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Tactile Actuators Using SMA Micro-wires and the Generation of Texture Sensation from Images

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Abstract—**Humans communicate with each other by using not only verbal media but also the five senses such as vision, audition, olfaction and tactile sensations. Various devices and systems have been introduced for supporting human communication, and most of them are based on visual and auditory media. For presenting tactile sensations, some tactile actuators have been introduced recently, however these actuators require real objects to generate the various tactile sensations and input data to be associated with output tactile sensations should be prepared manually by a user. This study introduces an algorithm to automatically generate parameters from an object's image for driving tactile actuators. A tactile presentation system is constructed, and the validity of the texture sensations is verified by a user's experiment.**

I. INTRODUCTION

With the widespread availability of computers and mobile devices, we use them for exchanging visual and auditory information for daily communication. We obtain various information from multimedia devices, and such devices recently have a touch panel interface to allow a user to intuitively and interactively use them. A touch panel consists of a touch-sensitive panel and a graphical display, and accepts user's intuitive touch inputs together with visual and auditory feedback. For example, several graphical buttons are arranged in a visual display, so that a user is led to give a command from multiple selections presented in the display. Once he selectively touches one of visual buttons for the selection, the system accepts his input to react by presenting visual and auditory feedback echoes. In the real situation of touching a "real" button, he would feel the touching force, together with the tactile sensation of a button material. Such haptic and tactile feedback would not be obtained from touch panel inputs.

In the study of the presentation of tactile sensation, the development of different tactile and haptic displays have been introduces for the interaction with virtual objects and VR environment. For example, a haptic stylus was developed by POST-PC Research Group, Electronics and Tele-communications Research Institute from South Korea [1)]. They developed a haptic stylus interface with a built-in compact tactile display module and impact module and able to significant feedback to represent Braille, texture and button. This device is able to support touch screen operations by providing tactile sensations when a user touches an image displayed on a monitor. Another example is a research conducted by Human-Computer Interaction Institute of Carnegie Mellon University [2)]. They employ pneumatics method as an actuation form by creating dynamic physical buttons. The technique allows the structure of physical form and appearance such as buttons to be dynamically modified along with the interface that appears through the touch screen monitor. Another research is related to adding tactile sensations into touch screen interface, which was conducted by Interaction Lab of Sony CSL [3)]. The research presents the design, implementation and evaluation of tactile interfaces for small touch screen in mobile devices such as PDAs and digital video camera. However, in the presentation of various tactile sensations, these devices require real objects to generate the same tactile sensations, which might cause the difficulty for applying them in a real situation with various different objects.

To achieve the objective of this study, fundamental features such as a simple structure of a tactile actuator and the automatic generation of driving parameters are inevitable for the tactile presentation. In order to be embedded into a compact tactile display, a thread form of a shape memory alloy (SMA) is constructed titanium and nickel shown in Figure 1 is being utilized as a micro-vibration actuator for the tactile display [4),5)]. This paper proposes a method to automatically generate the driving parameters for the tactile actuators from texture features extracted from images by using an image processing technique. By preparing texture pictures, the image features are automatically extracted, and then translated to the driving parameters for the SMA actuators to present corresponding tactile sensations. We construct a tactile pen, in which tactile actuators are installed in the grip part, and conduct an experiment to verify the validity of the tactile presentation system.

II. TACTILE ACTUATOR USING SMA WIRE

The tactile actuator consists of a SMA micro-wire as a micro-vibration actuator for presenting mechanical vibratory stimuli to human skin. The SMA micro-wire has the diameter of 75μm, and responds to the specific temperatures, T_1 and T_2, which are 68 degrees and 73 degrees, respectively. By applying a weak current to the SMA, heat is generated by the internal resistance, and the SMA shrinks up to 5 [%] lengthwise at the temperature T_2. When the current stops and the temperature drops to T_1, it returns to the original length.

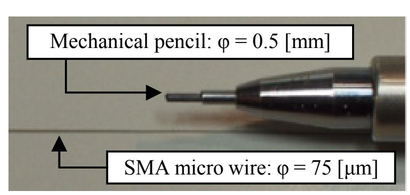

Fig.1. SMA micro-wire with 75μm diameter

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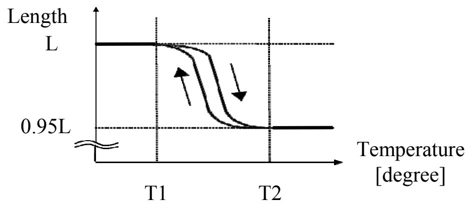


Fig.2. Thermal behavior of SMA micro-wire

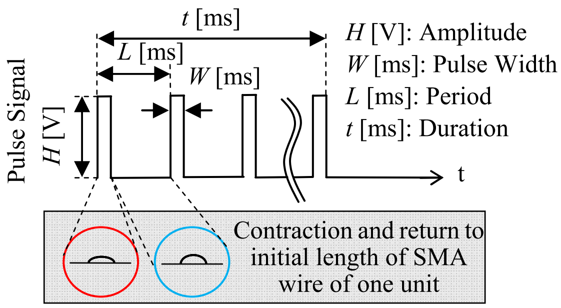
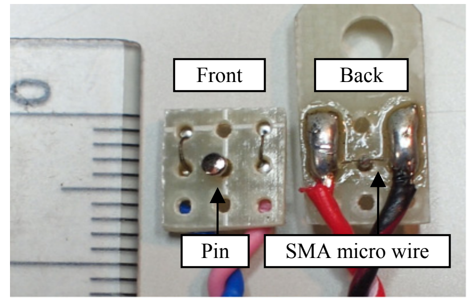


Fig.3. Pulse Signal for Driving SMA

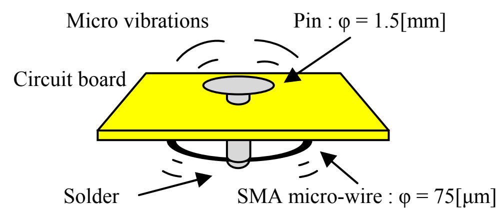
Figure 2 shows an outline drawing that explains the relationship between the temperature of the SMA wire and its length. The SMA wire is so thin that it rapidly cools after the current stops, and returns to its original shape when the temperature shifts from T_2 to T_1. This means that the shrinkage and the return to initial length of the SMA wire can be controlled by the pulse current as shown in Figure 3. The vibration frequency is determined by the frequency of the pulse signal. To control the magnitude of the vibration, on the other hand, the amplitude of pulse signals H and the duty ratio W/L should be determined based on the calories exchanged. When the tactile actuator generated micro vibrations to 50Hz, a high speed camera verified that SMA micro-wire perfectly synchronized with the ON/OFF pulse current, and shrunk in the contraction state to about 2µm toward the length.

In this study, a pin-type tactile actuator is developed as shown in Figure 4. Micro-vibration generated by the SMA actuator is conducted to the pin fixed to the wire by soldering, so that it generates greater vibratory stimuli to a finger or a palm of a user. We confirm that the vibration up to 300Hz is generated by synchronizing with properly prepared pulse-signals, and the mechanical vibrations are preferably perceived by tactile mechano-receptors under the skin such as Meissner corpuscles and Pacinian corpuscles, which respond to the frequencies lower than 100Hz, and also from 50 to 300 Hz, respectively[4)-6)].

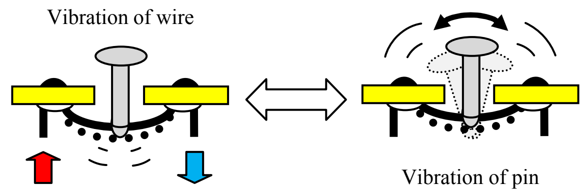
Micro vibrations are controlled by driving pulse currents, which are composed by the parametric values of the frequency, the amplitude and the duty ratio. The relations between the vibratory stimuli and the presented tactile sensations are studied in our previous studies published in 6). For example, the frequency is related to different tactile sensations; rough sensation is presented by the lower frequencies around 10 – 30Hz, on the other hand, smooth stroking sensations are generated by the higher frequencies around 50 – 100Hz. The duty ratio and the amplitude of the pulse signal have close relations with the strength of tactile sensations. In this manner, by suitably selecting parameter values that generate pulse current, particular tactile sensation is presented to a user.



a) Picture of a tactile actuator



b) Construction



c) Vibration of tactile actuator

Fig.4. Tactile actuator

Incidentally, human is able to imagine tactile sensation by just seeing a texture image. From a furry picture, we imagine soft and smooth tactile sensation, or bumpy rock surface may give rough and coarse impression to us. It means that a visual texture could be related to the tactile sensation perceived by a human in touching it. Based on the above assumption, we try to automatically generate tactile stimuli from a picture, and then translate them into a pulse current to drive the tactile actuators to present the tactile sensation.

III. Generation of Texture Sensation from Images

Humans are able to feel the texture sensations of an object by touching it with finger tips, and also imagine the surface textures and tracing sensations from visual information. In this study, by using an image processing technique, we try to extract visual features from a picture, and then convert them into pulse signals by selectively determining the frequency, the amplitude and the duty ratio. We pay attention to the cyclic patterns included in a picture, and try to relate them with features of tactile sensations. Cyclic patterns are extracted by Fourier Transform, and parametric values are obtained as the spatial frequency and the spectrum amplitude. Figure 5 shows an example of a picture *a*) and its Fourier Transform *b*), and the cyclic texture pattern in the picture is successfully extracted as the spatial frequency and its intensity. By relating the spatial frequency with the pulse frequency, and also the spectral intensity with the duty-ratio of a pulse signal, the driving pulse signals for the tactile actuators will be automatically generated. In addition, the tactile sensation perceived in rubbing an object surface should be changed, according to the moving speed of a finger.

In this study, we assume the following relations among the spectral features of a texture image and the presented tactile sensations;

$$f_p = \alpha(v_p)\cdot g(f_s) \qquad (1)$$

$$p_w = h(i_s) \qquad (2)$$

where f_p represents the driving pulse frequency, p_w shows the pulse width, f_s presents the spatial frequency extracted from an input image, i_s represents the spectral intensity given by the second peak in a FT image, and v_p presents the speed of a rubbing motion. The function α is a function that modifies the driving frequency of the actuators according to the speed of a user's motion, so that the user perceives the different response of a tactile sensation reacting to his actions. The functions α, g and h give the conversion from the image features and user's rubbing actions into the driving parameters for the tactile actuators. In this study, the functions would be determined by the users' experiments.

IV. Tactile Pen System

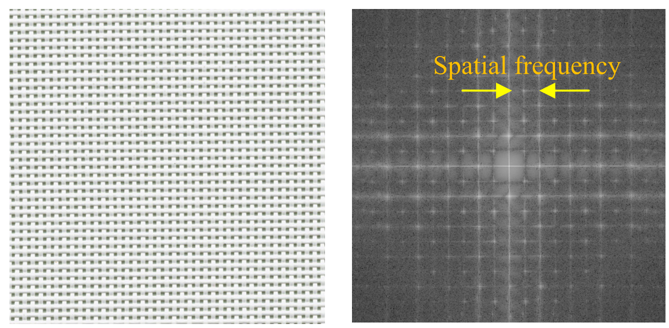
The tactile pen system is constructed as shown in Figure 6, which consists of a tactile pen connected with a tablet device, a tactile controller, a PC and a visual display. Two pin-type tactile actuators are mounted in the grip of the tactile pen, so that the tactile stimuli are presented to the user's thumb or the index finger. Tactile actuators present different tactile sensations based on the driving signals generated from the tactile controller. A tablet-device connected to a PC via USB is used for tracking the user's pen motion. A pointer in a visual display presents the trajectory in the tablet device. A texture picture is, at the same time, displayed in the visual display, and a user strokes the tactile pen on the tablet device, as if he rubs the texture picture in the display, and feels the tactile sensation presented by the tactile actuators in the pen grip.

A. Detail of Tactile Pen

The structure of the tactile pen is shown in Figure 7. Two actuators are mounted in the grip, and by placing a thumb or an index figure, a user feels tactile sensations, just by gripping the pen. The driving power is supplied by two AA-type batteries, so that the driving pulse-current from the tactile controller is given to the actuators. By using two actuators, various tactile sensations are presented. Simple vibrations are perceived as particular tactile sensations according to the frequencies and the duty-ratios of pulse current. Complex stroking or rubbing tactile sensations are presented by using tactile high-level perceptions such as the phantom sensations and the apparent movements.

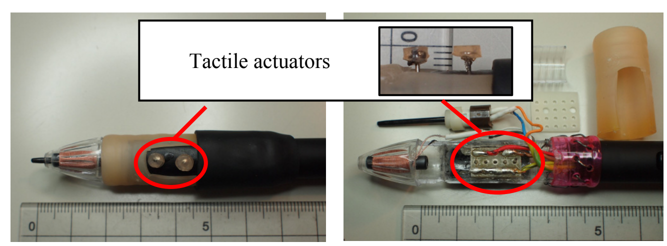
B. Preliminary Experiment of Tactile Pen System

To establish the relation between tactile stimuli generated from a picture and the perceived sensations, functional associations as Equations (1) and (2) are assumed. The functions $g(\cdot)$, $h(\cdot)$ and $\alpha(\cdot)$ should be determined for reproducing tactile sensations in rubbing a virtual object by a pen, and we conducted a preliminary experiment.



a) Input image *b*) FT image

Fig.5. Input image and its Fourier Transform



a) Tactile actuators in grip *b*) Inner structure

Fig.7. Detail of tactile pen

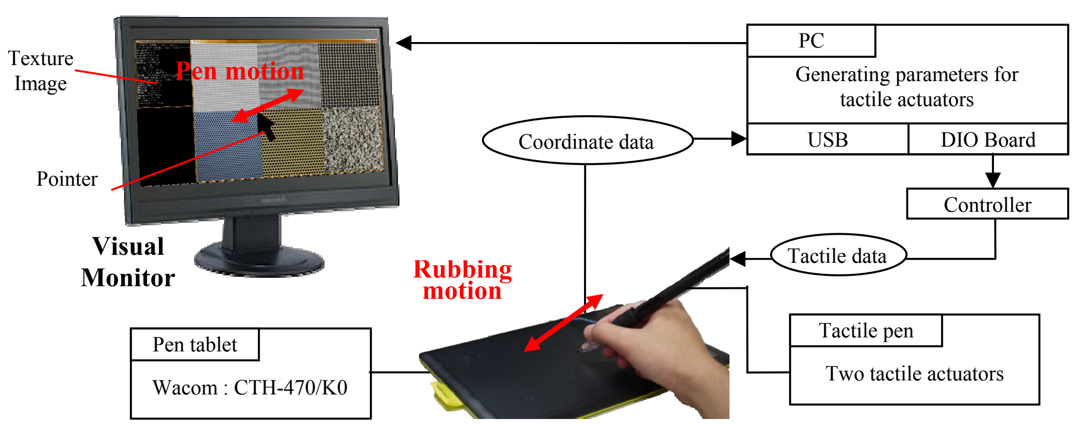
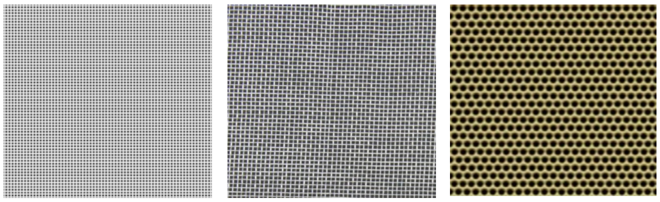


Fig.6. Construction of the tactile pen system

TABLE 1. Image characteristics

image	*Spatial frequency*[m^{-1}]	*Spectral intensity*
Image 1	799	0.874
Image 2	563	0.878
Image 3	287	0.928



1) image 1 2) image 2 3) image 3

Fig.8. Images used in preliminary experiment

In this experiment, three texture images having different spatial frequencies shown in Figure 8 and Table 1 are prepared, and displayed in a visual monitor. For the three pictures, relations between the extracted visual features and the presented tactile sensations are given by the equations (1) and (2), and the functions g, h and α are experimentally determined as introduced below.

C. *Experiment for Function* $g(\cdot)$

The function $g(\cdot)$ transforms the spatial frequency into the driving pulse frequency of the tactile actuator. Since the driving pulse frequency is a parameter that generates different kind of tactile sensations imagined from different images, it is primarily important to determine this function.

It is well-known that a psychological intensity depends on the Weber-Fechner law, which tells that the relationship between stimulus and perception is logarithmic. If the tactile sensation imagined from an image follows the psychological intensity, the relation should be considered by the basis of the Weber-Fechner law.

We assumed two different functions with different coefficient parameters, which are the liner function and the logarithm function shown as,

$$g(f_s) \;=\; k_1 \cdot f_s \tag{3}$$

$$g(f_s) \;=\; k_2 \cdot ln(f_s+1) \tag{4}$$

and the graph shapes with different values of coefficients k_1 and k_2 are shown in figure 9.

We conducted a users' experiment by the help of 8 subjects aged from 22 to 28 years old, for the evaluation of the presented tactile sensations, according to the different functional relations. The following two questions were given to the subjects, after the experience of the tactile presentation.

i) Matching degree between the images and the presented tactile sensations.

ii) Perception of difference among three different images.

The experimental results were presented in Figure 10. Only small differences between two different functions were recognized by the subjects, however the logarithm function gave slightly better performance. The difference of coefficient parameters caused the different impressions of the perceived tactile sensations, and the coefficient value of 40, presented by "I", gave the best performance.

D. *Experiment for Function* $h(\cdot)$

The relation between the spectral intensity obtained by Fourier Transform of an image and the driving pulse width for the tactile actuator is given by the function $h(\cdot)$. The pulse width of a driving signal is a parameter that changes the magnitude of the micro-vibration generated from the tactile actuator, which is considered to be associated with the spectral intensity obtained by an image.

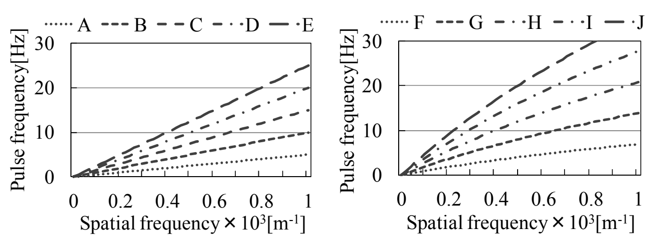
In order to examine how the variations of spectral intensity affect texture sensation on the object, the proportional relationship and the inverse-proportional relationship are prepared as

$$h(i_s) \;=\; k_3 \cdot i_s + 1 \tag{5}$$

$$h(i_s) \;=\; 5 - k_4 \cdot i_s \tag{6}$$

Since the tactile actuator has a constraint that the driving pulse width is restricted by the duty-ratio to satisfy the amount of the heat exchange shown in Figure 2, the range of the coefficient parameters k_3 and k_4 is determined as shown in Figure 11. Since the variation of pulse widths is limited and the range is narrow, we examined only the linear relations, by excluding logarithmic functions.

In the user's experiment, the discomfort level between the images and the presented tactile sensations was evaluated, by employing 8 subjects. Three different images shown in Figure 8 were prepared, and different levels of tactile stimuli were presented, which were evaluated by the subjects. The results are shown in Figure 12, and the linear relation with the coefficient of 40 shown by "D" gave the best performance.



a) Linear relation *b*) Logarithmic relation

Fig.9. Possible functions in experiment of $g(\cdot)$

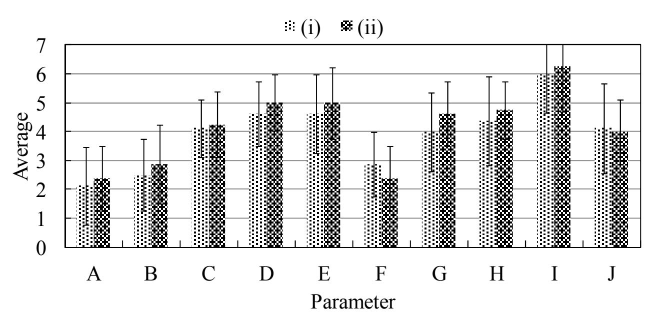
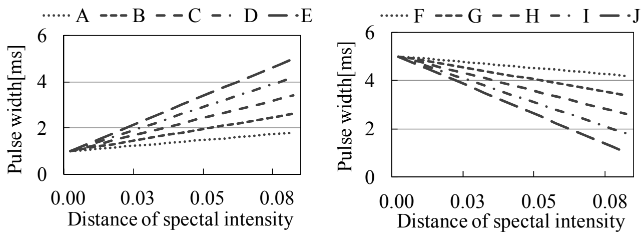


Fig.10. Results of experiment for function $g(\cdot)$



a) Proportional relation *b*) Inverse- proportional relation

Fig.11. Possible functions in experiment of $h(\cdot)$

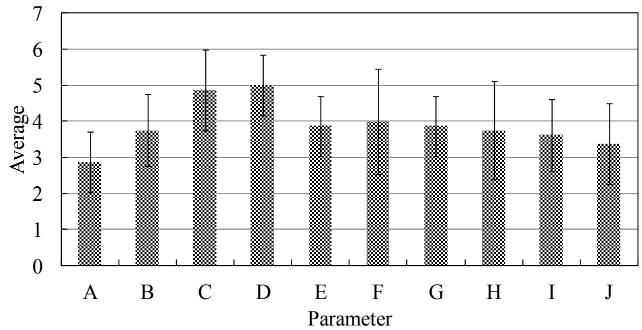


Fig.12. Results of experiment for function $h(\cdot)$

E. Experiment for Function $\alpha(\cdot)$

The function $\alpha(\cdot)$ presents the relation between the moving speed of the pen and the presented intensity of the tactile sensation. In this study, the obtained $g(\cdot)$ is modulated by the function $\alpha(\cdot)$, which is calculated based on the rubbing speed. In this study, we assume the non-linear relation given by the sigmoid function as

$$\alpha(v_p) = 2.9/(1+exp(-k_5 \cdot (v_p-60)))+0.1 \qquad (7)$$

and the graphs with different coefficients k_5 are shown in Figure 13. In this experiment, the following two questions were given to the 8 subjects, after experiencing the tactile presentation.

i) Matching of the rubbing motion speed and the intensity level of tactile sensation.

ii) Perception of difference according to the change of rubbing motion speed.

Figure 14 shows the experimental results, and presents that the modulation of tactile intensity in accordance with the rubbing speed performed preferable impression to the users. The coefficient 0.05 presented by "B" gave the best results.

V. Assessment of Proposed Method

Based on the preliminary experiments, the relation between image characteristics and the tactile parameters for driving the vibration actuators were determined. The tactile presentation system was assessed by a users' experiment. In addition to the three images used in the preliminary experiments, three new images shown in Figure 15 were also employed in the assessment. The characteristics extracted by Fourier transform are presented in Table 2, and the six characteristics are all different with each other to generate different parameters for driving the tactile actuators.

Six images that gave different texture impressions were arranged in a visual monitor as shown in Figure 16, and users made stroking motions on the tablet device to feel the textures presented from the tactile pen. Ten subjects aged from 22 to 28 years old participated in the experiment. Firstly, they experienced the tactile presentation enough to feel the tactile sensation from all the six pictures, and then evaluated the system with the following four items by the scale from 1 to 7, in which greater value gave better evaluation.

i) Accordance between visual images and the tactile sensations.

ii) Difference among visual images.

iii) Change of tactile sensations according to stroking velocity.

iv) Comfort of tactile presentations through the tactile pen.

The result of the assessment is shown in Figure 17. In the item ii), the standard deviation of the scores was greater than those of the other items, and on the other hand, the item iii) gave the smallest standard deviation. Some subjects reported the discordance of the tactile sensations with the visual impressions of the images, although they felt the differences among the images. The accordance between the visual impressions and the presented tactile sensations might be dependent upon the individual impressions based on the tactile experiences. The relation between the image and its tactile sensation should be established individually, and this would be further examined in the future work.

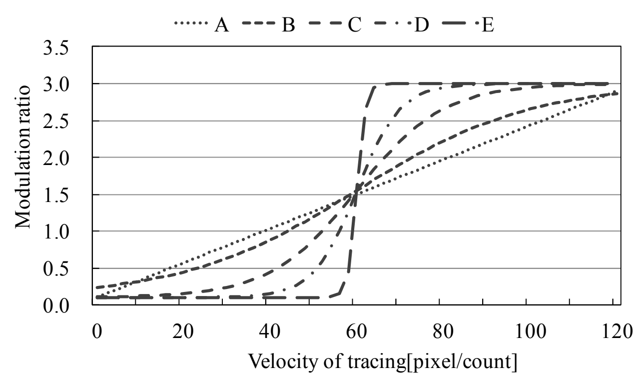


Fig.13. Possible functions in experiment of $\alpha(\cdot)$

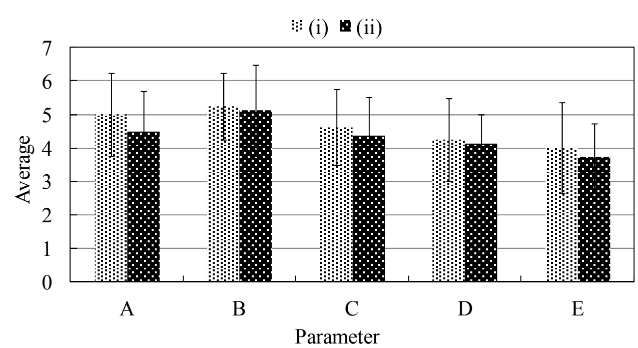


Fig.14. Results of experiment for function $\alpha(\cdot)$

TABLE 2. Image characteristics

Image	*Spatial frequency*[m^{-1}]	*Spectral intensity*
Image 4	265	0.789
Image 5	443	0.857
Image 6	4217	0.213

1) image 4 2) image 5 3) image 6

Fig.15. Added images

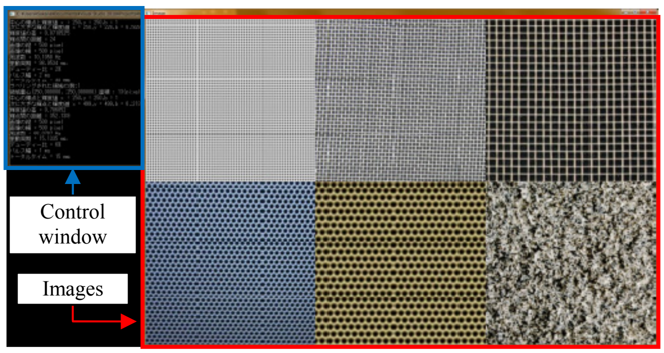


Fig.16. Displaying images on visual monitor

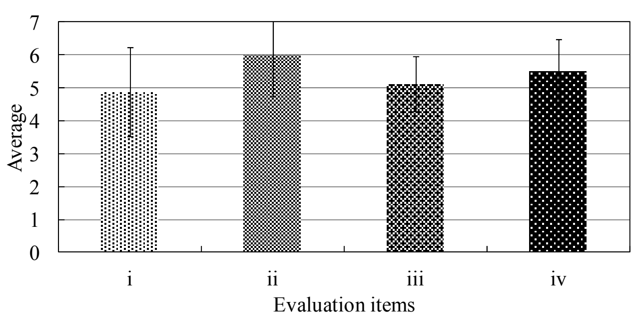


Fig.17. Result of assessment

VI. CONCLUSION

This paper presented the development of a tactile pen, together with a new tactile presentation system. The system automatically generated the driving parameters for the tactile pen to present various tactile sensations in accordance with texture images. The visual features were extracted from a texture image using the image processing technique, which were translated into the parameter values for driving tactile actuators. The relations among the visual features and the driving pulse currents were established by employing non-linear functions, and the driving parameters were determined by the preliminary experiments.

The validity of the tactile system was verified by users' experiments. In the experiment, six different texture images were displayed in a visual monitor, and users rubbed them through the tactile pen to feel the tactile sensations associated with the textures. During the experiment, all the users enjoyed the tactile sensations presented in accordance with the virtual objects in a visual monitor, and most users preferably evaluated the virtual-touch system. In the questionnaire after the experiment, some subjects commented that the change of the tactile intensity was sensitive against the speed of rubbing motion, and they sometimes felt uncomfortable sensations. The perceived tactile sensation is occasionally dependent upon the individual impressions based on the tactile experiences, and the presentation should be adaptive to individuals by adjusting parameters.

The proposed tactile pen system successfully presented various tactile sensations automatically associated with visual images. In the current system, only the visual features extracted by Fourier Transform were employed. In the next system, we will examine other image processing techniques to extract further different visual features from images such as non-cyclic pattern and characteristic textures to be associated with the driving pulse signals for the tactile actuators. In the future work, we could feel the sensations of the clothes and some materials without real objects in the internet shopping.

ACKNOWLEDGMENT

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