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Development of a 2-DOF Softness Feeling Display for Tactile Tele-Presentation of Deformable Surfaces

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Abstract— **This paper presents a 2-DOF controlled softness display and its application to a tactile tele-presentation system. It has been reported that softness feelings can be displayed by reproducing contact area, or contact width, on a fingertip. Several softness displays based on the contact area control have been reported in past studies, but all of them had only one degree-of-freedom (DOF) for their contact area control. Resultantly, the reproduced contact area was symmetric, which could only produce uniform surface feelings. In some practical deformable surfaces, however, the contact conditions are not uniform over fingertip surfaces; for example, if there is a small lump beneath a soft deformable surface, resultant contact area can become asymmetric. To reproduce such asymmetric contact conditions, a softness display should have more controlled DOFs. This paper reports our trial to realize a multi-DOF controlled softness display. As a first step, this particular paper describes a 2-DOF controlled display. The display has two DC motors which independently control both sides of the contact area. Resultant asymmetric contact area can facilitate, e.g., discrimination of lump location in soft deformable surfaces. The display was integrated into a tactile tele-presentation system together with a contact width sensor, which measures asymmetric contact condition. Using the tele-presentation system, discriminations of lump location are demonstrated.**

I. INTRODUCTION

Recently, reproduction of tactile feelings has attracted many interests in the field of human-machine interaction. High-fidelity reproduction of tactile feelings has promising applications in the fields of, e.g., tele-medicine, computer games, virtual reality, or communication over the Internet. Since it is still quite difficult to render wide-range tactile feelings, reported studies have typically focused on some specific tactile elements, such as surface roughness feelings [1]–[7], softness feelings [8], [9], or thermal feelings [10]–[12]. Among those feeling elements, softness feelings would be important for some application fields, especially in tele-medicine. In tele-medical systems, reproduction of softness feelings can be utilized in tele-palpation or tactile exploration during tele-surgery.

Reproduction of softness feelings has been studied from two different viewpoints. For a long time, many studies tried to reproduce softness feelings by using force displays. In those studies, surface softness was modeled as a spring; reaction force from the display is controlled depending on the penetration depth. On the other hand, some recent studies have tried to reproduce softness from the cutaneous viewpoint. From the cutaneous viewpoint, surface softness can be defined by the rate of contact area variation in finger-object contact [8], [9]. When a fingertip touches a surface, the contact area between the fingertip and the surface grows as the contact force increases. The increase rates are characteristic to surface softness; in softer surface, the contact area grows more rapidly than harder surface since the surface deforms to wrap the fingertip. According to the literatures, human relies more on the cutaneous sensation than the kinesthetic one in sensing or feeling surface softness [9], [13]. Therefore, if only one of the two effects, which are cutaneous effect and kinesthetic effect, is to be utilized in a softness display, the use of cutaneous effect can result in better, or more intuitive, operation feelings.

This work focuses on remote reproduction of surface softness feelings based on the cutaneous effect. In [14], we have reported a tele-presentation system for surface softness, where the width of contact area (simply referred to as contact width in the followings) was measured at a remote site using a finger-like sensor, which is then reproduced on a softness display at a master site. The prototype tele-presentation system demonstrated that operators could discriminate softness of remote surfaces through this system.

In the literatures that report the softness reproduction based on contact area, the contact area was controlled by pneumatic or hydraulic pressure [8], [9]. In our previous studies, the softness display controlled contact width between an operator's finger and the display using a flexible sheet as similar to [9], but the control was done by a DC motor [14], [15]. In all of the reported softness displays, the displays had only 1 degree-of-freedom (DOF) for their contact area control, which can produce only symmetric contact condition. To reproduce uniform soft surfaces, which result in symmetric contact, 1-DOF control would be sufficient. However, in some deformable surfaces, the contact conditions are not always uniform over a fingertip surface. For example, if there is a lump beneath a soft deformable surface, resultant contact area can be asymmetric. And such a case could be quite important in medical palpation.

To reproduce such an asymmetric contact condition, a softness display should have more control DOFs. In this particular paper, as a first step to realize multi-DOF softness displays, we propose a 2-DOF controlled softness display and its application to a tactile tele-presentation system. The softness display described here has two DC motors that asymmetrically control the contact width. The asymmetric contact width control realizes non-uniform softness feelings. For example, if a remote surface contains a lump, the location

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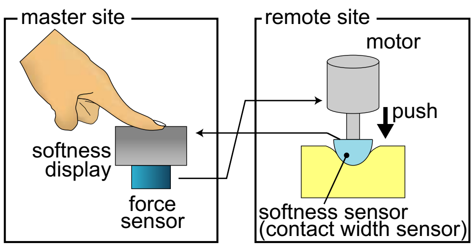

Fig. 1: Concept of softness tele-presentation system [14]

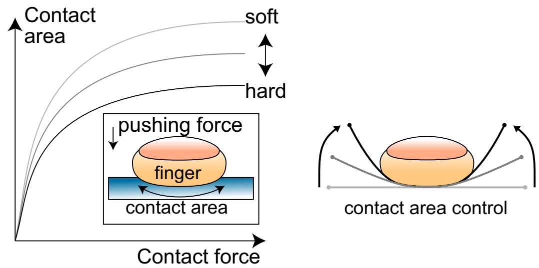

Fig. 2: Typical variation of contact area and its reproduction using a sheet

of the lump can be roughly transmitted to the operator through the 2-DOF controlled display.

In the next section, the paper reviews our proposal on remote softness presentation system. Then in section III, a newly designed 2-DOF softness display is described. In section IV, an overview of the developed tele-presentation system and the improved finger-like contact width sensor are described, which are experimentally tested in section V.

II. Concept of Softness Tele-Presentation System

A. System Overview

Figure 1 shows the concept of the softness tele-presentation system that we proposed in [14]. The system consists of a tactile softness display, a softness sensor, and a linear motor to reproduce contact force. The softness display, which is placed in the master site, produces softness feelings by controlling the contact width between the finger and the device. The display is equipped with a force sensor that measures the contact force given by the finger. The measured contact force is sent to a remote site, which is then reproduced by a linear motor placed in the remote site. The softness sensor (contact width sensor, in this case) is attached on the linear motor, which pushes the sensor to a remote sample by the same contact force measured at the master site. During the contact, the contact width between the sensor and the remote sample is measured, which is fed back in realtime to the master site to be reproduced on the softness display. In this manner, a user in the master site can feel softness of a remote object, in realtime.

In this context, the sensor should preferably have the same dimensions and visco-elastic characteristics as a human finger. If so, the sensor is able to measure the correct contact area variations that would occur on a real human finger. In our work at present, the sensor dimensions and visco-elastic characteristics are not the same as a human finger, but resemble it to some extent. To resemble a human finger, the sensor is made of soft urethane resin and detects contact condition by a small CCD camera, of which details will be described in a later section. Based on this proposal, a prototype tele-presentation system has already been built and reported in [14], which demonstrated realtime transmission of surface softness feelings from the remote sensor to the local softness display.

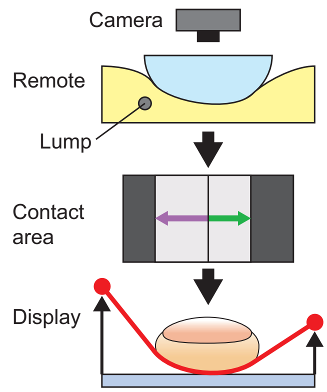

Fig. 3: Reproduction of asymmetric contact condition

B. Improvement for Non-Uniform Surface Rendering

The display device in the tele-presentation system produces softness sensation based on the idea of contact area control [8], [9]. Figure 2 schematically illustrates the change of contact area when a finger pushes various surfaces, as well as how the change of contact area is reproduced on a display. When a fingertip touches and pushes a surface, the contact area grows as the force increases for all the cases, but the rate of growth is different depending on the object softness; the area grows faster on a softer object.

In [8], [9], the contact area was controlled by pneumatic or hydraulic force. In our previous studies, we focused on contact width alone and controlled it by a DC motor [14], [15]. Although the shape of the contact area was not correctly reproduced on the display in that case, the display could still render softness feelings with a satisfactory reality.

In this particular paper, the display is improved to be able to generate asymmetric contact width. The improved concept is schematically shown in Fig. 3. For that purpose, the display is equipped with two DC motors that independently control two ends of the sheet. Resultant asymmetric contact width can produce asymmetric feelings on a fingertip, which allows an operator to, e.g., discriminate lump location under a soft surface.

To cope with this improvement of the display, the image processing program for the contact width sensor should also be improved. In the improved program, the contact width is measured independently on both sides of the sensor. Then, the independently measured widths are reproduced

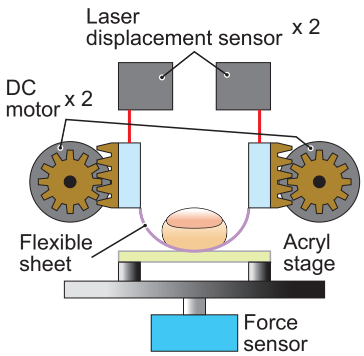

Fig. 4: Schematic illustration of the developed 2-DOF softness display

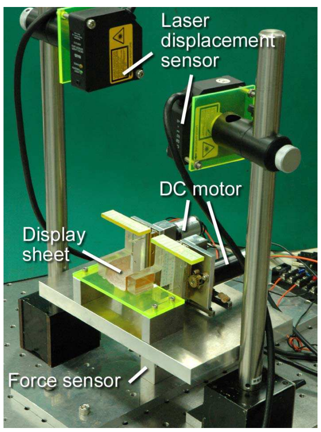

Fig. 5: Appearance of the 2-DOF softness display

on the display, also independently. With this configuration, the system becomes able to transmit non-uniform softness feelings from a remote site. In the experimental section, this paper demonstrates simple discrimination of lump locations beneath the soft surfaces.

III. A 2-DOF Controlled Softness Display

A. Overview

Figures 4 and 5 show a schematic overview and an appearance of the developed softness display. As a basic principle, the display reproduces the contact width on an operator's fingertip by wrapping a flexible sheet. The sheet, which is situated on a rigid plastic plate, is made of 150 μm-thick polyimide and tissue paper. The both edges of the sheet are glued to plastic blocks of which heights are controlled by DC motors through rack-and-pinion mechanisms. To facilitate feedback control of the heights, the heights of the plastic blocks are measured using two laser displacement sensors (NAIS ANR1215, ANR1282). When the sheet wraps around a fingertip, the distance between the two plastic blocks will naturally reduce (as schematically illustrated in the right-hand side of Fig. 2). Therefore, the plastic blocks and their corresponding gears and motors are set up on linear sliders that allow free lateral motions of those parts. A bias spring is set between the two modules that keep a nominal width

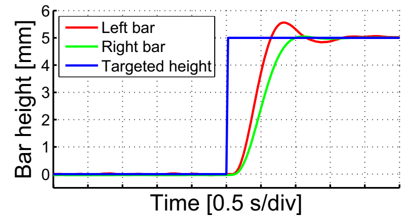

Fig. 6: Responses of the height control against a 5-mm step input

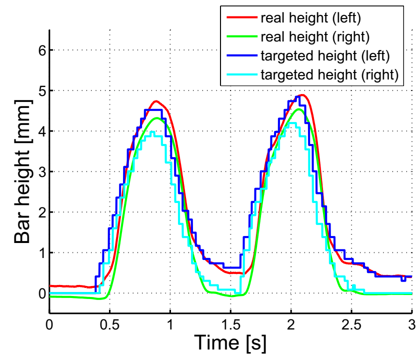

Fig. 7: Responses of the height control in a tele-presentation experiment

when the ends of the sheet are not pulled up. The whole structure, including the sheet, rack-and-pinion mechanisms, and motors, is placed on a force sensor so that the system can measure the contact force given by an operator.

B. Response of Height Control

The heights of the plastic plates, which are equivalent to the heights of the both ends of the sheet, are controlled by PID feedback loops implemented on a DSP board (d-space, DS1104). Step responses of the height control for the two ends are shown in Fig. 6. Although their responses are slightly different, their response times are, more or less, the same and are around 100 ms. Fig. 7 shows controlled variations of the heights in a tele-presentation experiment described in the later section. Stepwise references, which are the measured contact width at a remote site, are given to the PID controller. It can be seen in the plot that the heights smoothly track the given references, although there exist time lag up to 100 ms.

IV. Contact Width Sensor and Tele-Presentation System

A. Contact Width Sensor

In our tele-presentation system, a contact width sensor is employed in the remote site to measure softness of a remote surface. In this paper, we utilize the same sensor principle as described in [14], although the sensor itself has been newly fabricated. As mentioned previously, the sensor should have the same dimensions and the physical parameters (i.e., stiffness and viscosity) as human fingers so that it can detect the correct contact width that a real human finger would

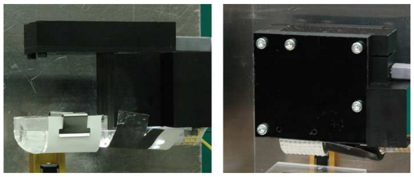

Fig. 8: The contact width sensor (left: without light shield housing, right: with housing)

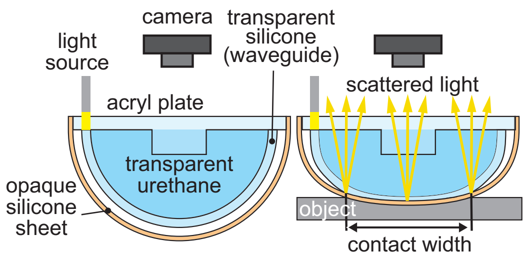

Fig. 9: Structure and principle of the contact width sensor

experience. At present, our sensor does not have the same dimensions or same visco-elasticity as a real human finger. At least to resemble a human finger, we utilized transparent urethane resin and an optical sensing principle, which seem suitable to realize a sensor that has similar characteristics as a real human finger.

The appearance and the structure of the sensor are shown in Fig. 8 and 9. The size and materials are the same as our previous work [14], although detail dimensions are slightly different. The size of the main components of the prototype (urethane resin and opaque silicone sheet) is roughly 25 mm in length and 20 mm in width. The sensor is composed of five parts, which are soft transparent body, a transparent waveguide, an opaque cover, a camera, and a light source. The soft body is made of transparent urethane resin (00-500 from EXSEAL Corporation). The waveguide is transparent silicone sheet (LGF from Fuji Polymer Industries Co. Ltd.) and the opaque cover of 0.7-mm thickness is made of silicone resin (KE-12 from Shin-Etsu Chemical Co. Ltd.). The camera used in the prototype is MCM-4603 from Micro Vision Co. Ltd. (frame rate: 30 fps). LED chips are used as a light source, which were aligned on a flexible universal print board so that they can fit into the curved waveguide. The opaque cover, which is also flexible, is fixed so that it has a slight air gap against the waveguide. Within the soft body, a rigid mechanical support is embedded to resemble a bone and a nail in a human finger. The existence of such a mechanical support would be important to resemble human fingers, since it is reported that the nail plays an important role in tactile sensation [16].

Figure 9 also shows the measuring principle. When the sensor touches an object, the opaque cover deforms and contacts with the waveguide. Then, the light propagating within the waveguide is scattered at the contact area. This scattered light is observed by the camera and processed by a PC. Since the sensor is sensitive to ambient light, a light shielding housing is newly designed that shuts out ambient light.

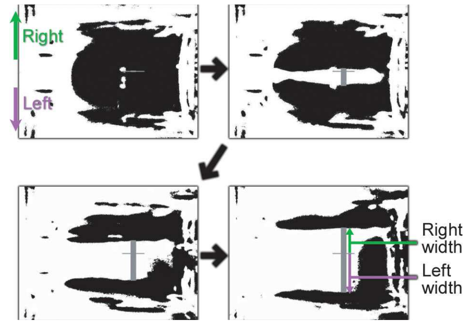

Fig. 10: Binarized camera images taken during contact. The top left is the image before contact. A PC program binarizes the image from the camera and calculates contact width independently for left and for right, by scanning the gray region in the binarized image.

Figure 10 shows an example of the images taken by the camera during contact with a surface sample. A PC program made using OpenCV detects the width of the contact area. The program first binarizes the image then calculates the width of contact area, for both left side and right side of the sensor. For the width calculation, the program scans the gray region shown in Fig. 10. The shape of the gray region was adjusted so that the program can robustly detect the contact width. The program runs at around 30 Hz, which is the frame rate of the CCD camera.

As a result of the slow frame rate, the reference values for the bar height control become stepwise as shown in Fig. 7. However, the realized height variations are found smooth, as shown in the same figure, and thus did not give vibrating sensations to subjects.

B. Sensor Characteristics

Details of the contact width sensor characteristics were reported in our previous paper [14]. This section focuses on the new feature that realizes the measurement of non-symmetric soft samples.

Two uniform surface samples were measured using the contact width sensor. The samples are a hard aluminium block and soft urethane resin. The contact width sensor was pushed against the samples by a linear voice-coil motor (VCM). The force reference to the VCM was increased from -0.5 N to 7 N, and then decreased down to -0.5 N. The changing rate of the force was either 0.3 N/s or 2.5 N/s. A force sensor measured the force given by the VCM to facilitate feedback control of the force.

Figure 11 shows measured contact width variations in this setup. In the contact width variations, hystereses were observed between pushing and retreating processes. The hystereses depend on the force changing rate, the slower contact results in smaller hysteresis. This was also reported in our previous paper [14], but the hystereses are slightly improved in this work. The reasons of this hysteresis have already been discussed in [14]. Although there are some

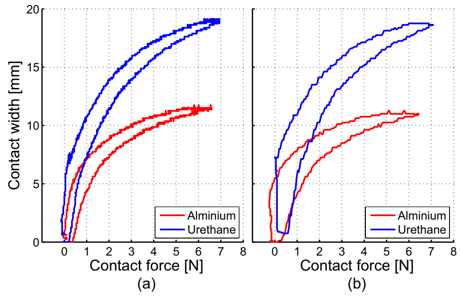

Fig. 11: Measured contact width for two uniform surfaces (Force change rate: 0.3 N/s for left, 2.5 N/s for right)

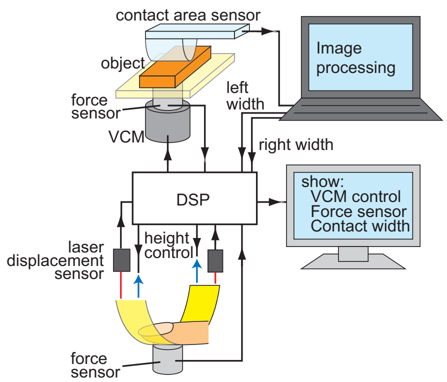

Fig. 12: Overview of the prototype softness tele-presentation system

minor reasons (e.g., a creep of a polymer), the major reason would originate in the stickiness of the opaque cover sheet; once the sheet sticks to the waveguide, it cannot immediately unstick from the waveguide.

The sensor responses against non-uniform surface samples are described in the next section.

C. Tele-Presentation System Overview

The newly developed softness display and the improved contact width sensor were integrated into a softness tele-presentation system. The overview of the system is provided in Fig. 12. In this prototype system, the master site and the remote site shared the same experimental area, for ease of experiments; the remote site was not literally remote. The controllers for the softness display and for the VCM in the remote site were built on the same DSP (d-space, DS1104). Image processing of the sensor was carried out in an independent PC running Windows XP. The PC and the DSP were connected through RS-232C serial interface.

At the master site, a human subject touches and pushes the display by the index finger. The force sensor in the display measures contact force given by the subject, which is then sent to the VCM controller of the remote site. At the remote site, the thrust force of the VCM is controlled based on the measured force (not at the same force, as described later). Then, the camera observes the scattered light, from which contact widths are calculated. The calculated widths are sent to the softness display controller. The data transmission of

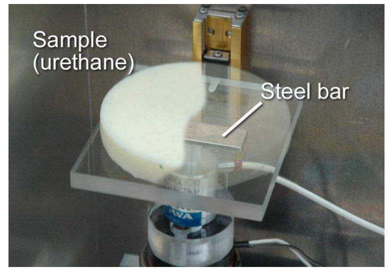

Fig. 13: Urethane resin as a deformable surface and steel plate resembling a lump. In the right hand side of the picture, the urethane resin was made transparent by digital processing so that the steel plate beneath it becomes visible.

the contact widths were done through RS-232C. For ease of experiment, the measured widths were normalized so that the maximum width becomes 127 (7 bits). At the controller in the master site, heights of both ends of the sheet are calculated so that the resultant contact widths match the measured widths. Then, the heights are controlled by the PID controller to produce the softness feeling. For the conversion from the contact width to the bar height, a preliminary experiment measured the relationship between the height and the contact width, which showed that the relationship is almost linear. However, the measurement was done for one subject only, which leaves a possibility that the relationships are non-linear for some people. In this work, the same conversion was applied to all the subjects, neglecting the difference of their finger sizes.

In this prototype system, the developed sensor does not have the same dimensions and stiffness as human fingers. Resultant measured contact width variation does not correspond to the real contact width variation between a human finger and the object; the scales are different, the shapes of the curves are also different. To compensate the differences, the measured contact force was doubled when sent to the remote site [14]. In addition, the measured contact widths were scaled down and offset was added when sent back to the master site.

V. Experiment: Discrimination of Lump Location

To verify the potential performance of the developed system, a simple discrimination experiment was performed. In this experiment, a 1.5-mm thick and 9-mm wide steel plate resembling a lump was placed beneath a soft urethane resin with 5-mm thickness, as shown in Fig. 13. The resin with the steel plate was set at the remote site and its surface feelings were presented to subjects through the tele-presentation system. An example of the measured contact width in this experiment is shown in Fig. 14. Depending on the location of the steel plate, asymmetric contact widths appeared.

Five male and one female subjects, all in their 20s, participated in the experiment. In the test, the location of the steel plate was randomly selected and the subject was asked whether the steel plate is located in the left side or in

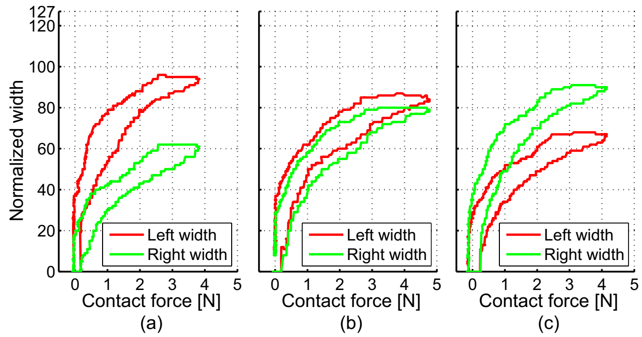

Fig. 14: Result of the discrimination test. Location of the steel plate is -5.5 for (a), -0.5 for (b), and 5.5 for (c).

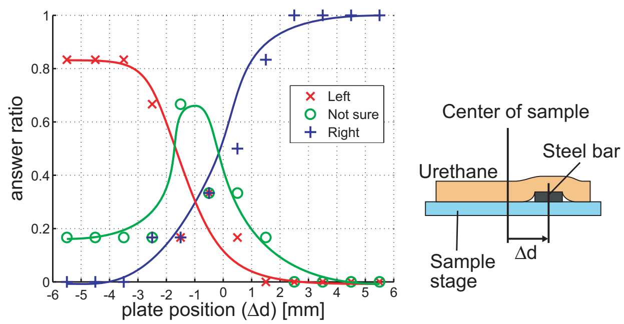

Fig. 15: Result of the discrimination test

the right side. The options they were given as their answers were "left", "right", or "not sure". Each subject performed 12 tests. In each test, the location of the steel plate was selected from 12 different locations; every location appeared one time throughout the whole experiment for each subject.

The results are summarized in Fig. 15 The plot shows the percentage of the three answers. The percentages of "left" and "right" meet at around -1 of the steel plate position. This means the perceived lump locations were shifted to the left side by 1 mm. This would be due to the slightly different responses of the two DC motor systems. Another possible reason is that all of the subjects used their right index fingers. The cause of this shift needs to be further investigated in the future work.

Although the system could deliver the lump location, the obtained feelings were not really realistic. The subjects sometimes felt as if the finger was rotated by the film, which needs to be improved in a future fabrication.

VI. Conclusions

In this paper, a newly designed 2-DOF controlled softness display was described. It was reported that softness can be displayed by controlling contact area between a finger and a display. However, the reported displays control the contact area with 1-DOF. Resultant contact area could only render uniform surface feelings. The 2-DOF display described here controlled the both sides of the contact area independently. The independent control facilitates discrimination of, e.g., lump location which is embedded beneath a soft deformable surface. The display was integrated into a tactile tele-presentation system and an experiment to discriminate lump location was performed. In our future work, we will improve the contact width sensor so that its characteristics can better resemble those of real human fingers. In addition, the number of controlled DOF will be increased so that the display can generate more complicated contact condition; for example, another motor can be added to control the height of the center of the contact area.

References

[1] Y. Ikei, K. Wakamatsu, and S. Fukuda, "Vibratory tactile display of image-based textures," *IEEE Computer Graphics and Applications*, vol. 17, no. 6, pp. 53–61, Nov./Dec. 1997.

[2] M. Konyo, S. Tadokoro, and T. Takamori, "Artificial tactile feel display using soft gel actuators," in *Robotics and Automation, 2000. Proceedings. ICRA '00. IEEE International Conference on*, vol. 4, San Francisco, CA, USA, 2000, pp. 3416–3421.

[3] P. M. Taylor, A. Moser, and A. Creed, "The design and control of a tactile display based on shape memoryalloys," in *Developments in Tactile Displays (Digest No. 1997/012), IEE Colloquium on*, London, UK, jan 1997, pp. 1/1–1/4.

[4] T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, and S. Tachi, "Surface acoustic wave tactile display," *IEEE Computer Graphics and Applications*, vol. 21, no. 6, pp. 56–63, 11 2001.

[5] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi, "Tactile feeling display using functional electrical stimulation," in *Proc. 1999 ICAT*, 1999.

[6] H. Tang and D. J. Beebe, "A microfabricated electrostatic haptic display for persons withvisual impairments," *IEEE Transactions on Rehabilitation Engineering*, vol. 6, no. 3, pp. 241–248, Sept. 1998.

[7] A. Yamamoto, T. Ishii, and T. Higuchi, "Electrostatic tactile display for presenting surface roughness sensation," in *Industrial Technology, 2003 IEEE International Conference on*, vol. 2, Dec. 2003, pp. 680–684.

[8] A. Bicchi, E. P. Scilingo, and D. De Rossi, "Haptic discrimination of softness in teleoperation: the role of the contact area spread rate," *IEEE Transactions on Robotics and Automation*, vol. 16, no. 5, pp. 496–504, Oct. 2000.

[9] K. Fujita and H. Ohmori, "A new softness display interface by dynamic fingertip contact area control," *5th World Multiconference on Systemics, Cybernetics and Informatics, 2001*, pp. 78–82, 2001.

[10] S. Ino, S. Shimizu, T. Odagawa, M. Sato, M. Takahashi, T. Izumi, and T. Ifukube, "A tactile display for presenting quality of materials by changingthe temperature of skin surface," in *Robot and Human Communication, 1993. Proceedings., 2nd IEEE International Workshop on*, Tokyo, Japan, Nov. 1993, pp. 220–224.

[11] L. A. Jones and M. Berris, "Material discrimination and thermal perception," in *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings. 11th Symposium on*, Mar. 2003, pp. 171–178.

[12] A. Yamamoto, B. Cros, H. Hashimoto, and T. Higuchi, "Control of thermal tactile display based on prediction of contact temperature," in *Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on*, vol. 2, Apr./May 2004, pp. 1536–1541.

[13] W. M. B. Tiest and A. M. Kappers, "Kinaesthetic and cutaneous contributions to the perception of compressibility," in *Haptics: Perception, Devices and Scenarios*, ser. LNCS, M. Ferre, Ed., vol. 5024. Springer, 2008, pp. 255–264.

[14] F. Kimura, A. Yamamoto, and T. Higuchi, "Development of a contact width sensor for tactile tele-presentation of softness," in *Procedings of IEEE International Symposium on Robot and Human Interactive Communication, 2009*, 2009, pp. 34–39.

[15] H. Yokota, A. Yamamoto, H. Yamamoto, and T. Higuchi, "Producing softness sensation on an electrostatic texture display for rendering diverse tactile feelings," in *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*, Mar. 2007, pp. 584–585.

[16] Y. Tanaka, A. Sano, M. Ito, and H. Fujimoto, "A novel tactile device considering nail function for changing capability of tactile perception," in *Haptics: Perception, Devices and Scenarios*, ser. LNCS, M. Ferre, Ed., vol. 5024. Springer, 2008, pp. 543–548.