Electro-tactile Display with Real-time Impedance Feedback

Hiroyuki Kajimoto[1,2]

[1] The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585 Japan
[2] Japan Science and Technology Agency
kajimoto@kaji-lab.jp

Abstract. An electro-tactile display is a tactile interface composed of skin surface electrodes. Such displays comprise many useful features such as durability and energy efficiency, but their use is limited by the variability of the elicited sensation. One possible solution to this problem involves monitoring skin electrical impedance. Previous studies established the existence of a correlation between impedance and threshold, but did not construct true real-time feedback loops. In this study, we constructed a system with a 1.45-μs feedback loop, and evaluated the feasibility of the system.

Keywords: Electro-tactile Display, Impedance, Real-time Feedback.

1 Introduction

An electro-tactile (electrocutaneous) display is a tactile interface that uses surface electrodes to directly activate sensory nerves under the skin. Its merits include small and thin size, low cost, energy efficiency and durability, and many works proposed applications utilizing the merits, such as a wearable tactile display for visually handicapped people [1-3] and multi-touch interface with tactile feedback [4]. However, the variability of the elicited sensation has hindered its practical use.

This variability results from two problems (Fig. 1). *Temporal changes* occur when the contact conditions are altered by sweat and motion. The sweat reduces sensation, while abrupt motion of the skin generates an electric shock sensation.

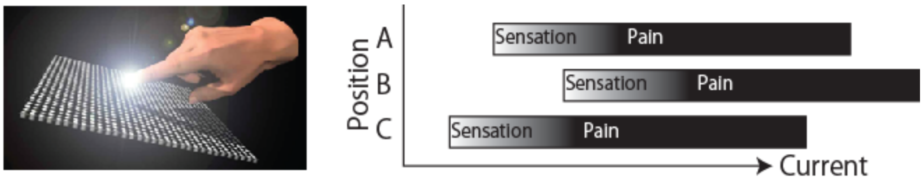

Fig. 1 Two factors contributing to the sensation variability of electro-tactile displays. (Left) Temporal changes caused by sweat and contact. (Right) Spatial variation of thresholds.

Spatial variation also contributes to variability. The threshold for tactile sensation (absolute threshold) is quite close to the pain threshold. Furthermore, the spatial variation of the threshold is large. Thus, if hundreds of electrodes are used, and the stimulating currents are the same, it is impossible to exceed the absolute threshold at all electrodes, without also exceeding the pain threshold at some.

1.1 Previous studies

Several solutions aimed at stabilizing the sensations generated by electro-tactile displays have been proposed. These can be classified into three categories.

The first category is to increase the difference between the absolute and pain thresholds. Collins [3] found that using a smaller pulse width (20–50 μs) was effective, while Polleto and van Doren [5] suggested applying a low-level pulse before the main pulse. Kaczmarek et al. [6] optimized several parameters such as number of pulses/burst to obtain maximal dynamic range. These methods represent important advances, but their effectiveness is limited.

The second category involves adjusting the stimulation in response to the user's explicit feedback [7]. A pressure sensor is placed under the electrode, and the electrical current is controlled by the sensor value. This simple method is quite effective for one finger and might be applied to multi-touch situation if multi-touch sensor is used, but requires user to control each finger pressure independently.

The third category measures the electrical impedance of the skin and controls the pulse using the measured value. This was originally done using an analog circuit. There are two main types of techniques for electrical stimulation: voltage regulation [8], and current regulation [1-5], while another type regulates energy [9]. These variations can provide different strategies to deal with impedance fluctuation using analog circuits.

In order to tackle the problem in a more general way, it is necessary to construct a measurement-stimulation control loop, such that the electrode can be used for both stimulation and measurement. Tachi et al. [9] regulated pulse width, based on the finding that perceived strength is related to input energy (current × voltage × pulse width). Watanabe et al. [10] found a correlation between skin resistance and absolute threshold. Gregory et al. [11] applied similar technique for fingertip. Takahashi et al. [4] monitored contact conditions by measuring impedance, and used the results to develop an electro-tactile touch panel.

1.2 Real-time feedback

Although feedback using skin impedance has been attempted in the previous studies, these have not been used real-time. In some of them the current pulse was regulated by impedance information acquired by a previous pulse (Fig. 2 (left)). It works if the finger is fixed to the electrodes, but it is not applicable to touch panel situation.

In some other studies, pre-pulse was used for measurement, with small enough values not to elicit a sensation (Fig. 2 (right)). The main pulse was applied after the initial measurement, *under the assumption that conditions did not change during this short period of time*. However, when hundreds of electrodes are used, this assumption is not justified. Analog switches are commonly used to construct low-cost systems with hundreds of electrodes [12]. A pair of top/bottom switches is connected to an electrode (Fig. 3). If the top switch is on, the electrode works as an anode, while if the bottom switch is on, it works as a cathode. The system only requires a single current source, thus significantly reducing the hardware costs. Using this system, only one point is stimulated at a time, and a two-dimensional pattern is produced by scanning.

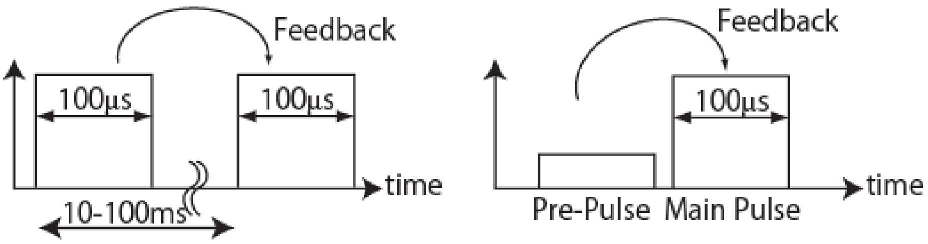

Fig. 2. Previous Methods. (Left) Current pulse is regulated by impedance information acquired by a previous pulse. (Right) Combination of measuring pre-pulse and stimulating main pulse.

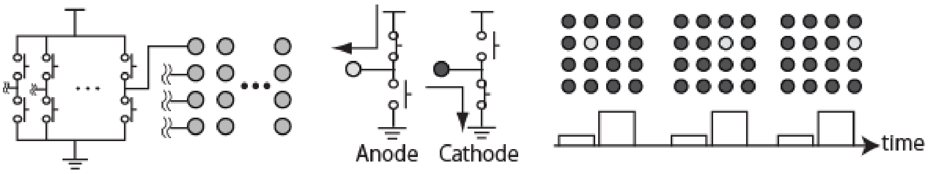

Fig. 3 Each electrode is connected to a pair of switches and can work as either an anode or a cathode. A two-dimensional pattern is produced by scanning.

Assuming a system with 100 electrodes and a refresh rate of 50 Hz, the allowed time period for one point stimulus is just 200 µs (= 20 ms/100 points), while the typical stimulating pulse width is 100 µs. However, if the contact conditions are altered by an abrupt skin movement, then an electric shock sensation lasting for 50% of the length of a stimulus (100 µs) may be generated, because it is not possible to feedback change during stimulation.

Measurement of skin impedance using pre-pulses also presents problems. Skin impedance is known to be highly dependent on applied voltage [13]. Therefore, if the pre-pulse is well below the absolute threshold, then the acquired data may not contain the full threshold information.

In light of these problems, we aimed to stabilize electro-tactile stimulation using true real-time impedance feedback. This involves dividing single stimulation into numerous sub-pulses, each containing a measurement and a feedback control (Fig. 4).

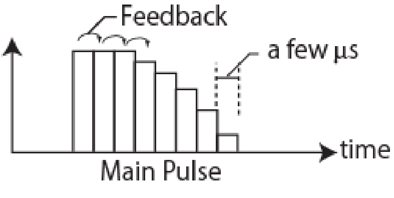

Fig. 4. Proposed method. A single stimulation is divided into numerous pulses, each containing a measurement and a feedback control.

2 System structure

Fig. 5 and Fig. 6 illustrate the system structure. To achieve high-speed feedback, the measurement and control loops should be less than a few microseconds. The system used a microprocessor (SH-7144F, Renesas Technology) as a main controller, and included a D/A converter (TLV5619, Texas Instruments, 12 bit, 1 Msps) and an A/D converter (LTC1851, Linear Technology, 12 bit, 1.25 Msps), both with parallel data input/outputs.

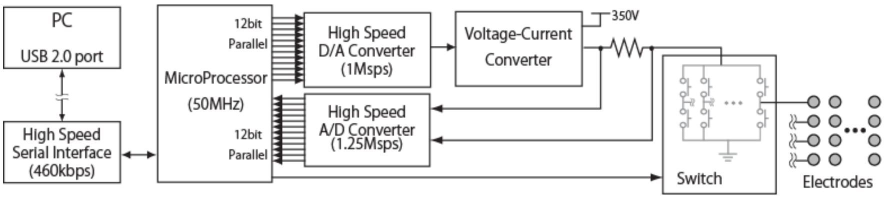

Fig. 5 System structure.

The stimulating pulse was generated by the D/A converter and converted to a current pulse by a voltage/current converter, driven by a high-voltage source (350 V). The current pulse passed through a resistor to measure the voltage and current. As the stimulating pulse was regulated by current, it was not usually necessary to measure the current, except when the voltage became saturated.

As described in Section 1.2, the switches (HV507, Supertex) controlled by the microprocessor selected a stimulating electrode one at a time.

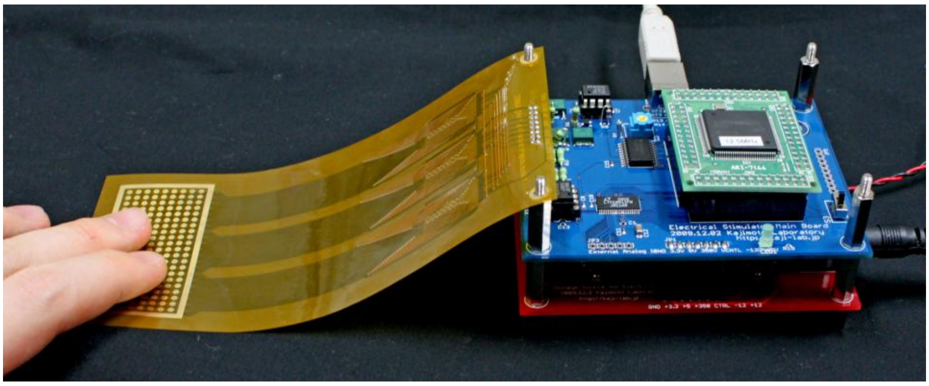

Fig. 6 Control circuit and electrodes.

3 Hardware evaluation and preliminary experiments

We evaluated the hardware and conducted two preliminary experiments to test the feasibility of the system. The author was the participant in all the experiments.

3.1 Feedback loop speed

The speed of the feedback loop was measured based on 30 control-measurement loops (Fig. 7 (left)). D/A signal was set and A/D value was acquired for each loop. The output was 5 mA for the first 15 measurements and 0 mA for the second 15. The subject's left index finger touched the electrode during the measurements.

Fig. 7 (right) shows the voltage data acquired by the A/D and the true voltage waveform measured using a digital oscilloscope (TPS2024, Tektronix). The two sets of data were in good agreement and confirmed that the duration of the feedback loop was about 1.45 µs, which fulfilled the requirements of the system.

```
for(i=0 ; i<15 ; i++){
        DAout(5mA);
        val[i] = ADin();
}
for(i=15 ; i<30 ; i++){
        DAout(0mA);
        val[i] = ADin();
}
```

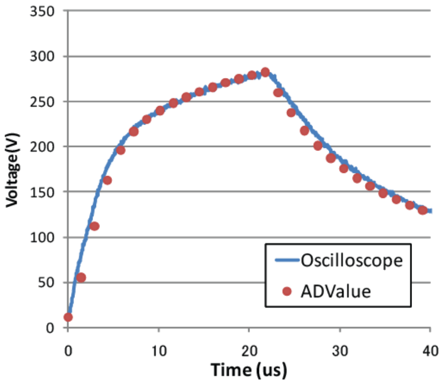

Fig. 7 (Left) Pseudo code for feedback loop measurement. (Right) Voltage waveform measured using an oscilloscope and the A/D converter.

3.2 Contact detection

Similar measurements to those described in Section 3.1 were repeated six times under different contact conditions. In five of the six trials, one of five fingers contacted the electrode, while one measurement was done without contact.

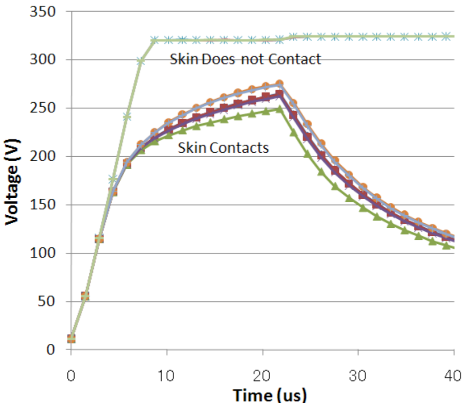

Fig. 8 Voltage waveforms when skin does or does not contact the electrodes.

Fig. 8 shows the acquired voltage waveform. As the current was regulated (5 mA), a higher voltage meant higher impedance. It was possible to distinguish between measurements made with and without contact, as the voltage became saturated in the absence of contact. The system was able to distinguish between the two conditions after about 6 µs. This was fast enough to avoid an electric shock sensation caused by abrupt motion.

3.3 Correlation between impedance and threshold

To confirm the presence of a correlation between skin impedance and threshold, we measured the absolute thresholds and voltage waveforms. The absolute thresholds were obtained by the method of adjustment. A 20-µs current pulse was applied to one electrode, and the participant adjusted the amplitude of the pulse to find the absolute threshold. Just after the threshold was reached, a 5-mA, 20-µs current pulse was applied and the voltage waveform was obtained (as in Sections 3.1 and 3.2). The stimulating position was changed for each trial. Five finger pads were used as the stimulating locations. Trials were performed 70 times.

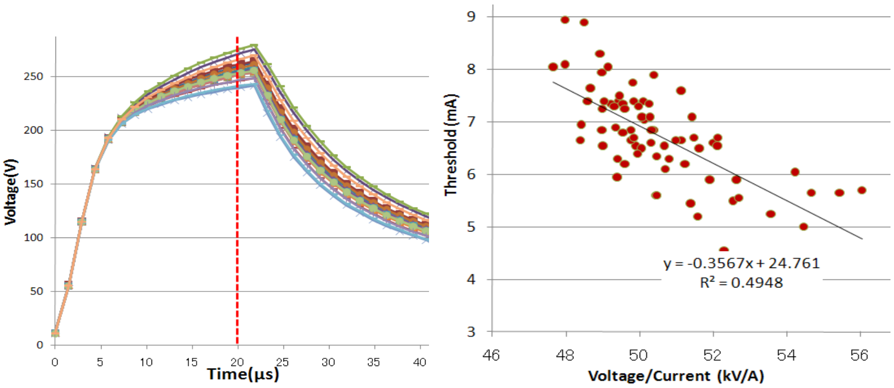

Fig. 9 (Left) Voltage waveforms of finger skin when current pulses were applied. Typical 20 of the 70 waveforms were plotted. (Right) Correlation between skin impedance (voltage/current) and threshold. Voltage values obtained at 20µs were divided by the current value (5 mA)

Fig. 9(left) shows typical 20 of the 70 waveforms produced. As these voltage waveforms were generated under constant current pulses, higher voltage waveforms corresponded to higher resistive components of skin impedance. Voltage values obtained at 20 µs were divided by the current value (5 mA), to demonstrate the relationship with absolute threshold (Fig. 9(right)).

The graph shows a clear negative correlation (R^2=0.49). The horizontal axis is roughly equivalent to skin resistance, indicating that skin with a higher resistance requires a smaller electrical current. This result is in agreement with the results of previous studies [9] [10].

4 Conclusion

This study investigated the problem of stabilizing electro-tactile displays. Although previous studies found a correlation between skin impedance and threshold, they failed to fully integrate the measurement and control phases.

We proposed to apply true real-time impedance feedback by dividing the stimulating pulse into numerous sub-pulses, each containing a measurement and a feedback control. We constructed a system that enables this high-speed feedback, evaluated the system and concluded that skin impedance (voltage/current) has sufficient information for the prediction of absolute threshold.

Future studies will involve the construction of a control algorithm and the application of the electro-tactile display to various fields.

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