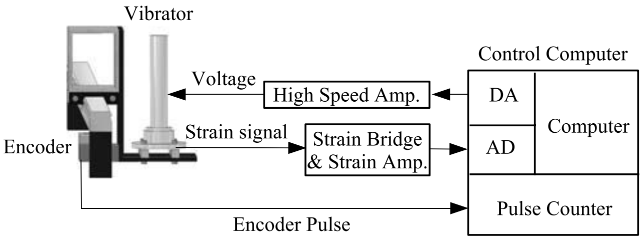

Fig. 2. Block Diagram of the Master-side System

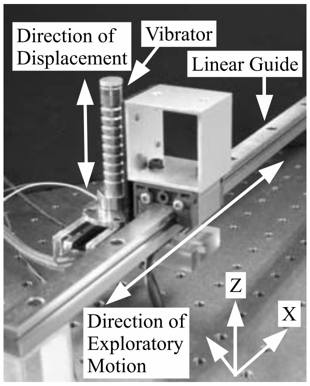

Fig. 3. Image of the Master-side Setup

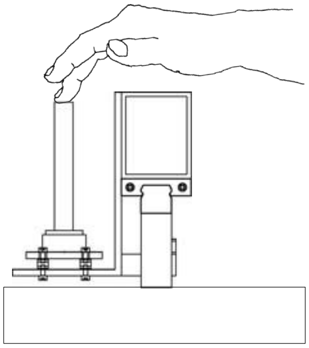

Fig. 4. Contact between the Finger and the Vibrator

Figure 3 illustrates an image of the tactile display device. The operators held their right middle finger on the vibrator and moved their hand along the linear guide (X-axis). The vibrator generated the deformation along the Z-axis. The operators were instructed not to touch any parts of their hands to the equipment except the right middle finger, as shown in fig. 4.

The users agreed that the vibrations transmitted by the equipment resembled the ones they perceived when they explored rough surfaces such as grating scales through a stylus.

B. Slave-side

1) Tactile Sensor: The tactile sensor of the developed tactile-roughness-transmission system needs to estimate the spatial wavelength of texture surfaces. The estimation method is described in subsection IV-A. In addition, the sensor needs to have an elasticity similar to that of human fingers because the developed system determines the amplitude of vibratory stimuli presented to the operators from the magnitude of the sensor's deformation.

The developed system installed a human-finger-like tactile sensor [17]. Its structure is illustrated in fig. 6. The sensor has the strain gauges as transducers embedded inside a silicone rubber body. Ridges that emulate the epidermal ridges of human fingers are arranged around the outer layer of the sensor. The width of the ridge is 0.6 mm. The strain gauges are placed beneath the ridges and designed to sense the

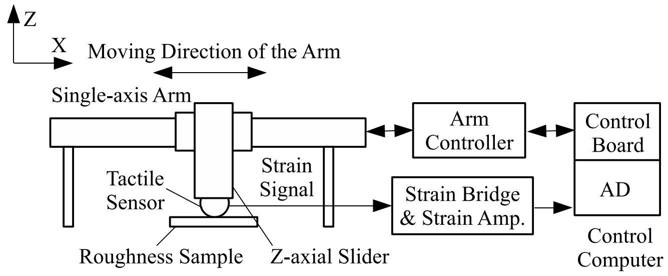

Fig. 5. Schematic Diagram of the Tactile-Sensor-Side System

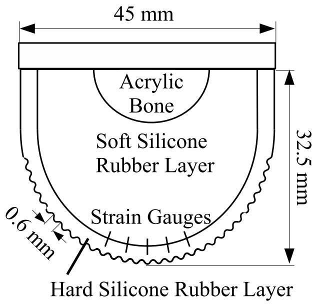

Fig. 6. Tactile Sensor used in the Tactile Transmission System

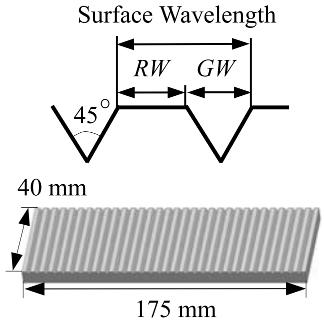

Fig. 7. Trapezoidal Grating Scale: Cross-sectional View and Overall View

vibratory information of the ridges when the sensor contacts an object. The dimensions of the sensor should be as large as those of average human finger. However, currently, the sensor is three times as large as a human middle finger, and its thickness is 10 mm.

The wavelength-estimation method used in this study has a generality that is applicable to other tactile sensors. However, the sensor is capable of estimating friction coefficients between the target objects and their Young's moduli. The application of the sensor can be extended to the transmission of perceived friction and softness, which the authors plan to develop.

2) Slave-side System: A schematic view of the slave-side system is presented in fig. 5. The sensor is attached to a single axial arm (YAMAHA MR12T) through a Z-axial slider. The arm is activated along the X-axis and is controlled by a computer. The outputs of the strain gauges of the tactile sensor are transmitted to the AD board of control computer by means of a strain amplifier. The strain signals were sampled at 1 kHz.

The roughness specimens scanned by the tactile sensor are grating scales with alternate grooves and ridges, as shown in fig. 7. The ratio of RW(ridge width) to GW(groove width) is 1 and the surface wavelength λ is defined as $RW + GW$. The tactile sensor is thrust 1 mm deep into the specimens with the static reaction force in the normal direction being approximately 0.6 N. However, this figure is not important in this study, and it was confirmed that the sensor worked properly with the pressing depth of up to 2.5 mm (2.1 N).

C. Connection of Master and Slave Systems

The developed tactile-roughness transmission system comprises the master-side system and the slave-side system described in III-A, III-B, respectively. They are connected by Ethernet. The tactile sensor in the slave-side system is position-controlled by the position of the operator's hand at the master side. The communication rate was set to 250 Hz.

IV. ESTIMATION OF SURFACE WAVELENGTHS AND VIBRATORY AMPLITUDE OF TACTILE SENSOR

As mentioned in II, the frequency f and amplitude A of the vibratory stimulus are controlled for displaying tactile-roughness to the operators.

f is determined by the surface wavelength λ and the hand velocity v using the relationship $f = v/\lambda$. The tactile sensor is required to estimate λ. The method for the estimation of λ using the tactile sensor is described in IV-A.

A is determined from the amplitude of the strain signals of the tactile sensor. The amplitude of the strain signals is also described as a function of λ and v, $g_A(\lambda, v)$. The function $g_A(\lambda, v)$ is experimentally identified in IV-B.

A. Surface-Wavelength Estimation by FFT

1) FFT-based Wavelength Estimation Method: When the tactile sensor scans the target texture, the sensor vibrates because of collisions. The spatial wavelength of the object can be estimated from the frequency of this vibration on the basis of the relationship $\lambda = v(t)/f(t)$, where $f(t)$ is the vibratory frequency of the sensor at t, $v(t)$ is the velocity of the sensor.

From the time sequential data of the strain outputs, FFT is computed. The power spectrum density acquired by means of the FFT reveals the vibratory frequencies of the sensor. FFT-based estimation is suitable for the proposed tactile-roughness transmission system because FFT deals with multiple frequency components in real time. However, this study transmits the fundamental frequency only. In order to extract a single fundamental frequency, the frequency with the maximal power was defined as $f(t)$.

The window size of the FFT was experimentally determined to be 32 ms. The size was selected from among the following values –16, 32, 64 and 128 ms– so that the estimation error was minimal when the sensor scanned the grating scales with surface wavelengths ranging from 0.5–3.0 mm at an average exploratory velocity of humans. The average velocity was assumed to be $v(t) = 197.0 \sin(2\pi 1.07t)$ mm/s from a past study where the operators conducted a tactile exploration of virtual textures using the same tactile display device as that used in this study [8].

2) Experimental Validation of Estimation Method: Figure 8 illustrates the surface wavelengths estimated by the FFT-based method when the sensor scanned the roughness specimens at constant speeds. Three different scanning speeds were used. They were the mean and mean plus-minus two times the standard deviation of the average exploratory velocity mentioned above, and their values were 73.5, 125.4, and

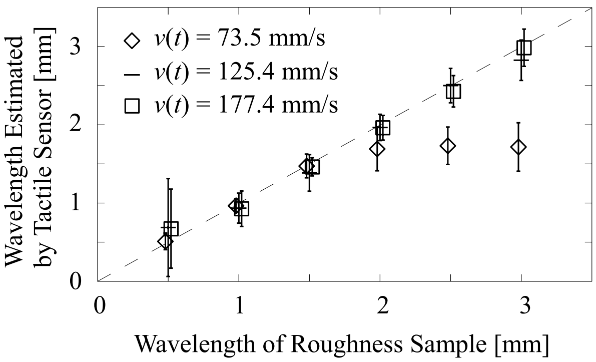

Fig. 8. Estimated Surface Wavelengths of Roughness Samples by FFT-based Method When the Sensor Scanned Samples at Constant Speeds

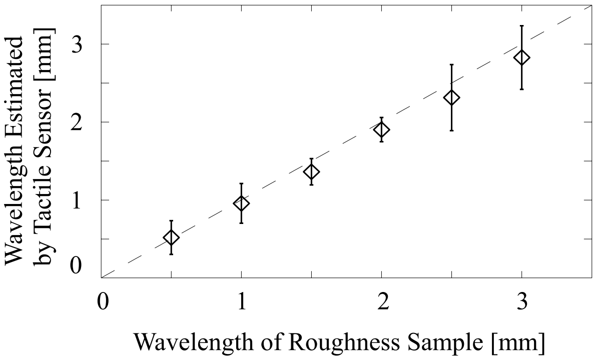

Fig. 9. Estimated Surface Wavelengths of Roughness Samples When the Sensor Scanned Samples at Sinusoidal Velocity

177.4 mm/s, respectively. The sensor scanned the specimens over a length of 175 mm. The figure indicates the average of the estimated wavelengths per ms. Apparently, the estimation errors were larger when the sensor scanned the specimens with wavelengths ranging from 2–3 mm at the minimal speed of $v = 73.5$ mm/s. This was due to the frequency resolution of the FFT. The lower the vibratory frequency, the further significant is the effect of resolution on the estimation error.

Figure 9 presents the estimation results when the scanning velocity was sinusoidal. The velocity was $v(t) = 197.0\sin(2\pi 1.07t)$. The estimation was conducted on the basis of the data acquired for five cycles, i.e., 4.665 s. The dots in the figure are average values per ms and standard deviations. The estimation was approximately correct except for the wavelengths ranging from 2–3 mm as well as that at the constant speeds.

B. Determination of Amplitude of Sensory Signal as a Function of Wavelength and Velocity

The function $g_A(\lambda, v)$, which determines the amplitude of sensory outputs of the tactile sensor, was experimentally determined. The amplitude of the output signal was obtained from the FFT of the signals. The maximal power among the power spectrum was used as the amplitude of the signals of the sensory outputs. In order to determine the function, the maximal signal power was recorded by varying λ and v in the experiment. As a result, it was found that the signal power was significantly affected by λ, but rarely affected by v. Therefore, the signal power was found to a function of λ. The experimental conditions, results, and the determined function are presented in detail in this following sections.

1) Experimental Conditions: In the experiment, the sensor scanned the specimens at constant speeds. Then, the FFT of gauge signals generated during the scanning was computed and the maximal power among the power spectral density was recorded. The scanning speed was in the range of 50–230 mm/s, and the wavelength was varied in the range of 0.8–2.0 mm.

2) Experimental Results: Figure 10 shows the plots of the computed signal powers and scanning speeds for the roughness specimens with different surface wavelengths. The signal power was recorded every 1 ms and averaged. Contrary to our predictions, the signal power was not significantly affected by the scanning speed. Within the investigated range, the powers did not exhibit a specific trend respective to the scanning speeds, and were comparatively flat. Hence, the effect of the sensor speed on the signal power was ignored. However, from a dynamic point of view, it should be noted that the power spectral densities were found to vary due to the stick-slip effect.

Figure 11 shows the relationship between the signal power and the surface wavelength of the roughness specimens. The error bars indicate the standard deviations among the scanning speeds. The relationship between the signal power and the wavelength of the specimens is nonlinear, and the power exhibits a local maximum for the wavelength of 1.2–1.6 mm. The width of the distal ridges of the tactile sensor is 0.6 mm, which is almost the same as the groove width of these roughness specimens. The local maximum is observed only if these two parameters match. Therefore, it depends on the dimensions of the tactile sensor, and the sensor needs to be downsized in the future for improving the reality of tactile sensations. The relationship between the power and the wavelength is approximated ($R^2 = 0.94$) by using a fourth-order function as follows:

$$\begin{aligned} g_A(\lambda) = 30770\lambda^4 - 162663\lambda^3 + 309743\lambda^2 \\ -248938\lambda + 72298. \end{aligned} \tag{2}$$

This equation is used to determine the amplitude of the vibratory stimuli presented to the operator in V. Since in this study, the master-slave system does not have a degree of freedom in Z-axis, the pressing force of the sensor to the roughness samples is constant. In case that the proposed method is extended to the system with Z-axial movements, the pressing force needs to be involved in the local model and (2).

V. EXPERIMENT: TRANSMISSION OF TACTILE ROUGHNESS

An experiment to transfer the tactile roughness of the grating scales to the operator is conducted. Three types of experiments are conducted.

In experiment 1, the roughness-transmission experiment is conducted while the proposed measure is applied to the master-slave system. For comparison, experiments 2 and 3 are conducted when the proposed measure is not applied,

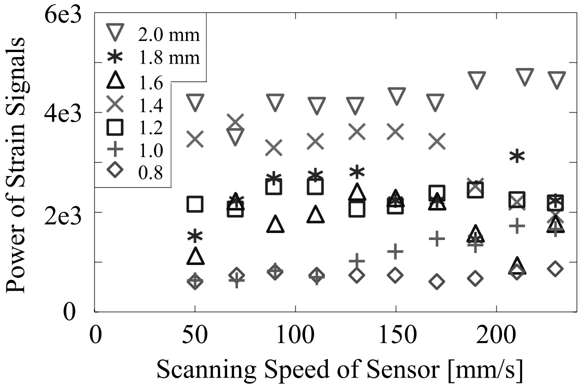

Fig. 10. Power-v Plot: Relationships between Signal Powers and Scanning Speeds by Surface Wavelength of Roughness Specimens

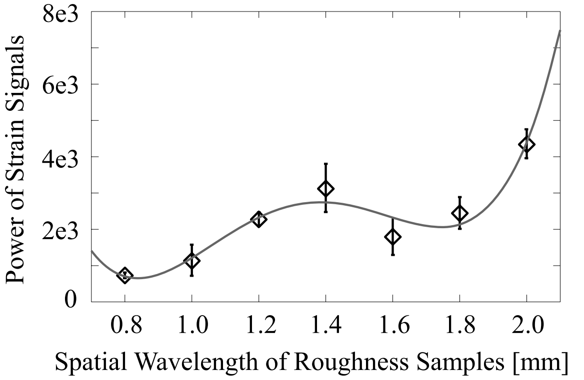

Fig. 11. Power-λ Plot: Relationships between Signal Powers and Surface Wavelength of Roughness Specimens

and time delays are simulated between the hand movements of operators and the tactile feedbacks. In experiment 2, the delay is a constant value. In experiment 3, the delay varies, emulating jitter. The manner in which these simulated time delays are generated is described in V-B.

In order to equalize the quality of tactile stimuli in all types of experiments, the stimuli are produced by the same method, which is described in V-A. Then, after the experiments, these experimental results are compared with each other.

The participants were eight staff and students of Tohoku University who were in their 20s and 30s. All eight participants participated in experiments 1, 2, and 3. First, they performed experiment 1. Then, they performed experiments 2 or 3. Four participants performed experiment 2 followed by experiment 3 while the others performed the experiments in the opposite order.

A. Vibratory Stimuli

For the vibratory stimuli, f and A of the vibration were controlled. The relationship $f = v/\lambda$ determined f. The amplitude of sensory outputs of tactile sensor determined A using (2). The applied voltage $y(t)$ to the vibrator was

$$A(\lambda) = \frac{B}{P_{max}} g_A(\lambda), \tag{3}$$

$$f(\lambda, v) = \lambda/v, \tag{4}$$

$$y(t) = A(\lambda)\sin(2\pi f(\lambda, v)t) + B, \tag{5}$$

where P_{max} was 6000 in order to adjust the output voltage level to the maximam output voltage of the equipment.

B. Simulated Temporal Gap

A method for simulating the time delay between the hand movements and tactile feedbacks in experiments 2 and 3 is described. The delayed stimuli are produced from buffered hand movements. The voltage applied to the vibrator is given by

$$y(t) = A(\lambda)\sin\left(\frac{2\pi v(t-D)t}{\lambda}\right) + B \tag{6}$$

where D is the simulated time delay. In experiment 2, D is 120 ms, which is two times the detection threshold of the time delay [8]. In experiment 3, which emulates jitter, D is subjective to a normal distribution whose mean and standard deviation are 120 ms and 40 ms, respectively. D is sampled every 200 ms, i.e., 5 Hz in experiment 3.

C. Task & Procedure

The participants explored the roughness samples at the slave side through the developed master-slave system. At the same time, they were allowed to touch the grating scales by their bare fingers as comparison stimuli. The number of comparison stimuli was 12 and their wavelengths were 0.4–2.6 mm. The participants chose the comparison stimulus which was felt closest to the tactile roughness they perceived through the master-slave system. They could report the middle of the one stimulus and the another stimulus as the answer. They were allowed to touch the comparison stimuli whenever they wanted using their right hand or left hand. Some of the participants touched the vibrator with their right middle finger and touched the comparison stimuli with their left hand. The other touched the vibrator and the comparison stimuli alternatively with their right hand. At the slave side, seven types of stimuli were prepared. Their wavelengths were 0.8–2.0 mm.

The one trial was limited to 20 s and the order of stimuli presentation was random. Each stimulus was presented three times and the answers from the second and third trials were employed as the formal answers. Before the experiment, the participants practiced for the task as long as they wanted. Individual practice was approximately 5 min. The number of participants was four. They heard pink noise through headphones.

D. Experimental Result

Figure 12 shows the results of experiment. The vertical axis is the average wavelength of the comparison samples that the participants reported, and the horizontal axis is that of the presented samples. The error bars are the standard deviations among the participants. The answers reached the local peak at λ=1.2–1.6 mm, and drew a s-shaped curve. The s-shaped curve reflected the profile of (2) and fig. 11.

Figure 13 shows the average and standard deviations of coefficients of correlation between the roughness samples presented at the slave-side and the samples reported by the participants. In experiment 1, in which that the proposed

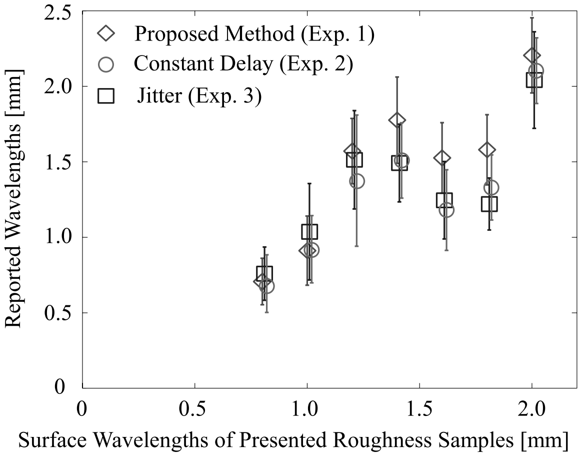

Fig. 12. Results of Roughness-Transfer Experiment: Presented Roughness Stimuli and Stimuli Selected by Participants

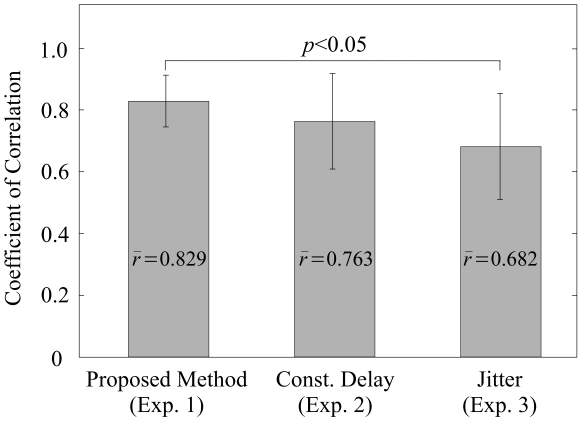

Fig. 13. Average Coefficient of Correlationship Between the Presented Roughness Samples and Reported Roughness

measure was applied, the participants' answers had strong correlation with the presented samples ($r = 0.83$). Experiment 2, a constant delay existed, exhibited the second highest coefficient. Experiment 3, jitter was simulated, exhibited the lowest coefficient. Welch's t-test showed significant difference between experiment 1 and 3 ($t = 2.70$, $df = 10.13$, $p = 0.027$, one-tailed).

From above experimental results and analysis, the operators could most accurately experience the roughness of textures presented at the slave-side, when the delay between the exploratory motions and tactile feedbacks was cancelled by the proposed method in experiment 1. Also, according to the interviews after the experiments, the participants recognized the existence of the delay, and the tactile feedbacks were unnatural in experiments 2 and 3. Thus, it was experimentally confirmed that the proposed method can transmit roughness sensations of textures through teleoperation with a communication time delay.

VI. CONCLUSION

A tactile-roughness transmission system applicable to master-slave systems with a communication time delay was developed. At the master side system, tactile stimuli were generated on the basis of the local model of target textures and were synchronized with the exploratory motions of the operators.

A tactile-roughness transmission experiment was conducted using the developed system. The result indicated that the proposed method could more effectively transmit the perceived roughness to the operators than the system in which the delay was not compensated.

REFERENCES

[1] R. D. Howe, W. J. Peine, D. A. Kontarinis and J. S. Son, Remote Palpation Technology, *IEEE Engineering in Medicine and Biology*, Vol. 14, No. 3, pp. 318–323, 1995

[2] M. V. Ottermo, Virtual Palpation Gripper, *Ph.D. Thesis of Norwegian University of Science & Technology*, 2006

[3] J. T. Dennerlein, P. A. Millman and R. D. Howe, Vibrotactile Feedback for Industrial Telemanipulators, *Proc. of the Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME Intl. Mechanical Engineering Congress & Exposition*, pp. 189–195, 1997

[4] A. M. Murray and R. L. Klatzky, Psychophysical Characterization and Testbed Validation of a Wearable Vibrotactile Glove for Telemanipulation, *Presence*, Vol. 12, No 2, pp. 156–182, 2003

[5] M. Shimojo, T. Suzuki, A. Namiki, T. Saito, M. Kunimoto, R. Makino, H. Ogawa and M. Ishikawa, Development of a System for Experiencing Tactile Sensation From a Robot Hand by Electrically Stimulating Sensory Nerve Fiber, *Proc. of the 2003 IEEE Intl. Conference on Robotics and Automation*, pp. 1264–1270, 2003

[6] A. Yamamoto, K. Kim and T. Higuchi, Tactile Telepresence System using PVDF Sensors and Electrostatic Stimulator, *IEEE Transactions on Visualization & Computer Graphics*, Vol. 12, No. 2, pp. 168–177, 2006

[7] K. Warwick, M. Gasson, B. Hutt, I. Goodhew, P. Kyberd, B. Andrews, P. Teddy and A. Shad, The Application of Implant Technology for Cybernetic Systems, *Archives of Neurology*, Vol. 60, No. 10, pp. 1369–1373, 2003

[8] S. Okamoto, M Konyo, S. Saga, and S. Tadokoro, Identification of Cutaneous Detection Thresholds against Time-delay Stimuli for Tactile Displays, *Proc. of the 2008 IEEE Intl. Conference on Robotics and Automation*, pp. 220-226, 2008

[9] S. Okamoto, M. Konyo, T. Maeno and S. Tadokoro, Roughness Feeling Telepresence System on the Basis of Real-time Estimation of Surface Wavelengths, *Proc. of the 2007 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pp. 2698-2703, 2007

[10] S. Lederman, Tactual Roughness Perception: Spatial and Temporal Determinants, *Canadian Journal of Psychology*, Vol. 37, No. 4, pp. 498–511, 1983

[11] J. W. Morley, A. W. Goodwin and I. Darian-Smith, Tactile Discrimination of Gratings, *Experimental Brain Research*, Vol. 49, pp. 291–299, 1983

[12] T. Yoshioka, B. Gibb, A. Dorsch, S. Hsiao and K. Johnson, Neural Coding Mechanisms Underlying Perceived Roughness of Finely Textured Surfaces, *The Journal of Neuroscience*, vol. 21, pp. 6905-6916, 2001

[13] E. Gamzu and E. Ahissar, Importance of Temporal Cues for Tactile Spatial-Frequency Discrimination, *The Journal of Neuroscience*, Vol. 21, No. 18, pp. 7416–7427

[14] C. J. Cascio and K. Sathian, Temporal Cues Contribute to Tactile Perception of Roughness, *The Journal of Neuroscience*, Vol. 21, No. 14, pp. 5289–5296

[15] G. D. Goff, Differential Discrimination of Frequency of Cutaneous Mechanical Vibration, *Journal of Experimental Psychology*, Vol. 74, No. 2, pp. 294–299, 1967

[16] R. T. Verrillo, A. J. Fraiori and R. L. Smith, Sensation Magnitude of Vibrotactile Stimuli, *Perception & Psychophysics*, Vol. 6, pp. 366–372

[17] Y. Mukaibo, H. Shirado, M. Konyo and T. Maeno, Development of a Texture Sensor Emulating the Tissue Structure and Perceptual Mechanism of Human Fingers, *Proc. of the 2005 IEEE Intl. Conference on Robotics and Automation*, pp. 2565–2570, 2005