Two Methods of Hi-Fidelity Cutaneous Display: Multi-Primitive Stimulation and Stress Reproducing

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Abstract— **We propose a tentative tactile perception model and introduce three approaches to realize high-fidelity tactile display based on the perception model. The first method, ultrasonic tactile display reproduces high-resolution stress patterns with wide bandwidth. It is a multi-purpose device for synthesizing tactile feeling, and useful to clarify the human tactile perception. The second method is multi-primitive stimulation. The method suggests possibility to display realistic tactile feeling on a wide area of the skin with a simple-structure device. Finally we introduce a tactile illusion based on a property that the human cannot distinguish the sign (positive or negative) of the stress, which also helps simplifying the device structure.**

Keywords- high fidelity tactile display; haptic interface; ultorasound radiation pressure; multi-primitive stimulation; stress reproducing; suction pressure control

I. INTRODUCTION

In the researches related to haptic interfaces, two directions can be seen. One is to find appropriate scenes where tactile interfaces with their available capacities are effectively applied in robotic systems. The other important is to expand the capacity of tactile interface. In this paper we focus on the basic issue for sophisticating the cutaneous display, i. e. how to display realistic tactile feeling on the skin.

In order to realize such a high-fidelity tactile display, there are at least two strategies. One strategy is fabricating a device that can reproduce stress distribution on the skin with high resolution and wide bandwidth under sufficient controllability. The other strategy is constructing a device that gives the skin some alternative stimulation including nonmechanical stimulation [1 , 2 , 3] which produces equivalent tactile sensation to the actual touch sensation. Presumably we need the former device at the first stage of the development in order to understand the cutaneous perception, and at the next stage we should be able to design a simple structure of tactile display based on the latter strategy, like we display all colors to our eyes using a knowledge that our visual organs sense the light spectrum by the three filtered amplitudes of RGB.

In this paper, we show a tentative model of cutaneous perception to start with. Next we show the device reproducing skin stress with sufficient controllability, to examine the perception model. Then we present a framework of the latter strategy called multi-primitive stimulation.

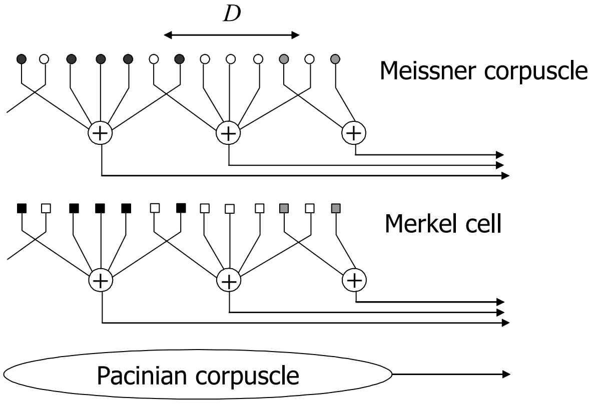

Figure 1. A tentative tactile perception model (SB model) to start the disucussion. Each nonoperational nerve bundle (Simple Bundle) in the population of superficial mechano-receptors (Meissner corpuscle and Merkel cell) samples 1 degree-of-freedom signal at a rate comparable to the visual frame rate.

II. BASIC MODEL OF CUTANEOUS PERCEPTION

The recent researches have come to uncover what physical parameters are detected by the mechanoreceptors. Maeno et al. discussed the roll of the skin structure using 2D FEM analysis [4]. Dandekar et al. calculated deformation of a 3D FEM model faithful to the monkey and the human fingers, and compared the strain at the receptor location with physiological data of nervous pulses under the same finger deformation. In that paper they suggested that Merkel cells (SA-I) detect the strain energy at the receptor locations [5]. Nara et al. showed that the helical structure of Meissner corpuscle (RA-I) gives the selective sensitivity to the shear stress (in a coordinate system parallel to the skin surface) [6]. Their logics are compelling though we have to wait more scientific experiments to fully convince us. At least it would be safe to say that the two kinds of superficial mechanoreceptors have different properties in both spatial and temporal selectivity attributed to their physical structures.

The next sensing structure we have to clarify is how the nerves connect and what kind of processing is carried out among them to extract information from the skin surface. Regarding this problem, each researcher seems to have his/her own individual idea, and we have no common perception model.

Here we start with a tentative model named "simple bundle model (SB model)" illustrated in Fig. 1. In this model, we assume the following not-obvious matters.

[Hypothesis 1] Two kinds of superficial mechano-receptors, Meissner corpuscle (RA-I) and Merkel cell (SA-I) have indivisual sensitivities to the deformation. The two kinds of mechano-receptors are bundled independently into fibers connected to the brain.

[Hypothesis 2] The brain detects 1 degree-of-freedom intensity signal (coded into the pulse frequency) for each bundle at a sampling rate comparable to the visual frame rate.

While Hypothesis 1 seems to be already accepted by many researchers, Hypothesis 2 might confuse the readers. Of course the mechano-receptors are sensitive to high frequency vibration as many literatures reported [7], and the human can distinguish the frequency from the ratio of the intensities perceived by multiple kinds of mechano-receptors, even under the hypothesis. Hypothesis 2 means there is only one way of calculation for outputing 1-DOF intensity inside one bundle, and that the pulse frequency counted within the sampling interval is all of the information. We assume tactile hyper-acuity [8] is also realized by sensing intensity distribution of neighboring bundles whose receptive fields overlap each other.

This "simple bundle model" might be quit natural for some readers that have not been unfamiliar with tactile issue, while it might also be too simple for other researchers. We propose we start with this simplest model. We believe this model holds good until a phenomenon inconsistent with this model is found. Whether SB model is true or false is significant for tactile display design because we will be opened to many alternative structures for a tactile display if the SB model is true.

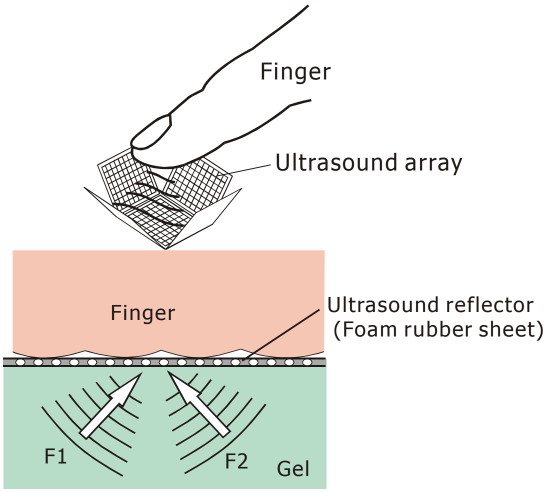

Figure 2. Tactile display using acoustic radiation pressure.

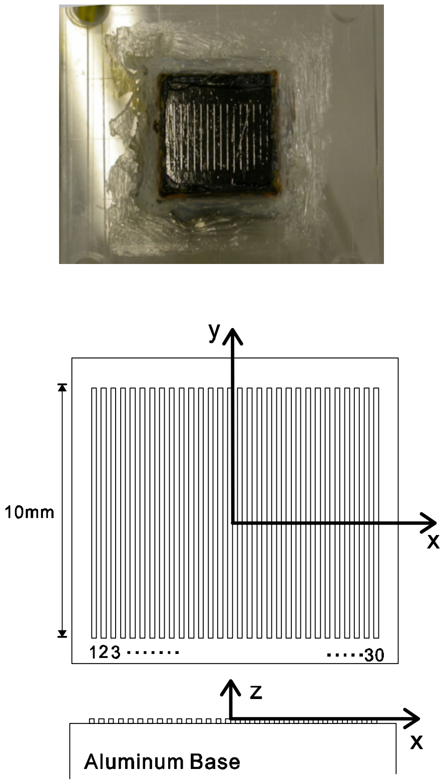

Figure 3. Linear ultrasonic transducer designed for a tactile display. A semicylinderrical acoustic lens is attaqched on it.

III. STRESS REPRODUCING

One straightforward method to understand cutaneus perception including judging the above mentioned model is to clarify what tactile feeling arises for controlled stress distributions on the skin. For such a scientific purpose, the available technologies based on mechanical stimulators [9] have limited controllability. The greatest difficulty is controlling a contact condition between the mechanical stimulator and the skin that might move unexpectedly. Controlling numerous pins in a wide bandwidth remains as a challenge. Our proposal is to use ultrasonic radiation pressure. One obvious merit using ultrasound is that both spatial resolution and temporal bandwidth are easily obtained. It was first shown by Dalecki et al. [10] that radiation pressure can provide enough force to produce tactile feeling. In this paper we show an arrayed ultra sound device especially designed to clarify the human tactile perception [11,12].

Fig. 1 shows the basic principle of the display. Users put their fingers on an elastic gel covered with a thin ultrasound reflector. The reflector is easily realized by a thin foam rubber sheet using the large impedance mismatching between the solid and the air. When we focus the ultrasound near the surface, radiation pressure proportional to the acoustic energy density is induced. The radiation pressure P by a vertical beam to the surface is given as

$$P = \alpha E = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where E, p, ρ and c respectively denote energy density of the sound beam near the surface, acoustic pressure, density of the sound medium, and the sound velocity. The α is a constant related to the reflection property of the surface. If all the acoustic energy is absorbed on the surface, α is equal to 1, while for the surface that reflects all the sound energy, the α is 2.

Since the sound power carried by the beam is given as

$$W = E / c \tag{2}$$

the smaller the sound velocity is, the larger the radiation pressure becomes for a constant power loss. The sound velocity of air, for example, is about 340 [m/s] while that of water is about 1,500 m/s. However, because of the easiness in impedance matching between a PZT sound emitter and a sound medium, we chose ultrasound-conductive gel or water as a sound medium.

The first advantage of using ultrasound for tactile display is the large margin of frequency between the ultrasound and human tactile perception. If we use 3 MHz ultrasound, the frequency is 3,000 times larger than the bandwidth of tactile perception 1 kHz. Then, it is easy to scan the focused beam over an effective area. If the focused spot diameter is 1 mm, a 1 cm by 1cm area can be scanned within 1 ms even if the beam stays for 10 µsec (30 times larger than the period of the sound) for one stimulating point.

The second advantage is the spatial resolution. If we use 3 MHz ultrasound, the wavelength is 0.5 mm in water or ultrasound-conductive gel. This means such high frequency sound can generate fine pressure pattern by radiation pressure without any fragile mechanical parts.

The third advantage is that it is free from contact problems because the device surface is elastic. When we stimulate the skin mechanically with hard pins, it is difficult to control the contact condition and contact pressure precisely. Unexpected forces arise by the movements of the user's skin.

The fourth advantage is that force direction is also controllable. Since the direction of the applied force depends on the beam direction, the 3D force vector on the skin can be controlled theoretically.

The focused beam profile measured at 3 cm from the ultrasound array and the frequency characteristics are shown in Fig. 4 and 5, respectively. The ultrasound medium is water. The reason why the frequency characteristic curve is not ideally flat is that the dynamics of the ultrasound medium affected it. We attained stable 2 gf of the total force by radiation pressure. The prototype was fabricated by Nihon Dempa Kogyo Co., Ltd. Japan, with special consideration to the heat diffusive structure.

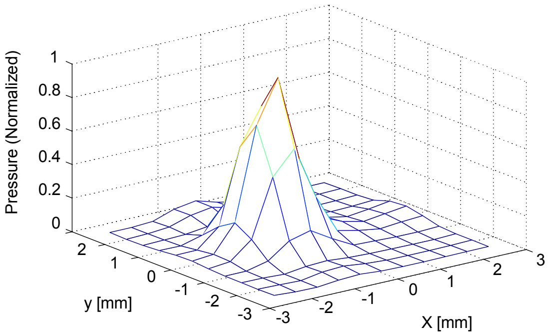

Figure 4. Spatial distribution of radiation pressure for a 3MHz- 30ch linear transducer.

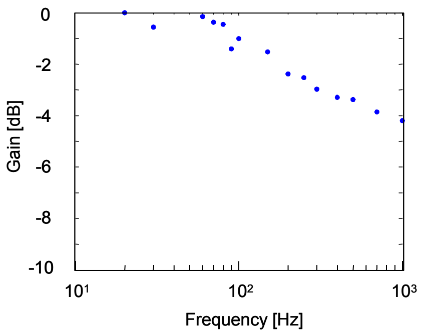

Figure 5. Frequency characterisitics of radiation pressure for a 3MHz-30ch linear transducer.

Using this device, we can plan effective psychophysical examinations of SB model. For example, we know that the human can detect the slide of the pin-like object on the skin sensitively. We can imagine existence of some special detectors to sense a slide of such a pressure pattern. If some local slide detectors are found, we have to discard the SB model.

We know that apparent motion [13,14,15] occurs when vibrators attached on the skin are switched sequentially, but we have not actually confirmed whether sequential vertical motions without vibration induce the same feeling as a real sliding motion. If we use a pin array with 5 mm interval on the finger, for example, and push the pins sequentially with every 30 ms interval, we usually differentiate it in perception from a real sliding motion. This differentiation can be explained by the following possibilities 1 or 2.

1. Our tactile organs have local sliding detectors. The SB model is incorrect.
2. We simply distinguish them by the difference of the surface-force temporal profile attributed to the imperfectness of the stimulator.

Dismissing the possibility 2 is not straightforward by the traditional stimulator, though this is critical to examine the perception model. If the total-force profile is different, it would be easily detected by the output of Pacinian corpuscle.

The proposed device is ideal to solve such kind of problems. It can display sequential vertical force (at fixed points, like "wave") keeping the total force constant (shifting the center of the total force). We can compare this stimulation with a continuous sweep of a force spot by the identical device. The experimental results will be published in the near future.

IV. MULTI-PRIMITIVE TACTILE STIMULATION

In the discussion of SB model, we did not mentioned the size of receptive area "*D*" in Fig. 1. Here we have another hypothesis on *D*.

> [Hypothesis 3] The spread of receptors bundled into a single fiber is comparable to the two point discrimination threshold.

Two-point-discrimination threshold (TPDT) is well known as a parameter of tactile resolution. The TPDT is defined as the minimum distance to discriminate two-point contact as two when the two stimulations are given simultaneously. On a palm TPDT is as large as about 10 mm [16]. If we consider the largeness of TPDT, the hypothesis 3 might seem unnatural because we can easily distinguish the sharpness of object with a very high sensitivity. For example, a tip of a pencil and the bottom-end of it can never be misidentified.

One possible explanation consistent with the Hypothesis 3 is that the human detects the sharpness of the object by the two-degree-of-freedom values from the SA-I and the RA-I receptors. A recent research clarified the perceived sharpness strongly depends on the temporal change rate of the stimulation more than actual sharpness, in the intensity range with no algetic perception [17]. Since the temporal change rate affects the ratio of RA-I response to SA-I response, this supports that explanation.

Multi-primitive tactile stimulation (MPTS) is an effective method for a wide area tactile display when SB model and Hypothesis 3 are true. In order to straighten up MPTS we tentatively define "TPDT area" at first. This is an area whose side is equal to the TPDT. Secondly, we also introduce an idea, degree-of-freedom (DOF) of stimulation, which includes the idea of resolution. Then we raise a question "How many DOF is required within a TPDT area to display all variation of cutaneous feeling?"

Intuitively, we might imagine that high resolution is necessary in order to display a fine texture. If we divide the TPDT area into n-square elements to stimulate independently, it means that the DOF used for stimulation per TPDT area is *n*-square, or 3 times *n*-square if we also control the force directions. On the other hand, if we seek an appropriate basis in all possible stress patterns, the actually required DOF for producing all tactile sensations might be smaller than dividing the area into small regions. We call these fundamental stress patterns "primitives," while we call displaying tactile feeling by such primitives multi-primitive stimulation (MPTS) method.

If SB model is correct, the minimum number of the primitives *m* should be as small as two, the number of kinds of the superficial mechanoreceptors. The number is dramatically smaller than the number required in single-primitive stimulation (n^2 or $3n^2$). This hypothesis is proved when we find appropriate primitives. We are now searching the primitives that can selectively stimulate the two kinds of mechanoreceptors [18].

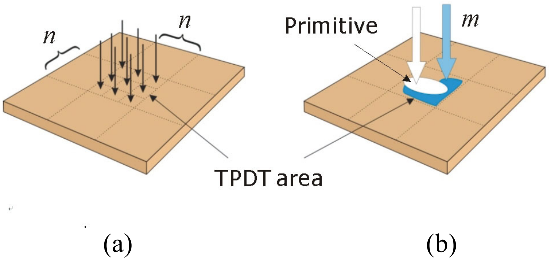

Figure 6. Two approaches to create various sensations. (a): Using primitives of δ-functions with a high density. (b) Using appropriate primitives with small degree-of-freedom per TPDT area.

Figure 7. Schematic illustration of suction pressure stimulation. Pulling the skin by air suction makes compressed sensation as if something is pushing up

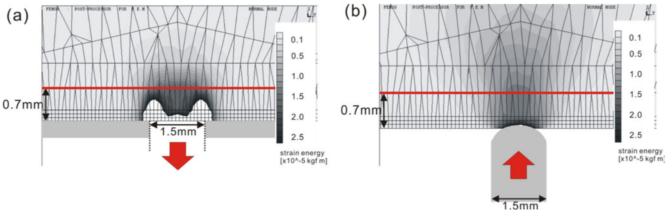

Figure 8. Distributions of strain energy by suction pressure (a) and positive pressure by a sticklike object (b). The distributions at the skin surface are different from each other.

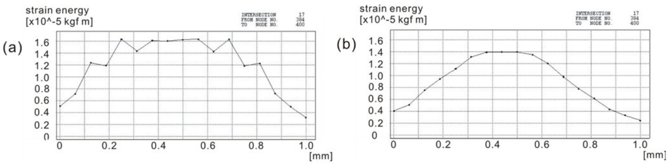

Figure 9. Distributions of strain energy near the receptors. The cases of suction pressure (a) and positive pressure by a stick-like object (b). The distributions are similar to each other.

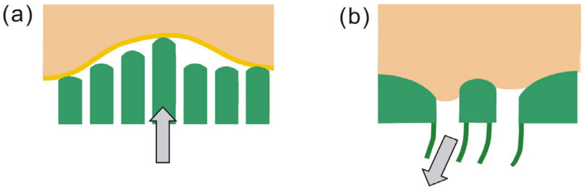

Figure 10. Large displacement of a pin in a tactile display array interferes with the neighboring pin-contact to the skins. (b) Suction pressure stimulation causes small interference with neighboring stimulators.

V. FINDING INSENSITIVENESS

Finally we will introduce a useful illusion found by Asamura in our laboratory. The illusion is that we feel a stick-like object push the skin when we vacuum the skin through a hole of several millimeter in diameter [18] as shown in Fig. 7. The FEM results in Fig. 8 showed that the overall distribution and the sign of the stress tensor were much different between the two cases, air suction and pin-pushing. However the strain energy distributions at the superficial receptor level shown in Fig. 9 were similar in both cases. In the human tactile organ, the receptors are supposed to sense the energy density, which means each receptor cannot distinguish the sign (positive/negative) of the strain/stress [5]. Using this illusion, we can display feeling of contact with objects, keeping the skin restricted. Finding insensitiveness in cutaneous perception will lead to many alternative structures for a tactile display like this.

VI. SUMMARY

We proposed a tentative tactile perception model (SB model) and introduced three approaches to realize high-fidelity tactile display based on the perception model. The first method, ultrasonic tactile display reproduces high-resolution stress patterns with wide bandwidth. It is a multi-purpose device for synthesizing tactile feeling, and useful to clarify the human tactile perception. The second method is Multi-primitive stimulation. The method suggests possibility to display realistic tactile feeling on a wide area of the skin with a simple-structure device. Finally we introduced a tactile illusion that the human cannot distinguish the sign of the stress, which also helps simplifying the device structure.

[1] N. Asamura, N. Yokoyama and H. Shinoda, “Selectively Stimulating Skin Receptors for Tactile Display,” IEEE Computer Graphics and Applications, Vol. 18, No. 6, pp.32-37, November.-December, 1998.

[2] Kajimoto, Kawakami, Maeda, Tachi, "Tactile Feeling Display using Functional Electrical Stimulation, " Proc. of The Ninth International Conference on Artificial reality and Telexistence (ICAT'99), 1999.

[3] M. Konyo, K. Akazawa, S. Tadokoro, T. Takamori, “Wearable Haptic Interface Using ICPF Actuators for Tactile Feel Display in Response to Hand Movements,” J. of Robotics and Mechatronics, Vol. 15, No. 2, pp. 219-226, 2003.

[4] T. Maeno, K. Kobayashi, and N. Yamazaki, “Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors,” Bulletion of JSME International Journal, Vol. 41, No. 1, C, pp. 94-100, 1998.

[5] K. Dandekar, B. I. Raju and M. A. Srinivasan, “3-D Finite-Element Models of Human and Monkey Fingertips to Investigate the Mechanics of Tactile Sense,” Transactions of the ASME, Vol. 125, pp. 682-691, 2003.

[6] Takaaki Nara and Shigeru Ando, “The Mechanical Property of the Coiled Axon of Meissner Corpuscles for Human Tactile Sensing and its Application to a Biomimetic Tactile Sensor with a Helical Structure,” Proceedings of the 11th International Conference on Solid State Sensors and Actuators 2001, pp.1666-1669, 2001.

[7] S. J. Bolanowski, Jr., G.A. Gescheider, R.T. Verrillo and C.M. Checkosky: “Four ChannelsMediate the Mechanical Aspects of Touch,” J. Acoust. Soc. Am., Vol. 84, No. 5, pp.1680-1694, 1988.

[8] J. M. Loomis, “An investigation of tactile hyperacuity,” Sensory Processes, Vol. 3, pp. 289-302, 1979.

[9] J. Pasquero and V. Hayward, “STReSS: A Practical Tactile Display System with One Millimeter,” Proc. of Eurohaptics 2003, 2003.

[10] D.Dalecki, S.Z.Child, C.H.Raeman and E.Carlstensen: Tactile perception of ultrasound, Journal of acoustical society of America, pp3165-3170,1995

[11] T. Iwamoto, T. Maeda, H. Shinoda: Focused Ultrasound for Tactile Feeling Display, Proc. 2001 International Conf. on Artificial Reality and Telexistace, pp. 121-126, 2001.

[12] Takayuki Iwamoto, Daisuke Akaho, and Hiroyuki Shinoda: High Resolution Tactile Display Using Acoustic Radiation Pressure, Proc. SICE 2004, pp.1239-1244, 2004.

[13] J. H. Kirman, “Tactile Apparent Movement: The Effects of Interstimulus Onset Interval and Stimulus Duration,” Perception & Psychophysics, Vol. 15, pp.1-6, 1974.

[14] J. H. Kirman, “Tactile Apparent Movement: The Effects of Number of Stimulators, Journal of Experimental Psychology,” Vol. 103, pp.1175-1180, 1974.

[15] C. E. Sherrick & R. Rogers, “Apparent Haptic Movement,” Perception & Psychophysics, Vol. 1, pp.175-180, 1966.

[16] S. R. Geiger ed. “Handbook of Physiology, Section 1: The Nervous Sytem,” American Physiological Society, 1984.

[17] Yasutoshi Makino and Hiroyuki Shinoda, “Selective Stimulation to Skin Receptors by Suction Pressure Control,” Proc. SICE 2004, pp.2103-2108, 2004.

[18] Y. Makino, N. Asamura and H. Shinoda: “A Whole Palm Tactile Display Using Suction Pressure,” IEEE Int. Conf. on Robotics & Automation, pp.1524-1529, 2004.