SmartTouch - Augmentation of Skin Sensation with Electrocutaneous Display

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Abstract

An electrocutaneous display system composed of three layers is implemented for augmentation of skin sensation. The first layer has electrodes on the front side of a thin plate, the second has optical sensors on the reverse side of the plate, and the third is a thin film force sensor between the other two layers. Visual images captured by the sensor are translated into tactile information, and displayed through electrical stimulation. Thus, visual surface information can be perceived through the skin while natural tactile sensation is unhindered. Based on the sensor, the user can "touch" other modalities of surface information as well.

1 Introduction

In our daily life, we perceive the world around us through five major sensory modalities. The receptors that generate the respective sensations are the only gates to connect us with the outer world. It is a natural ambition to acquire sensing ability beyond the usual physical limits: the ability to see the unseeable, or hear the inaudible, often referred to as a sixth-sense. However, the related discussions are generally not within the scope of conventional science.

Augmented reality (AR) [2] is an engineer's alternative. In AR, artificial information is captured from the real world by some sort of a sensor, and displayed through our existing sensing channels. Hence, the users virtually acquire the physical ability of the sensor as their own.

1.1 Augmented haptics

We consider here the AR of haptics (augmented haptics), in order to touch the non-touchable. The system is essentially composed of a tactile display and a sensor. When contacting an object, information acquired by the sensor is translated into tactile sensation such as vibration or force by a tactile display. Thus, the person not only can make physical contact with the object, but also "touch" surface information of any modality.

SmartTool [14] is one realization of augmented haptics with a hand tool such as a scalpel or pen (Figure 1 left). SmartTool captures information with a sensor attached at the tip of the tool, and conveys it to the operator through a haptic force display. One of their proposed applications was in surgical operation. When a "smart" scalpel contacts a vital region such as an artery, the sensor detects surface information and the display produces a repulsive force to protect the region.

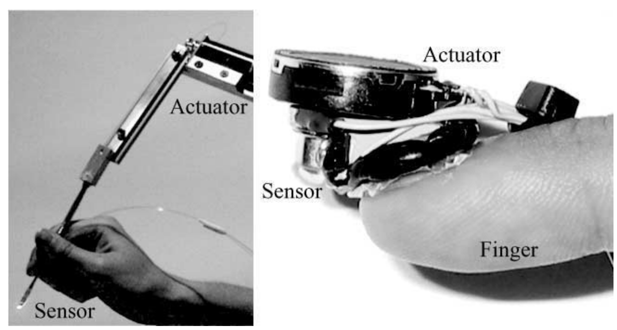

Figure 1. Examples of Augmented haptics. (Left) SmartTool [14], (Right) SmartFinger [1].

Another development in augmented haptics is SmartFinger [1](Figure 1, right), where a vibrating tactile display and a sensor are both mounted on the fingernail. The vibrator drives the finger vertically, which induces force between the finger and the contacting object. Thus, skin sensation is generated indirectly, while natural tactile sensation is unhindered by the display.

In this paper, we further pursue the AR of skin sensation. The device proposed here, referred to as "SmartTouch", is composed of a thin cutaneous display and a sensor mounted on the skin, which ultimately serves as a new functional layer of the skin (Figure 2).

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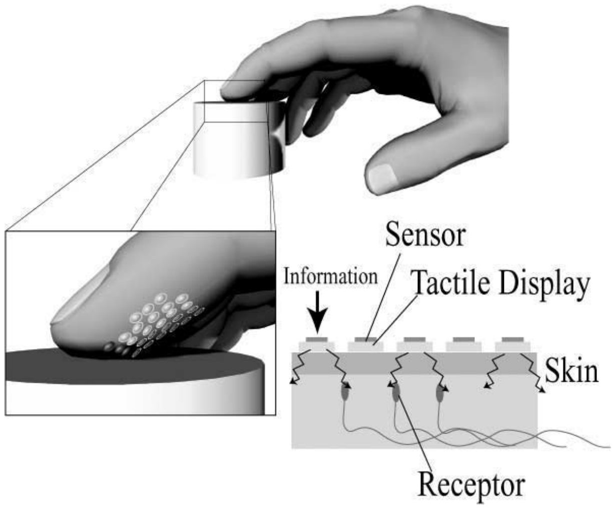

Figure 2. SmartTouch: A new functional layer of the skin composed of a sensor and tactile display.

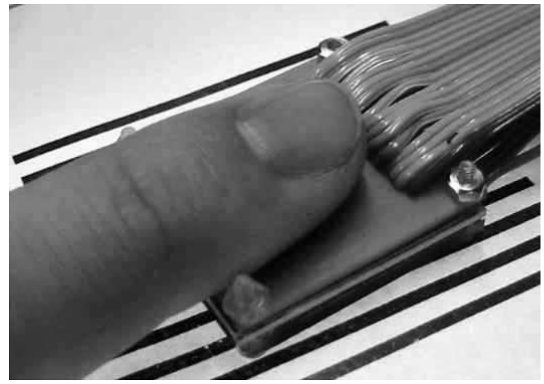

Figure 3. Prototype of SmartTouch: Visual image (black and white stripes) is captured by optical sensors and displayed through electrical stimulation.

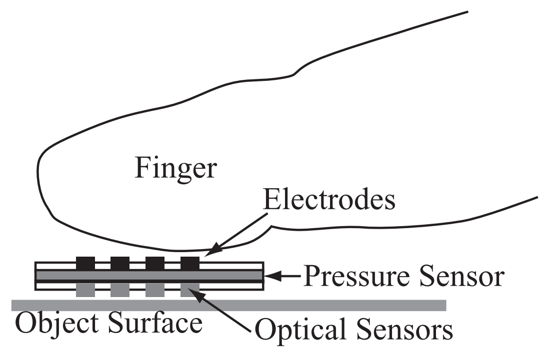

Figure 4. Cross-section of prototype SmartTouch.

2 Prototype system

Figure 3 and Figure 4 depict the prototype of SmartTouch and its cross-section. It is composed of three layers. The first layer has electrodes on the front side of a thin plate, the second has optical sensors on the reverse side of the plate, and the third is a thin film force sensor between the other two layers.

Visual images captured by the sensor are translated into tactile information, and displayed through electrical stimulation. As the system facilitates the recognition of printed materials through the tactile sense, it could be applied as a Braille display for the visually impaired. The total thickness of the system is 5.0[mm]. The electrode component is 1.6[mm], the optical sensor is 2.4[mm], the force sensor is 0.3[mm], and the remaining thickness is from insulator films between the layers.

2.1 Related works

There have been extensive research efforts on visual-to-tactile conversion systems. Bliss [3, 4] has developed the first converter system, while Collins [5] employed electrical and mechanical stimulation at the skin of the back. The representative commercial product Optacon [16] was developed in 1960s using a video camera and a matrix of vibrating pins. However, their aim was for a visually impaired person to read printed material, but not to "augment" the real world. Specifically in their system, the participant must have a video camera in one hand and tactile information is displayed onto another hand. On the contrary, in our system, the optical sensor and the tactile display are located at practically the same place, and work in combination as a new skin "receptor".

2.2 Electrical stimulation as a means to present tactile information

By mounting the display directly on the skin, cutaneous sensation can be presented with high spatial resolution, although the display itself will separate the contact with an object. But what kind of inconvenience arises as a consequence? Consider a horizontal motion of the finger. When the finger moves horizontally, the contact generates a frictional force. The force is perceived by the finger as a torsional moment. As the display becomes thicker, the in-

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creased distance between the finger and the object surface generates greater torsional moment, which results in unnatural haptic sensation (Figure 5).

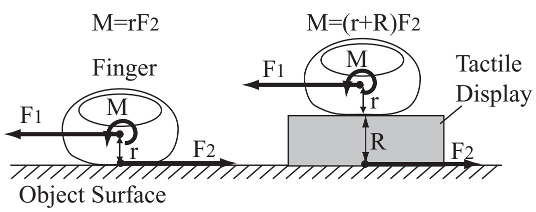

Figure 5. Horizontal motion of the finger and generated torsional moment. F1: Finger force, F2: Friction, r: Distance between the center of the finger and skin, R: Display thickness, M: Torsional moment of the finger.

This fact highlights the merits of electrical stimulation as a means to display tactile information. Under this paradigm, all that is needed to contact the skin is a matrix of electrodes, which can be readily fabricated into a thin wafer.

The tactile display was composed of a 4x4 matrix of stainless steel electrodes, each 1.0[mm] in diameter. The longitudinal and transversal interval of the electrodes was 2.5[mm] and 2.0[mm] respectively (Figure 6 Left). This interval was determined by the fabrication limit due to the size of the optical sensor described in the next section. The electrodes applied electrical current pulses to the skin (0.2[ms], 1.0-3.0[mA] current controlled) in order to generate tactile sensation.

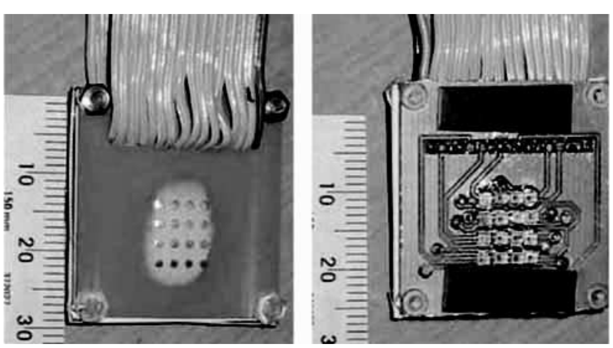

Figure 6. (Left) Electrodes. (Right) Optical sensors. Both electrodes and sensors were arranged 2.5[mm]x2.0[mm] interval, 4x4 matrix. The position of each electrode was strictly aligned with an optical sensor.

2.3 Optical sensor as a means to acquire visual surface information

For an optical sensor, we used a phototransistor (SHARP PT600T, 1.6[mm] x 1.6[mm] x 0.8[mm]). We placed the sensors just beneath the electrodes so that the horizontal displacement between the stimulation point and sensing point is less than 0.5[mm]. We used printed-paper as a contacting object. As we did not embed a light source to the system, the paper was lit with an LED lamp from below.

2.4 Force sensor as a means to measure finger pressure

To produce natural tactile sensation, the stimulation must correspond to finger pressure. Force controlled stimulation is especially important in electrical stimulation for safety reasons as well. We will discuss the issue in detail in Section 4.3.

To minimize the thickness of the system, we used a thin film force sensor (NITTA FlexiForce, thickness: 0.3[mm]). This sensor was placed between the electrode substrate and sensor substrate to measure finger pressure.

3 Hardware evaluation

3.1 Spatial resolution of the optical sensor

As described in Section 2.2 and in Section 2.3, the longitudinal and transversal interval of the electrodes and sensors was 2.5[mm] and 2.0[mm] respectively, which was determined by the practical fabrication limit due to the size of the optical sensor.

In our first preliminary experiment, each sensing element was contacted with an object surface directly, so that the sensor's field of vision was 1.0[mm] by 1.0[mm], which was the size of the aperture window of the element. As it was smaller than the interval of the sensors, there were some gap region where no sensor could see. Hence, when we move the system on the black and white stripes with the same interval as the sensors, in one case the sensors could not find the stripes, while suddenly they all sensed the stripes simultaneously, resulting in an instability of the displayed tactile sensation. Therefore, we must broaden the field of view of each sensor to give an appropriate spatial property.

The system obtain the visual image of the contacted surface by discrete sampling. The Sampling theorem states that to reconstruct original signal from sampled data, the original signal should not have frequency component higher than $1/2d$ ($d:$ sampling interval) [15]. From this viewpoint, the above mentioned phenomenon is seen as an aliasing effect.

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Hence we tried to satisfy the theorem by broadening the field of vision of the sensing element and low-pass filtering the original image. It was acheved by mounting spacer on the sensor substrate and keeping the gap between the sensor and the object surface to 0.5[mm](Figure 7).

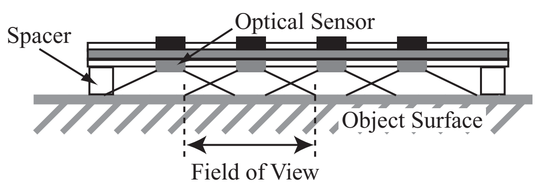

Figure 7. Broaden the field of vision of the sensing element by mounting spacer on the sensor substrate.

We measured the spatial frequency characteristic of the sensor by measuring the response of single phototransistor when sweeping on black and white stripes with different spatial interval. The stripes were considered as approximated sin waves so that we could obtain the frequency responce. The interval of the stripes were from 1.0[mm](0.5[mm] white and 0.5[mm] black) to 8.0[mm].

Figure 8 (top) depicts the response of the sensor as the system was swept along the stripes. Spatial frequency response (amplitude) was measured (Figure 8 (bottom)). From the figure, we see that the cutoff (-3dB) frequency of the sensor is $0.3[mm^{-1}]$, which is equivalent to the stripes with 3.3[mm] interval. This values agrees quite well with the Nyquist interval(two times the sampling interval) and hence, anti-aliasing filter was well designed.

Similar analysis was done by Fearing [6,7] to design tactile information transmittion system using tactile sensor and tactile display.

3.2 System latency

By combining the above components, electrical stimulation can be processed based on visual information obtained by the optical sensors. As the shortest distance between the two electrodes is 2.0[mm] and the sweep velocity of the finger is less than 100[mm/s] (from our preliminary experiment), the shortest travel time between the two adjacent electrodes is 20[ms]. To express this movement, the cycle time should be much less than the travel time. In our system, the waveform of the electrical stimulation pulse was dynamically generated and stored in double-buffered memory mounted on Digital to Analog boards (NATIONAL INSTRUMENTS DAQ6713). This allowed parallel processing of other tasks such as image capturing during stimulation, which suppressed the stimulation iteration period to

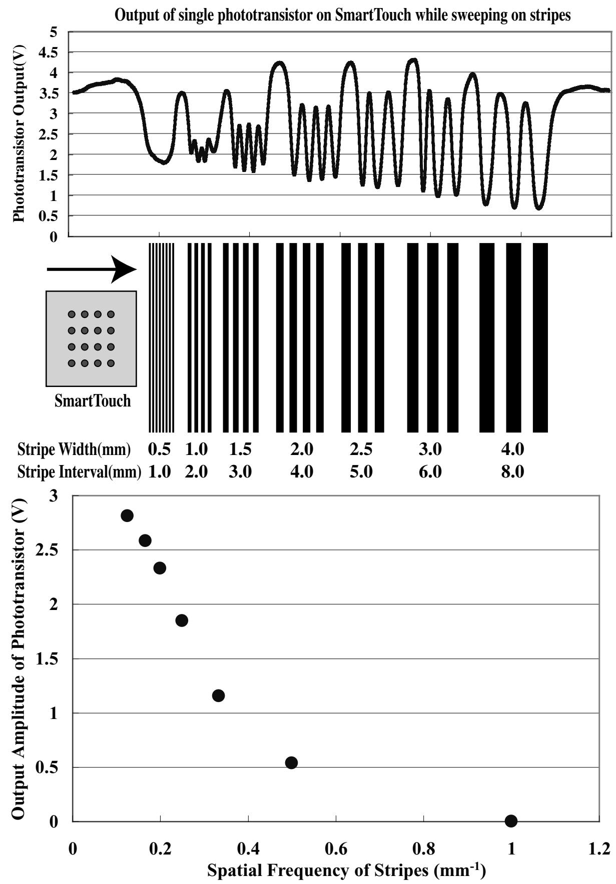

Figure 8. Response of the phototransistor when sweeping on black and white stripes with different spatial frequencies.

4.0[ms].

The latency between sensing and stimulation was measured. Figure 9 shows the normalized phototransistor output and stimulus current pulses as the system was swept over a boundary between black and white areas. As we will mention in Section 4.4, electrical current pulse was applied when time derivative of phototransistor output reached to certain threshold. From the figure, we observe that the latency was less than 4[ms].

4 Coding of electrical stimulation

After visual information of the object surface is obtained by the optical sensor, it is translated into tactile information to be displayed through electrical stimulation. The quality of the translation technique is the argument that is highly dependent on the application. In this research, we pursued the "naturalness" of the generated tactile sensation this time,

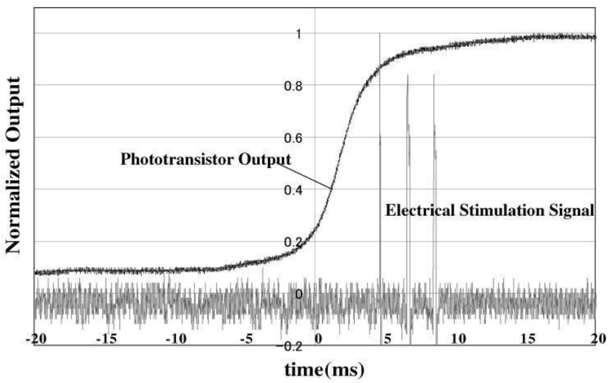

Figure 9. Phototransistor output and stimulus current (normalized). The latency between sensing and stimulation was less than 4[ms]

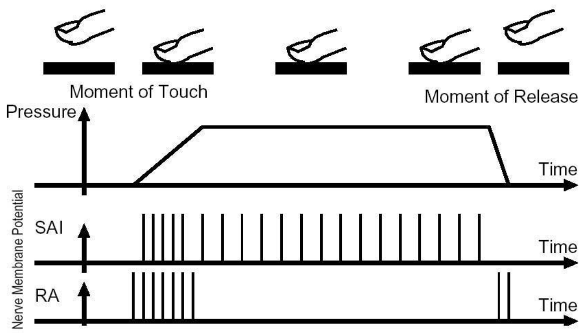

Figure 10. Firing pattern of mechanoreceptor when finger touches and releases the object. SAI: Merkel ending (pressure sensation), RA: Meissner corpuscles (vibratory sensation) (reconstructed from [18])

because electrical stimulation had a long history of rejected proposals due to ”unnatural and unpleasant” sensation. Our goal is for the display to convey the virtual existence of a physical substance through tactile sensation, regardless of the movement of the finger. We endeavored to realize the perception of luminance information as the unevenness of the object surface. For example, the black and white stripes as in Figure 3 are perceived as bumps of the same interval.

4.1 Receptor selective stimulation

Electrical stimulation of the fingertip is summarized as follows: when using two coaxial electrodes (central electrode with 1.0[mm] diameter, and outer electrode with 4.0[mm] inner diameter), electrical current pulse (0.2[ms], 1.0-3.0[mA], 10-50[pps]) generated vague pressure sensation if the central electrode is cathode (i.e. current flows from the outer electrode to the central electrode). On the contrary, if the current flows from central electrode (i.e. the central electrode works as an anode), acute vibratory sensation is elicited [9, 10]. Physiological studies revealed that there are two types of mechanoreceptors in the shallow part of the skin, referred to as Merkel cells and Meissner corpuscles. Merkel cells respond to static deformation, while Meissner corpuscles are activated when the deformation changes over time (Figure 10) [1]. Experiments in single nerve stimulation showed that Merkel cells generate pressure sensation, while Meissner corpuscles produce vibratory sensation [17].

Extending these observations to fingertip electrical stimulation, cathodic pulse selectively stimulates nerve fibers connected to the Merkel ending, while anodic pulse activates nerve fibers connected to Meissner corpuscles.

4.2 Translation from image to nerve firing pattern

Our main goal is to generate ”natural” tactile sensation. If this principle is reduced to the level of individual receptor activity, it becomes nothing more than artificially produce a nerve firing pattern that might arise in a real contact situation. Our transformation formula is as follows: if the luminance (regarded as bump height) reaches to a certain threshold, cathodic pulse is provided to produce pressure sensation. The pulse rate (10-50[pps]) is set proportional to the height. At the same time, anodic pulse is produced when the time derivative of the luminance reaches a certain threshold, which generates vibratory sensation (Figure 11). In mechanical contact, the skin deforms rapidly when pressed, and does not react as quickly when released. Hence, the anodic pulse is given only when it is seen that the bump becomes low to high.

It is worth noting that in this stimulation method, each electrode only requires the information from an optical sensor immediately beneath it.

4.3 Translation from contact force to the population of firing nerves

Although electrocutaneous display has quite a long history, it is also a history of rejected proposals because of the unpleasant feeling often referred to as an ”electric shock”. The reason why we feel ”shocked” by electrical, but not mechanical stimulation is as follows. Although mechanical interaction may provoke the same amount of sensation or more than electrical stimulation, it is also proactively regulated by the contact force. This dual controllability allows us to handle mechanical stimuli without feeling a shock.

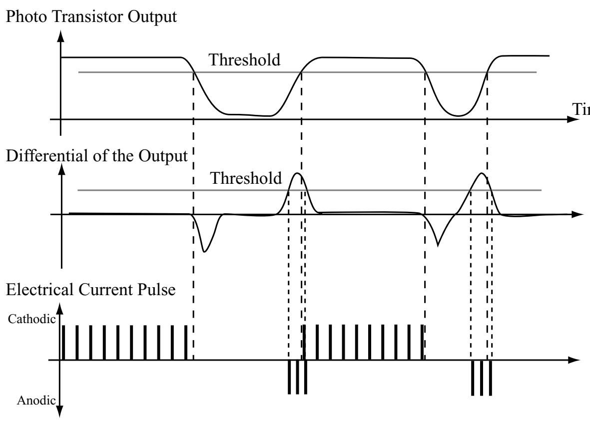

Figure 11. Phototransistor output, its differential and electrical stimulation pattern of single electrode.

Conversely, electrical stimulation itself does not have such relationship with contact force. Furthermore, the sensation peaks when the finger first contacts the electrode, because electrical current is focused on the small contact area. This is why we must control electrical stimulus by contact force. Contact force was measured by a thin film pressure sensor, and pulse energy (height or width) was set as a monotonically increasing function (temporary logarithmic) of this pressure. This allowed the population of the excited nerves to be actively controlled by force, while the nerve firing rate remained constant. The user could therefore actively modulate the intensity of sensation [11].

4.4 Stimulation timing

When we stimulate one point, surrounding electrodes are used as a return current electrode (ground) and hence, only one point is stimulated at a time, which requires time-division scanning [8, 11] (Figure12).

As mentioned in Section 3.2, the cycle time of the sensor and display system is 4.0[ms]. Each electrical pulse requires at least 0.2[ms] and our preliminary experiment revealed that 0.2[ms] additional rest time is required after the pulse. Hence 10 pulses could be packed into one cycle. This may seem quite sufficient for our 16 electrode system, but not if we consider the necessity to provide both anodic and cathodic pulses. Our current solution is as follows. The time-derivative part of the stimulation (anodic stimulation) as we mentioned in Section 4.2 is time-critical, because it informs the “change” to the user. Hence we first determine this part of the stimulation and then proportional part of the stimulation (cathodic pulse) is delivered using remaining time. At the same time we regulate the threshold

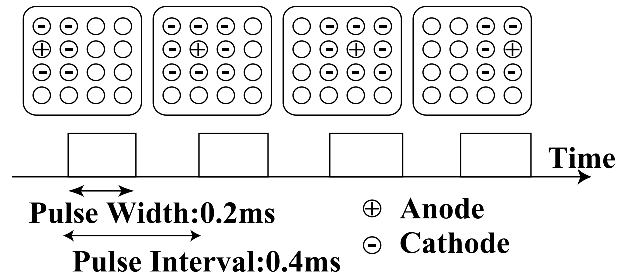

Figure 12. Scanning procedure in cathodic stimulation mode [11].

level mentioned in Section 4.2 to limit the total number of pulses.

In this manner, the stripes with large interval (about 3.0[mm]) generated mainly pressure sensation and was perceived as a rough bump, while stripes with small interval (about 1.0[mm]) generated mainly vibratory sensation and was perceived as a fine texture. All participants could clearly distinguish between the two types of stripes by moving their fingers.

5 Future work

This paper proposed an AR system of cutaneous sensation, the SmartTouch. In the prototype system, a mounted optical sensor converts visual information from a contact object into tactile information, and electrical stimulation is employed as a means to present tactile information.

Until now, there were only two types of applications for tactile display. One was Braille display for the visually impaired and the other was the haptic device to make the virtual world gets tactile textures and seems more real. What we try to emphasize in the SmartTouch is that if you combine sensor and tactile display, tactile display will come out to the real world.

Although this paper mainly focuses on visual-to-tactile translation, the use of SmartTouch is not limited to Braille for the visually impaired. By changing the sensor, other modalities of sensation can be translated to touch as well. We are now considering combining a tactile sensor matrix with an electro-tactile display, to perform tactile-to-tactile conversion. If the tactile sensor is more sensitive than human perception, we can enhance the natural tactile experience. Although it is not commonly known, human tactile sensitivity dramatically decreases with age [13]. Hence, many of us need tactile aid, just like hearing aid when we get old.

The goal of the SmartTouch is a very thin display and sensor directly mounted on the skin to serve as a new functional layer, so that the system is worn as an unconscious daily interface. Hence, it is interesting to consider how thin the system can actually be fabricated with existing technology.

First, as the display component only needs electrodes, fabrication of electrodes with less than 0.3[mm] in thickness is possible by using film substrate [8]. However, if we could "print" electrodes on the skin directly by using conductive ink, we could make the thickness of the display virtually zero.

The second component of the system is a sensor. If we insist in placing the sensor just on the electrode, the type of applicable sensor is quite limited by its thickness. This problem can be averted by placing the sensor not on the skin but around the finger (Figure 13). In this configuration, finger motion is computed by the time course of the sensor's output. The state of the contact object beneath the skin is obtained by using previous information of the sensor.

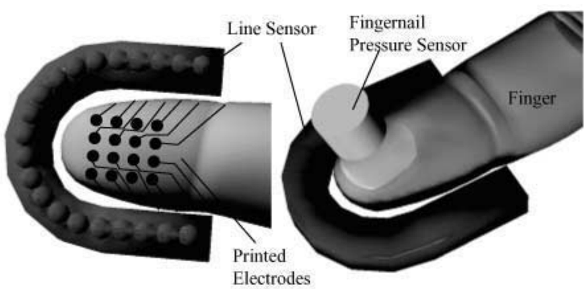

Figure 13. SmartTouch of the near future

For example, if we place a linear CCD sensor around the finger, the visual image is acquired in the manner of an optical scanner. At the same time, calculation of time-space correlation allows us to obtain finger motion, just like an optical mouse. Of course, this discussion assumes that the finger moves without leaving the contacting object, and the object surface does not change during the contact.

The final component of the system is a contact force sensor. It is already known that an optical sensor mounted on the fingernail can measure contact pressure by observing the color of the blood vessel under the nail [12]. Ultimately, we could fabricate ideal SmartTouch, a new layer of a skin, which does not hinder natural tactile sensation while detecting and presenting other surface information. Our next step is to realize this system.

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References

[1] H. Ando, T. Miki, M. Inami, and T. Maeda. The nail-mounted tactile display for the behavior modeling. In *Conference Abstracts and Applications of SIGGRAPH*, page 264, 2002.

[2] R. T. Azuma. A survey of augmented reality. *Presence*, 6(4):355–385, 1997.

[3] J. C. Bliss. A relatively high-resolution reading aid for the blind. *IEEE Trans. Man-Machine Systems*, MMS-10(1):1–9, Mar 1969.

[4] J. C. Bliss, M. H. Katcher, C. H. Rogers, and R. P. Shepard. Optical-to-tactile image conversion for the blind. *IEEE Trans. Man-Machine Systems*, MMS-11(1):58–65, Mar 1970.

[5] C. C. Collins. Tactile television - mechanical and electrical image projection. *IEEE Trans. Man-Machine Systems*, MMS-11(1):65–71, Mar 1970.

[6] R. S. Fearing and J. M. Hollerbach. Basic solid mechanics for tactile sensing. *Int. Journal of Robotics Research*, 4(3):40–54, 1985.

[7] R. S. Fearing, G. Moy, and E. Tan. Some basic issues in teletaction. In *IEEE Int. Conf. Robotics and Automation*, Apr 1997.

[8] K. A. Kaczmarek and M. E. Tyler. Effect of electrode geometry and intensity control method on comfort of electrotactile stimulation on the tongue. In *Proc. of the ASME, Dynamic Systems and Contorol Division*, volume 2, pages 1239–1243, 2000.

[9] K. A. Kaczmarek, M. E. Tyler, and P. B. y Rita. Electrotactile haptic display on the fingertips: Preliminary results. In *Proc. 16th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, pages 940–941, 1994.

[10] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi. Tactile feeling display using functional electrical stimulation. In *Proc. of The 9th Int. Conf. on Artificial reality and Telexistence*, pages 107–114, Dec 1999 http://www.ic-at.org.

[11] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi. Electro-tactile display with force feedback. In *Proc. World Multiconference on Systemics, Cybernetics and Informatics(SCI2001)*, volume XI, pages 95–99, July 2001.

[12] S. Mascaro and H. Asada. Understanding of fingernail-bone interaction and fingertip hemodynamics for fingernail sensor design. In *Proc. Tenth Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando*, pages 106–113, Mar 2002.

[13] W. Montagna. *Advances in Biology of Skin, Vol. VI, Aging*. Pergamon Press, 1964.

[14] T. Nojima, D. Sekiguchi, M. Inami, and S. TachiN. The smarttool: A system for augmented reality of haptics. In *Proc. IEEE VR'2002*, pages 67–72, 2002.

[15] J. G. Proakis and D. G. Manolakis. *Digital signal processing, principles, algorishms, and applications*. Prentice Hall, 1996.

[16] D. K. Stein. The optacon: Past, present, and future. In *http://www.nfb.org/bm/bm98/bm980506.htm*.

[17] A. B. Vallbo. Sensations evoked from the glabrous skin of the human hand by electrical stimulation of unitary mechanoseisitive afferents. *Brain Research*, 215:359–363, 1981.

[18] A. B. Vallbo and R. S. Johansson. Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Human Neurobiology*, 3:3–14, 1984.