SmartTouch: Electric Skin to Touch the Untouchable

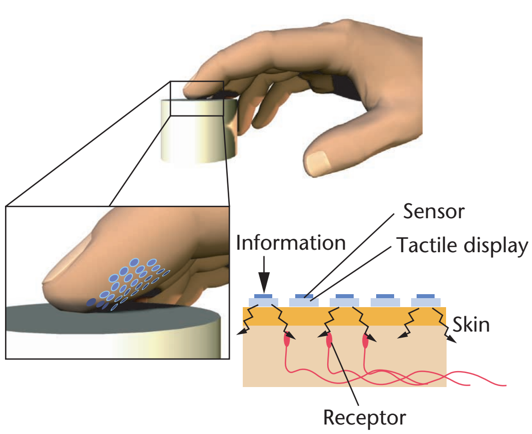
Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi
University of Tokyo

Masahiko Inami
University of Electro-Communications

Augmented haptics lets users touch surface information of any modality. SmartTouch uses optical sensors to gather information and electrical stimulation to translate it into tactile display.

Interactions with our surroundings make up a major part of our lives. In this relationship, we receive information from the world through the five major sensory modalities. Thus, we are fundamentally limited by the tiny sensory organs in charge of these sensations. Natural ambition arises, making us seek sensing abilities beyond the usual physical limits to build new relationships with the world. We want to see the invisible and hear the inaudible, an ability often referred to as a sixth sense.

Augmented reality[1] is an engineer's approach to this dream. In AR, sensors capture artificial information from the world, and existing sensing channels display it. Hence, we virtually acquire the sensor's physical ability as our own. *Augmented haptics,* the result of applying AR to haptics, would allow a person to touch the untouchable. (See the "Related Work in Augmented Haptics" sidebar.)



1 Augmented reality of skin sensations. A new functional layer of skin composed of a sensor and display acquire and convert surface information about an object into tactile information for display.

Our system, SmartTouch,[2] uses a tactile display and a sensor. When the sensor contacts an object, an electrical stimulation translates the acquired information into a tactile sensation, such as a vibration or pressure, through the tactile display. Thus, an individual not only makes physical contact with an object, but also touches the surface information of any modality, even those that are typically untouchable. Figure 1 illustrates the concept behind SmartTouch.

SmartTouch prototype

Figure 2 shows our SmartTouch prototype and a system cross section, which shows the systems' three layers:

- electrode layer on the front side of a thin plate,
- optical sensor layer on the plate's reverse side, and
- thin film force sensor between the first two layers

SmartTouch translates visual images captured by the sensor into tactile information and displays them through electrical stimulation. The system facilitates the recognition of printed materials through touch.

Electrical stimulation

By mounting a display directly on the skin, we can present tactile sensations with high spatial resolution. However, because the display is separate from the object's contact point, some problems can arise. Consider the motion of a finger when it moves horizontally, as Figure 3 illustrates. The contact generates friction, which the finger perceives as a torsional moment. As the display thickens—that is, as the distance between the object and display surfaces grows—the increased distance generates greater torsional moment, causing an unnatural haptic sensation. In other words, we should make the system as thin as possible.

For this reason, we use electrical stimulation to display tactile information. Under this paradigm, the only part of the system to contact the skin is a matrix of elec-

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Related Work in Augmented Haptics

Researchers have conducted a great deal of work on visual-to-tactile conversion systems. Bliss[1] developed the first converter system, and Collins[2] employed electrical and mechanical stimulation on the skin on the back.

Optacon,[3] a representative commercial product developed in the 1960s, uses a video camera and a matrix of vibrating pins. It attempts to allow a visually impaired person to read printed material rather than to augment the real world. Optacon requires a participant to hold a video camera in one hand while tactile information is displayed onto the other. In our system, the optical sensor and the tactile display are located in practically the same place and work together as a new skin receptor.

SmartTool[4] and SmartFinger[5] are two augmented haptics applications that use sensors to capture information from an object.

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 proposed application is surgery. 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.

SmartFinger uses a vibrating tactile display and sensor mounted on a fingernail. The vibrator drives the finger vertically, which induces force between the finger and the object it contacts. Thus, SmartFinger generates skin sensations indirectly, with natural tactile sensations unhindered by the display.

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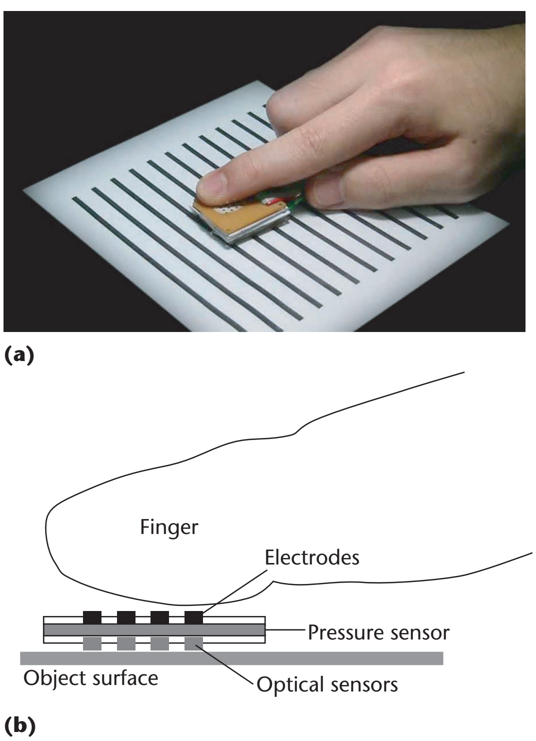
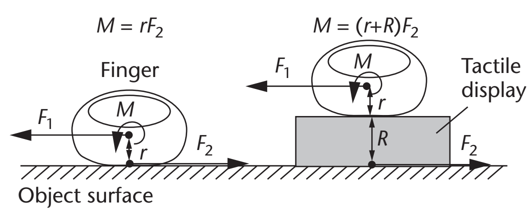


2 (a) SmartTouch prototype system in which optical sensors capture a visual image (black and white stripes) and display it through electrical stimulation, and (b) a cross section of the system.



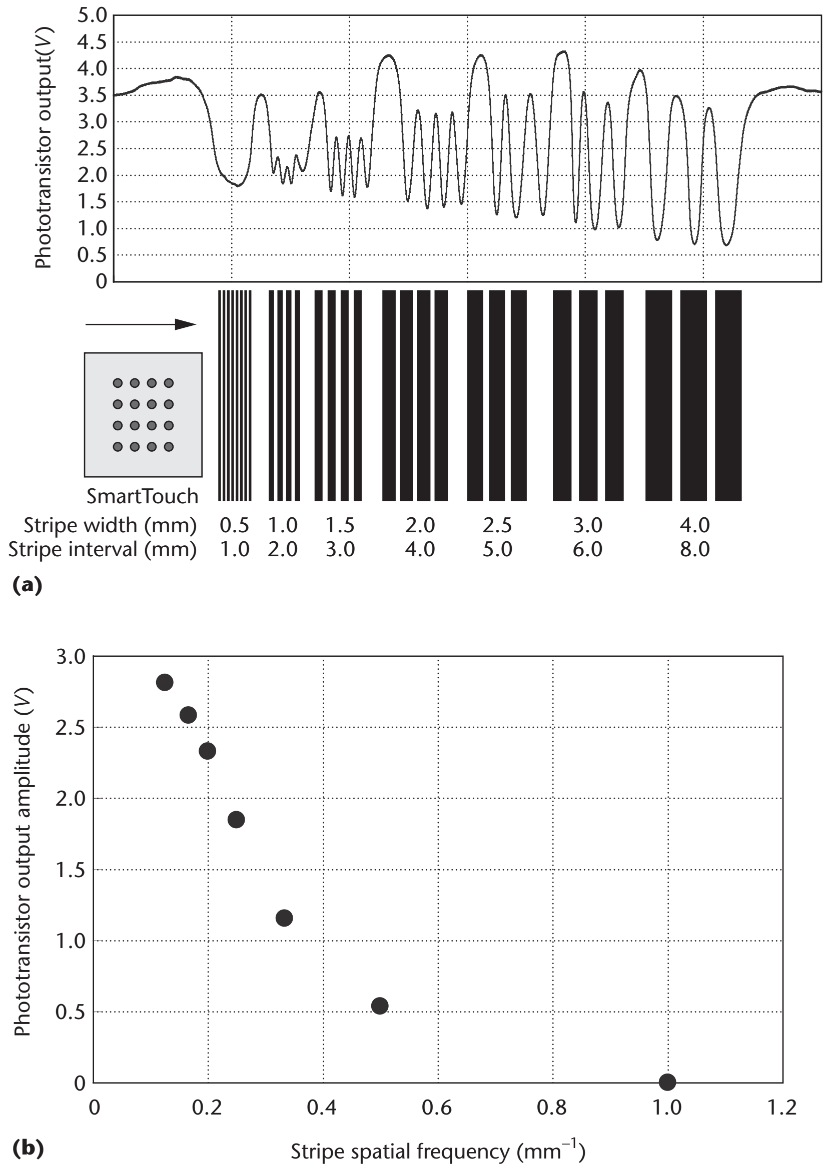
3 Effect of system thickness. The contact generates frictional force, which the finger perceives as a torsional moment. If the distance between object surface and display surface increases, it generates greater torsional moment, creating an unnatural haptic sensation.

trodes, which we can readily fabricate into a thin wafer.

The tactile display consists of a 4×4 matrix of stainless steel electrodes; each electrode is 1.0 mm in diameter. The electrodes' longitudinal pitch is 2.5 mm; their transversal pitch is 2.0 mm. The electrodes apply electrical current pulses (0.2-ms, 100- to 300-volt, and 1.0- to 3.0-mA current controlled) to the skin to generate the tactile sensation.

Optical sensor

We used a phototransistor (Sharp PT600T, $1.6 \times 1.6 \times 0.8$ mm) for our optical sensor. We placed the sensors just beneath the electrodes so the horizontal displacement between the stimulation point and the sensing point was less than 1.0 mm. Printed paper served as the contact



4 Spatial frequency characteristics of a SmartTouch sensor: (a) phototransistor response when swept on black and white stripes with varying spatial frequencies, and (b) phototransistor output amplitude.

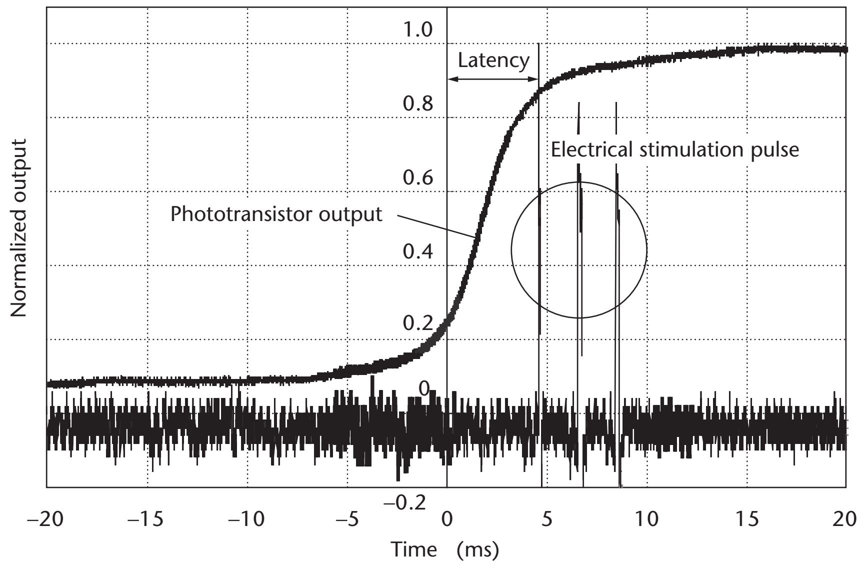
object. Because we didn't embed a light source into the system, an LED lamp lit the paper from below.

In the preliminary experiment, we placed each sensing element in direct contact with the object surface to create some gap region between the sensors where no sensor could see. Hence, when we move SmartTouch on black and white stripes using an interval identical to that of the sensors, the sensors initially could not locate the stripes; but then they all sensed the stripes simultaneously, causing the displayed tactile sensation to become unstable. To prevent such an effect, we widen each sensor's field of view to give it an appropriate spatial property.

The sampling theorem states that reconstructing an original signal from sampled data requires that the original signal not have a frequency component higher than $1/2\,d$, where d is the sampling interval.[3] From this viewpoint, we can consider the phenomenon in our first experiment as an aliasing effect. We therefore designed a spatial filter by broadening the sensors' field of view. We mounted spacers on the sensor substrate, keeping the gap between the sensors and the object surface to 0.5 mm.

We measured the sensor's spatial frequency characteristics by measuring a single phototransistor's response when being swept on black and white stripes with different spatial intervals, as Figure 4 shows. The interval of the stripes, which we consider to be approximated sin waves, was from 1.0 mm (0.5 mm white and 0.5 mm black) to 8.0 mm. Figure 4a depicts the sensor's response. To determine the spatial frequency response, we removed the DC component and measured the sensor's amplitude, as Figure 4b shows. From the figure, we see that the cutoff (–3 dB, or about 50 percent) sensor frequency is 0.3 mm^{-1}, which is equivalent to the stripes with a 3.3-mm interval. This value agrees with the Nyquist interval (two times the sampling interval) and hence demonstrates the antialiasing filter's design quality.

Fearing et al. performed a similar analysis to design a tactile information transmission system using a tactile sensor and tactile display.[4,5]



5 Phototransistor output and stimulus current (normalized). The latency between sensing and stimulation was less than 4 ms.

Force sensor

To produce a natural tactile sensation, the stimulation must correspond to finger pressure. We used a thin-film force sensor (NITTA FlexiForce, with a thickness of 0.3 mm), which we placed between the electrode and sensor substrates to measure finger pressure.

The history of the development of electrocutaneous displays is long and includes many failures associated with electric shock. A shock is typically perceived as a result of electrical stimulation, not of mechanical stimulation. Although a mechanical interaction can provoke as much or more sensation as electrical stimulation, the contact force proactively regulates it, eliminating the perception of shock.

Conversely, electrical stimulation doesn't have such a relationship with a contact force. Furthermore, the sensation peaks when the finger first makes contact with an electrode because electrical currents focus on a small contact area. Thus, we need a contact force to control electrical stimuli.

We set pulse energy (height or width) as a monotonically increasing function (temporary logarithmic) of this pressure, allowing force to actively control the excited nerves, while the nerve firing rate remained constant. The user can thus actively modulate the sensation's intensity.[6]

System latency

Combining the three layers lets SmartTouch process electrical stimulation based on visual information obtained by optical sensors. The shortest distance between adjacent electrodes is 2.0 mm, and our preliminary experiment shows that the finger's sweep velocity is less than 100 mm per second; thus, 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. Our system dynamically generates the electrical stimulation pulse waveform, storing it in a double-buffered memory mounted on digital-to-analog boards (National Instruments DAQ6713). This allows parallel processing of other tasks, such as image capture during stimulation, reducing the stimulation iteration period to 4.0 ms.

We measured the latency between sensing and stimulation. Figure 5 shows the normalized phototransistor output and stimulus current pulses as we swept the system over a boundary separating the black and white areas. We applied an electrical current pulse when the time derivative of the phototransistor output reached a certain threshold. As the figure shows, the latency was less than 4 ms.

Electrical stimulation coding

After the optical sensor obtains visual information of an object surface, we translate it into tactile information to be displayed through electrical stimulation. The translation technique used depends on the application.

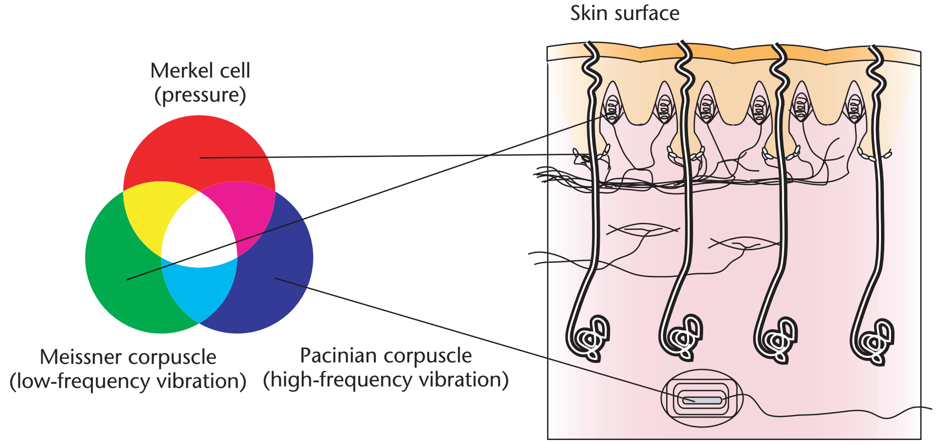
We endeavored to realize the perception of luminance information as the unevenness of the object surface. For example, test participants perceived the black and white stripes in Figure 2a as bumps with an identical interval.

Tactile primary colors

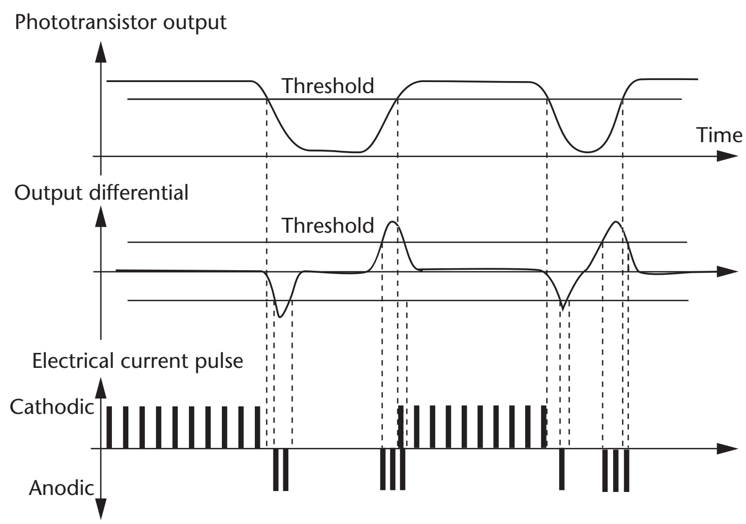
We have been developing a tactile display to present realistic skin sensations for virtual reality. The idea is to selectively stimulate each skin receptor type,[7] especially the four mechanoreceptors: Meissner corpuscles, Merkel cells, Ruffini endings, and Pacinian corpuscles. By combining these stimuli, as Figure 6 (next page) shows, we should be able to reconstruct complex tactile sensations—what we call our *tactile primary colors*, analogous to the three primary colors for vision.

Our approach uses electrical stimulation through the skin, or an electrotactile display. An electrical current from surface electrodes generates an electric field inside the skin, inducing nerve activity.

When using two coaxial electrodes (a central electrode with a 1.0-mm diameter and an outer electrode with a 4.0-mm inner diameter), the electrical current pulse (0.2 ms, 1.0 to 3.0 mA, and 10 to 50 pulses per second) generates vague pressure sensations when the central electrode is a cathode—that is, when the current flows from the outer electrode to the central electrode.



6 Tactile primary colors. We should be able to reconstruct any tactile sensation by combining receptors' activities.



7 Phototransistor output and its differential, and the electrical stimulation pattern of a single electrode.

On the contrary, if the current flows from a central electrode—that is, the central electrode works as an anode—it elicits an acute vibratory sensation.[8,9]

Physiological studies have revealed that two types of mechanoreceptors exist in the shallow part of the skin: Merkel cells and Meissner corpuscles. Merkel cells respond to static deformation, whereas Meissner corpuscles become active when the deformation changes over time.[10] Experiments in single-nerve stimulation showed that Merkel cells generate a pressure sensation, whereas Meissner corpuscles produce a vibratory sensation.[11]

If we extend these observations to fingertip electrical stimulation, we find that a cathodic pulse seems to selectively stimulate nerve fibers connected to Merkel cells, whereas an anodic pulse activates nerve fibers connected to Meissner corpuscles. Electrophysiological studies support this selective stimulation.[6] Mathematical analysis of a nerve-fiber electrical model revealed that a cathodic pulse selectively stimulates nerve axons running parallel to the skin's surface, whereas an anodic pulse efficiently stimulates vertically oriented nerves.[12] This fact and our experimental results agree with Cauna and Mannan's[13] anatomical observation that Meissner corpuscle nerves mainly run perpendicular to the skin's surface, and Merkel cell nerves generally run parallel to the skin.

In short, a cathodic pulse stimulates horizontally oriented nerves, which are mainly connected to Merkel cells in the human finger; an anodic pulse excites vertically oriented nerves, which are mainly connected to Meissner corpuscles. Consequently, we can display pressure and vibratory sensations. These findings support our attempts to use electrical stimulation to display natural tactile sensations.

Luminance to nerve-firing pattern translation

Our main goal is to generate a natural tactile sensation. Reducing this principle to the level of individual receptor activity makes it nothing more than artificially producing a nerve-firing pattern that might arise in a real contact situation.

In our transformation formula, if the luminance (regarded as bump height) reaches a certain threshold, a cathodic pulse produces a pressure sensation, as Figure 7 shows. We set the pulse rate (10 to 50 pps) proportional to the height. At the same time, when the luminance time derivative reaches a certain threshold, it produces an anodic pulse, generating a vibratory sensation.

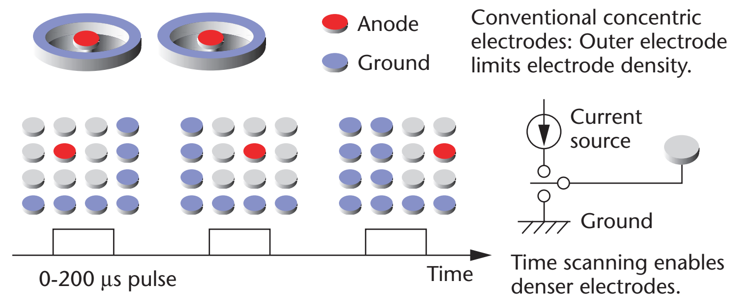
In this stimulation method, each electrode requires only the information from an optical sensor immediately beneath it.

Stimulation timing

When we stimulate a point, surrounding electrodes act as a return current electrode (*ground*), making it possible to stimulate only one point at a time. This requires time-division scanning,[6,14] illustrated in Figure 8. This configuration enables a much denser electrode fabric than conventional coaxial electrodes.

Because the sensor and display system cycle time is 4.0 ms, and each electrical pulse requires at least 0.2 ms, we could pack 20 pulses into one cycle. This isn't sufficient, however, even for our 16-electrode system, because we must provide both anodic and cathodic pulses. Our current solution is to constrain the number of stimulation points by regulating the threshold level mentioned previously.

In this manner, stripes with large intervals (about 3.0 mm) mainly generate a pressure sensation and appear as a rough bump; stripes with a small interval (about 1.0 mm) mainly generate a vibratory sensation and appear as a fine texture. Experiment participants could clearly distinguish between the stripe types by moving their fingers.



8 Time-division scanning in the anodic stimulation mode. Electrodes neighboring a stimulated point act as return current electrodes; thus only one point can be stimulated at a time.

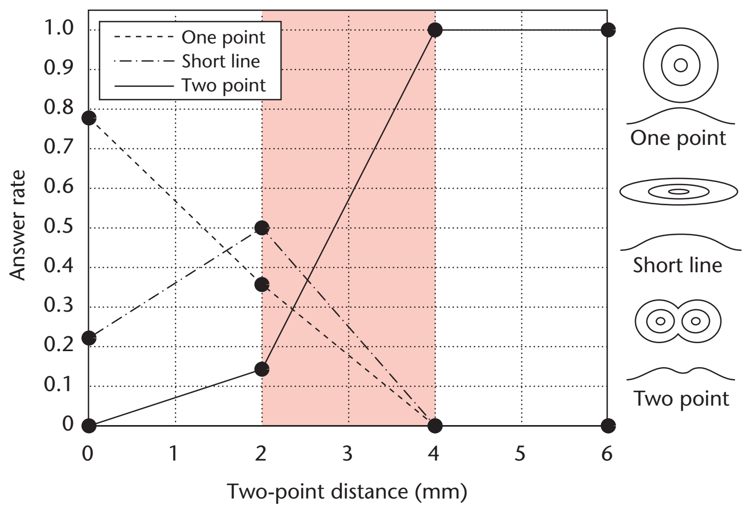
Psychophysical evaluation

We evaluated our prototype system through two sets of psychophysical experiments: a two-point discrimination test and a line-width discrimination test.

Two-point discrimination

To measure the display's static resolution, we stimulated two electrodes (each 0 to 6 mm apart) quasi-simultaneously using the time-scanning method. We applied 30-Hz anodic current pulses for one second. After the stimulation, we asked participants whether they felt one point, a short line, or two distinct points.

Figure 9 shows the results from six participants, each of whom took part in 40 trials. The graph shows that at 2 mm, participants most frequently perceive two points as a short line, whereas at 4 mm, they perceive two points as two distinct points. Hence, the static resolution is 2 to 4 mm.



9 Two-point discrimination with anodic pulse stimulation. The static resolution is 2 to 4 mm.

We conducted the same experiment using a cathodic current pulse. Unlike the anodic pulse, this pulse elicits a sensation that is typically blurred around the electrode, making it impossible to stably measure the spatial resolution. Kaczmarek et al.[9] first observed this crucial difference; our explanation is electrophysiological.[6]

A cathodic current activates nerve axons parallel to the skin surface. However, the brain mistakes the receptor connected at the axon tip as the one being activated. Therefore, a gap between the stimulation and sensation points always exists. The accumulation of this gap results in an unfocused sensation. This phenomenon is inherent to cathodic stimulation and can't be avoided by a simple application with a coaxial electrode.

On the contrary, an anodic pulse selectively stimulates vertical axons. Although the stimulation point and the connected mechanoreceptor might still have a gap, the gap is vertical, so it has negligible influence on the sensation. As a result, we obtain an acute tactile image.

The presentation of a spatial pattern is quite important in practical applications of SmartTouch. Hence, from now on, we will only use anodic current pulses. Although it doesn't dutifully follow our tactile primary color approach, we applied an anodic pulse when the luminance and its time derivative reached specified thresholds.

Line-width discrimination

Because SmartTouch assumes an active finger motion, we next measured the total system's dynamic resolution.

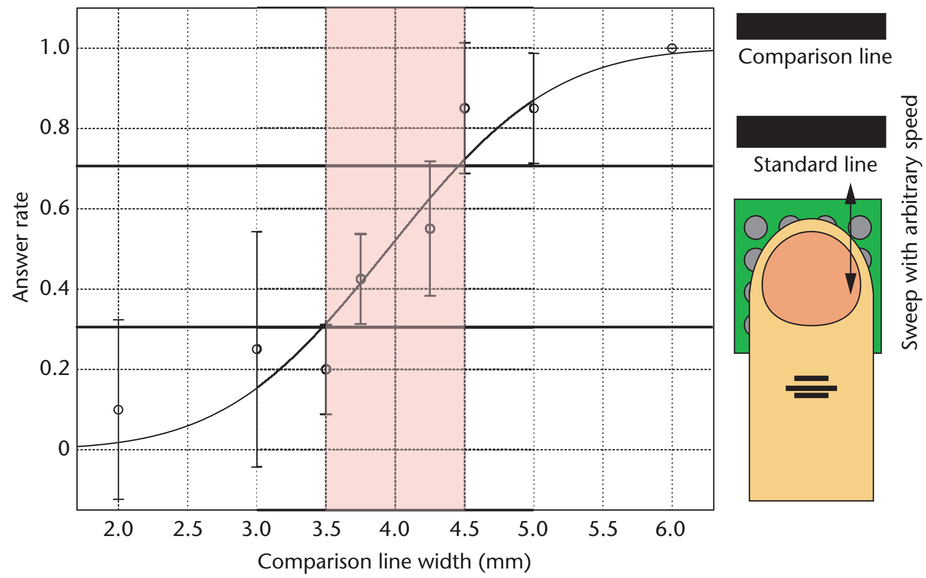
For this test, we wrote two lines on normal paper: one a 4-mm-wide standard line, the other a 2- to 6-mm-wide comparison line. The participants swept over the lines and indicated the widest line.

Figure 10 (next page) shows results from six participants, with eight trials for each line width. The horizontal axis is the comparison line width, and the vertical axis is the answer rate, measuring how often participants indicated that the comparison line was wider than the standard line. As the figure shows, the 70 percent correct thresholds are 3.5 mm and 4.5 mm. Hence, the 0.5-mm width is discriminated with a 70 percent certainty.

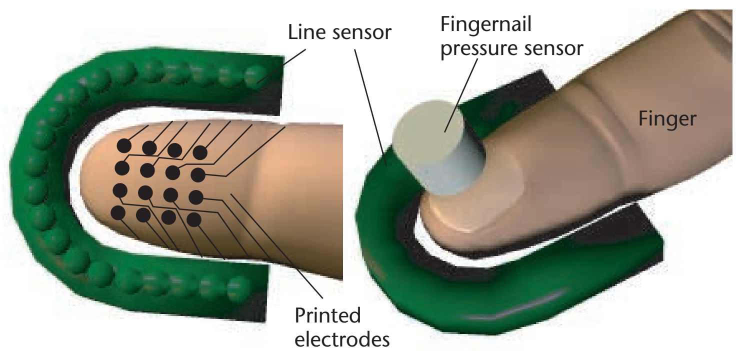
Future work

Until now, only two types of applications for tactile display existed: the Braille system for the visually impaired and a haptic device that adds realism to the virtual world through tactile textures. SmartTouch shows that combining sensor and tactile displays brings tactile display into the real world.

Although this article focuses on visual-to-tactile translation, the use of SmartTouch is not limited to Braille.



10 Line-width discrimination. The standard line width is 4 mm.



11 SmartTouch of the near future. We could realize SmartTouch as a new layer of skin that adds to natural tactile sensation without getting in the way.

By changing the sensor, other modalities of sensation can be translated to touch as well. We are now considering the combination of a tactile sensor matrix with an electrotactile display to perform tactile-to-tactile conversion. If the tactile sensor is more sensitive than human perception (the detection threshold of skin surface deformation is about 0.01 mm[10]), we can enhance the natural tactile experience.

Although not commonly known, human tactile sensitivity dramatically decreases with age,[15] making tactile aids (like hearing aids) a potential necessity.

Our goal for SmartTouch is a thin display and sensor directly mounted on the skin to serve as a new functional layer so that the system can be worn as an unconscious daily interface. Hence, it will be interesting to learn just how thin a system we can manufacture using existing technology. The display component needs only electrodes, which we can fabricate at a thickness less than 0.3 mm using a film substrate.[14] If we could print electrodes on the skin directly using conductive ink or a disposable tattoo, we could reduce the thickness of the display to virtually zero.

Other possible advances involve the second system component, the sensor. If we place the sensor not on our skin but around our fingers, we could ignore the sensor thickness. In this configuration, we compute finger motion by the time correlation of the sensor's output. We obtain the information under the skin using past sensor information.

Ultimately, we hope to fabricate an ideal SmartTouch, shown in Figure 11. The figure presents a new layer of a skin that doesn't hinder natural tactile sensation while detecting and presenting other surface information. ■

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Hiroyuki Kajimoto *is a research associate in the Department of Information Physics and Computing at the University of Tokyo. His research interests include tactile display, tactile sensors, and virtual reality. Kajimoto received an MS in mathematical engineering and information physics from the University of Tokyo.*

Naoki Kawakami *is an assistant professor in the Department of Information Physics and Computing at the University of Tokyo. His research interest is virtual reality. He received a PhD in advanced interdisciplinary studies from the University of Tokyo.*

Susumu Tachi *is a professor in the Department of Information Physics and Computing at the University of Tokyo. His research interests include virtual reality, telexistence, augmented reality, and robotics. Tachi received a PhD in mathematical engineering and information physics from the University of Tokyo. He is a founding director of the Robotics Society of Japan, a fellow of the Society of Instrument and Control Engineers, and founding president of the Virtual Reality Society of Japan.*

Masahiko Inami *is an assistant professor in the Department of Mechanical Engineering and Intelligent Systems at the University of Electro-Communications. His research interests include augmented reality and telexistence. Inami received a PhD in advanced interdisciplinary studies from the University of Tokyo.*

Readers may contact Hiroyuki Kajimoto, hiroyuki_kajimoto@ipc.i.u-tokyo.ac.jp.

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