Electro-Tactile Display with Force Feedback

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Abstract

In this paper, we deal with an electro-tactile display for the fingertip (electric Braille). Although electro-cutaneous stimulation (electrical stimulation from the skin surface) has a long history, its application was limited to clinical experiments for two main reasons: the difficulty in producing a sensation with sufficient resolution, and the unstable relationship between electrical current and the perceived sensation. We propose here two methods to solve these problems. One is to use anodic current stimulation to sharpen the elicited sensation. The other is to control current with finger pressure in order to regulate the sensation naturally.

Keywords: Electrocutaneous Display, Tactile Display, Force Feedback, Braille, Anodic Stimulation, Virtual Reality

1. Introduction

The authors have been developing a tactile display to present realistic skin sensation for Virtual Reality[3][4]. The idea is to selectively stimulate each kind of receptor in the skin, and to reconstruct complex tactile sensations by combining these stimuli. We call them "tactile primary colors," analogous to the three primary colors for vision. We've shown that selective stimulation is possible through electrocutaneous stimulation, and that it could easily be applied to important applications for a tactile display such as presenting Braille symbols. However, we encountered some practical yet critical problems, which shall be addressed in this paper.

2. Principle of Electrocutaneous Stimulation

Figure 1 shows a current stimulation from the skin surface and an electrical model of nerve fibers. We assume that a nerve is activated when the nerve membrane potential difference *Vm* reaches a certain threshold. Then it becomes a mapping problem between current source distribution *I*(x,y,t) on the skin surface and *Vm*, which can be solved with two processes.

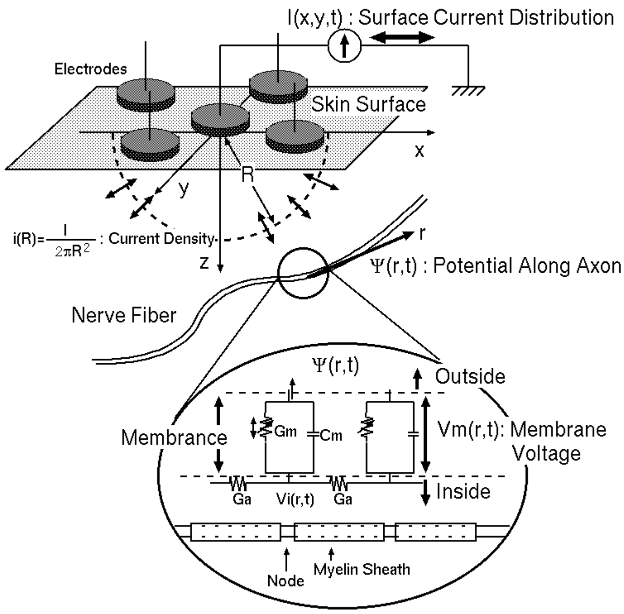

Figure 1 Electrocutaneous Stimulation

The first process is described as a mapping between *I*(x,y,t) and the external membrane potential *Ψ*(r,t) along a nerve. If *I* is constant, *Ψ* at (x,y,z) is calculated as:

$$\Psi(x,y,z)=\int i(R)\rho dR$$

where ρ is resistivity, R is the distance from the electrode, and *i(r)* is the current density.

The second process is a mapping between *Ψ* and the membrane potential difference *Vm*. By a simple analysis in which a nerve is considered as an infinite, time invariant cable, Rattay[6] concluded that the spatial second derivative of the potential along a fiber is proportional to the maximum *Vm*. It is called Activating Function:

$$ActivatingFunction(AF) = \frac{\partial^2 \Psi}{\partial r^2}$$

where *r* is the distance along a nerve axon. This can be used as a measure for nerve activation.

When electrical current is applied to the skin surface, and the nerve axon lies parallel to the skin (i.e. parallel to x-y plane, in the figure), the AF generated by a cathodic (negative) current is a positive value along the axon[3], which is why cathodic pulse is used in clinical applications.

3. Two Practical Problems

Electrocutaneous stimulation is superior to conventional mechanical tactile displays in many respects. They are smaller, more durable, more energy efficient, and are free from many mechanical difficulties such as resonance. However, despite its long history, application has been limited to clinical use for two reasons:

- It was difficult to confine the generated sensation to a small area. Even for electrodes with sufficient density, the generated sensation couldn't be localized under the electrodes.
- The relationship between the amount of current and the generated sensation was unclear and unstable. Sudden pain caused invasive impression, or even fear.

We propose two methods to address these issues.

4. Focused Sensation by Anodic Current

In conventional electrocutaneous stimulation, the elicited sensation is typically "blurred" around the electrode. Why? Of note is that cathodic (negative), or biphasic (negative and positive) current is typically used as a stimulus. As we have seen in section 2, cathodic current activates nerve axons parallel to skin surface (Figure 2 *Left*). However, our brain mistakes the receptor (mechanoreceptor, in this case) that is connected at the tip of the axon as activated.

Therefore, there is always some "gap" between the stimulation point and the sensation point. Accumulation of this gap results in an unfocused sensation. This phenomenon is inherent to cathodic stimulation and cannot be avoided by simple application with a coaxial electrode.

Since this unfocused sensation is caused by the stimulation of horizontal axons, the only way to avoid the gap is to selectively stimulate "vertical" axons (Figure 2 *Right*). In this case, although the stimulation point (axon) and the connected mechanoreceptor still may have a gap, the gap is vertical, so its influence on the sensation is negligible. As a result, an acute tactile image can be obtained.

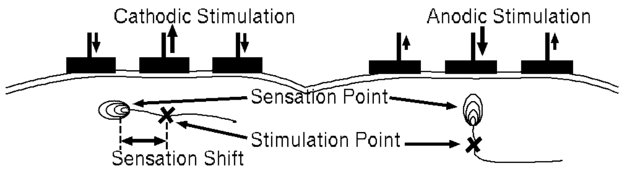

Figure 2 *Left* - Sensation shift by cathodic current stimulation. *Right* - Anodic current stimulates vertically oriented axons so that the shift of sensation does not occur.

We found that by changing the polarity of electrode from cathode to anode (positive), we can selectively stimulate vertical axons.

Since the AF is a second spatial derivative of an electrical potential along a fiber, the AF of horizontally oriented axons is a linear combination of $\partial^2\Psi/\partial x^2$ and $\partial^2\Psi/\partial y^2$, while that of vertical axons is $\partial^2\Psi/\partial z^2$.

From Gauss's law,

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = -\frac{\partial^2 \Psi}{\partial z^2}$$

always holds true inside the skin (nondivergent condition). This means that when the AF of a horizontal axon is positive, that of a vertical axon is negative, and vice versa. As cathodic current produced a positive AF around horizontal axons, we can selectively stimulate vertical axons by changing polarity of the electrode from cathode to anode[6].

In Kaczmarek's[2] discussion of the relationship between the polarity of pulse and the generated sensation in the fingertip, he observed that a negative pulse generated "diffuse sensation that is different, not only in magnitude, but in quality, from positive pulses". Though he had no clear explanation at that time, he speculated that different types of tactile receptors might be involved.

We reconfirmed that when the pulse's polarity was changed from cathode to anode, the generated sensation suddenly became both acute and vibratory.

We have already seen the reason for the acuity. The reason for the "vibratory" sensation is that in a human fingertip, the nerve axon connected to a Meissner corpuscle has a vertical orientation [7]. Therefore, the generated sensation should have a "low frequency vibration", which is a typical Meissner derived sensation.

On the contrary, in cathodic (negative) stimulation, we found that nerve axons that are connected to Merkel cells are activated, and elicited pressure sensation[3]. However, as the pure pressure is not as applicable to electric Braille, we will not pursue the matter further in this paper.

Anodic stimulation has another merit. Since the nerve axons responsible for pain are oriented horizontally, we can avoid the pain sensation. We speculate that this is why Kaczmarek has reported anodic pulse as a "better" sensation.

5. Force Based Current Control

The other problem to solve is the unstable relationship between the amount of current and generated sensation. This problem has two aspects. One is that the amount of generated sensation changes over time (typically a few minutes) due to deviation in electrical impedance. Most previous work on electrical stimulation deals with this problem. One successful result was obtained by Tachi[5], who suggested using energy (IxV) as a control parameter instead of current.

The other aspect of this problem is more serious – a sudden (~1[s]) change of sensation gives an "invasive" impression. It even causes fear. This is a typical phenomenon in electrical stimulation.

Why do we feel "invaded" by electrical, but not mechanical stimulation? Of note is that people mention an "electrical feeling" for occasions such as removing a sweater or touching a doorknob in winter, although there are no such things as "electricity receptors" inside the skin. In mechanical stimulation, we receive the same amount of pain or more if the object we touch is sharp, such as a needle or razor, but people are never "shocked" by them.

Figure 3 Handling sharp objects in daily life.

Furthermore, we handle such objects in daily life (Figure 3). This implies that we have a skill to control the amount of skin sensation through force application. However, in the case of electrical stimulation, the skin sensation is unrelated to force, so although people might not be harmed by the mild amount of electricity, they are often shocked by a sudden and unexpected sensation from simply touching the stimulation source. Therefore, our solution is as follows: by setting a force sensor (load cell) under the electrodes, we measure the finger pressure. The applied pulse height or width is set as a monotonically increasing function (possibly linear, or logarithmic) of this pressure (Figure 4). We can therefore control the amount of sensation by regulating finger pressure. Note that with this mechanism, what was once a *cutaneous* display, has become a *haptic* display.

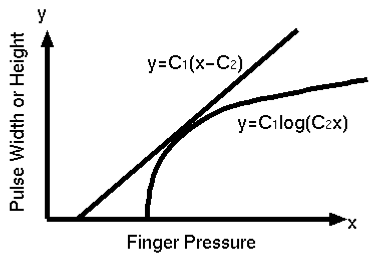

Figure 4 Pulse height or width set monotonically increasing function to finger pressure (linear and logarithmic).

6. Experiments and Results

Our experimental system is shown in Figure 5. It is composed of a 2x5 array of electrodes, each of which is a stainless steel rod, 1[mm] in diameter. The distance between each electrode is 2.54[mm].

Essentially, at any instant only one electrode serves as a stimulation electrode (anode), while all others are reference electrodes (cathode). The pulse duration was between 0 and 500 [μs], and at amplitude between 0 and 10[mA]. When two or more simultaneous stimulation points were necessary, raster scanning (ordinary beam scanning method in television) was applied (Figure 6). This is sufficient to avoid current interference.

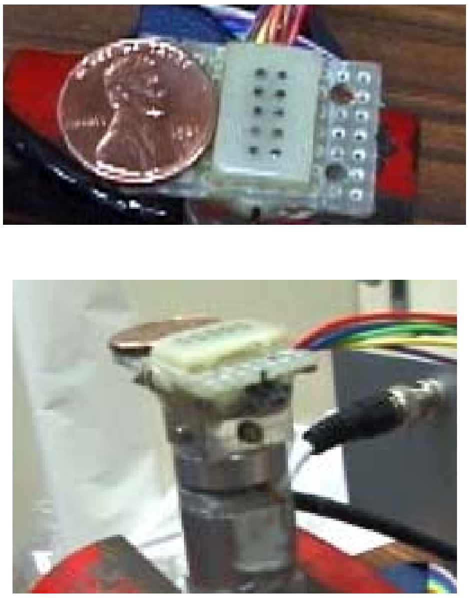

Figure 5 Force based current control. Force sensor with 6DOF is located under 2x5 electrode array.

The load cell is located under the electrode in order to directly measure the finger pressure. The pulse duration and amplitude are decided based on the finger pressure 1[ms] before the pulse is applied. The applied pulse height or width was set as a logarithmic function of the pressure (Figure 4 *Right*).

We used a 6 degree of freedom sensor in order to regulate the current based on both the magnitude and direction of the force, although this had little effect on the stability of the sensation. The scanning frequency was between 20 and 200 [Hz]. Subjects were two with normal vision and two visually impaired, but in the following qualitative results, there was no difference between the subjects.

All subjects felt a stable vibratory sensation. Sensation quality varies with scanning frequency, especially in a lower frequency (20 to 100[Hz]), which is the typical frequency of activity in the targeted Meissner corpuscle. However, when the frequency is higher than 100[Hz], we have much difficulty in discrimination. We suppose that some kind of saturation has occurred. At that high frequency, sensation was just like touching an Optacon[8], which is known as the standard vibratory Braille display.

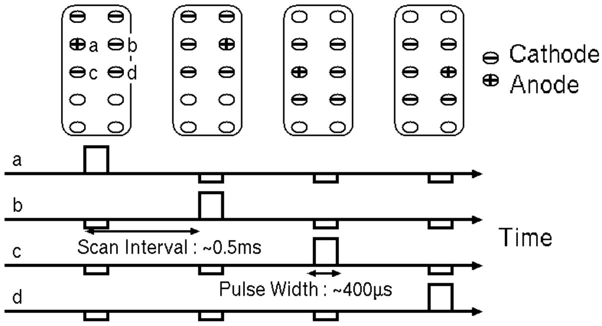

Figure 6: Scan procedure.

The mean threshold was 1.5[mA], but it varied greatly between individual subjects. In particular, the maximum threshold for one subject was at most 1.5 times greater than the minimum threshold. However, since the current was controlled by force, all subjects could stably and comfortably control the stimulation.

We also note that throughout the duration of the experiment, no subjects mentioned an impression of fear, which typically arises in conventional electrical stimulation. No difference was observed between amplitude control and pulse width control.

When one point was stimulated, all subjects could correctly identify the location of the stimulating electrode. When all points but one were stimulated, all subjects could identify the location of the missing point. These results suggest that the subjects are as adept at discriminating sensations as they are for mechanical stimulations.

7. Electric Mouse: Implementation of Active Touch

Many previous works mentioned that finger motion, or so called "active touch" is essentially important for tactile recognition. Some works mounted tactile display on a mouse so that people can move it freely[9]. Here we fabricated electric mouse that is an electrocutaneous version of these works (Figure 7).

Electrode is 0.7[mm] in diameter, 2.0[mm] interval, and 4x4 array. They are located at the center of the mouse. A force sensor is located under the electrode so that finger pressure is directly measured.

Figure 7 Electric Mouse. 4x4 electrode is located at the center.

The pulse amplitude was set at 1.0[mA]. Stimulation strength was regulated by changing the pulse width (0-400[μs]), and it was set as a logarithmic function of finger pressure.
According to the mouse motion, the stimulation pattern is changed so that the subject feels the existence of stationary object under the skin. Stimulation frequency is set as a function of mouse speed so that spatial frequency of the virtual surface, or so-called "texture" is presented. We are now under the stage of evaluation. One certain result was that all subject's recognition level became much higher as we have expected.

8. Conclusion.

Although electrocutaneous stimulation is widely useful and has a long history, its application has been limited to clinical experiments, mainly because of the difficulty in making localized point sensations, and the unstable relationship between the amount of current and generated sensation. In this paper, we proposed solutions to these problems. First, we showed both theoretically and experimentally that by using anodic current, a localized sensation is obtained. Second, we showed that by using force to control the amount of current, the formerly cutaneous display becomes a haptic display, and the typical invasive impression and sensation of fear were removed. Currently, pulse amplitude and width were set as a monotonically increasing function of finger pressure. However, changing this relationship to present more "natural" tactile sensations is an open topic and subject to future research.

Acknowledgments This work is partly supported by JSPS Research Fellowships for Young Scientists.

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