Forehead Electro-tactile Display for Vision Substitution

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ABSTRACT

The Forehead Retina System-composed of a small camera and 512 electrodes on the forehead-captures the view in front, extracts outlines from the view, and converts the outlines to tactile sensation by electrical stimulation. Forehead skin was chosen for stimulation in consideration of usability. An electrotactile display was used so that the system becomes small and durable. A gel layer was designed to prevent an unpleasant sensation during stimulation. The system primarily aims to enable the visually impaired to "see" the surrounding environment..

Keywords: tactile display, electrocutaneous display, electrical stimulation, TVSS, visual prosthesis, virtual reality

1 INTRODUCTION

According to a WHO report in 2003, up to 45 million people are completely blind and 135 million people have low vision [11]. However, there exists no standard vision substitution system for their use in their daily lives. The goal of our project is to provide a cheap, lightweight, yet fully functional system that provides rich and dynamic 2D information to the blind.

The Forehead Retina System (FRS)—composed of a small camera and 512 electrodes on the forehead—captures the view in front, extracts outlines from the view, and converts the outlines to tactile sensation by electrical stimulation (Fig. 1). Using this device, the users can “see” the surrounding environment with their forehead skin, without using their eyes.

Although the system is a combination technology of computer vision, tactile display, and wearable interface, this paper mainly discusses the display aspect of the system because forehead electrical stimulation seems quite unusual.

1.1 Related works

There have been numerous proposals to restore the sense of sight by surgical means [1][2]. Direct stimulation of the visual cortex by an electrode matrix accomplished by Dobelle [1] is a well-known example. However, these technologies are not yet mature and may require at least a decade before they are put to practical use.

Further, there have been many studies on sensory substitution, in which visual information is converted to tactile or aural information. Meijer [10] proposed the vision to aural conversion system. His idea involved expressing 2D information by combining the frequency domain information (spectral distribution) of sound and the position information of the sound source using binaural earphones.

However, the system requires long-term training, and it supposedly hinders sound from the environment; sound is critically important for the visually impaired to grasp the surrounding situation.

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Fig. 1 Forehead Retina System (FRS).

On the other hand, the vision to tactile conversion system was first developed by Collins [3], who used 400 vibration motors on the skin of the back and a CCD (Charge Coupled Device) camera. He called the system a tactile vision substitution system (TVSS).

However, although many similar systems have been proposed since then, they have not become widely used for the following two reasons:

One is the technical aspect of the stimulation. For tactile devices using a large number of mechanical actuators, the system becomes heavy, expensive, and requires a considerable amount of power.

To make the device small and energy efficient, we must vigorously utilize mechanical resonance so that input energy is not rapidly converted to heat. Many works chose 200 to 300 Hz as the resonant frequency, which is the most sensitive range for human tactile sensation. However, it is also the frequency that is clearly audible to the user. Therefore, the noise becomes a considerable problem if a few hundred actuators are required to be used simultaneously.

The other reason pertains to the region of stimulation. Many previous proposals placed vibration motors on the waistcoat to stimulate the skin on the back. Although a waistcoat is definitely “wearable,” its use is not as effortless as the most successful carry-on devices such as eyeglasses and cell phones.

Many other works used the fingertip as a stimulation point because the fingertip skin has the highest spatial resolution in human body. However, because our purpose is vision substitution rather than conventional tactile display, we cannot choose the finger as a stimulation point because it is used for other purposes in many situations.

1.2 Electrical stimulation

Electrical stimulation is lightweight, cheap, scalable, and consumes much less energy. At the same time, it does not generate sound and is free from mechanical resonance. Therefore, many works used electrical stimulation for tactile display [9]. Note that Collins [3] has also explored electrical stimulation in his TVSS.

Kaczmarek and Tyler [10] have developed a 144-pixel array for the tongue. Electrical stimulation on the tongue is reasonable because it is always wet and has a low electrical resistance so that tactile sensation is generated with low electrical voltage. The tongue is also the location that has the second highest tactile resolution. However, putting something inside one's mouth seems uncomfortable and the system would require sophisticated design.

We propose to use the forehead as a stimulation point. Although electrical stimulation has a long history, stimulation of forehead skin is not a common approach. However, in reality, it is quite reasonable because of the ease in putting the FRS on and taking it off. At the same time, although the forehead skin has a relatively low resolution compared to the finger or the tongue, it has a higher resolution than the skin on the back [13]. Furthermore, if the stimulation is applied on the back, finger, or tongue, the coordinate system transformation to change the image on the skin to that on an absolute coordinate system is complicated. However, if we use the forehead, this transformation becomes unnecessary.

There were some works on forehead stimulation using mechanical stimulation, especially for the navigation of the blind people [4][12]. However, as the system on forehead should not be large or heavy, system with large number of actuators was not practical.

2 SYSTEM

Fig. 2 shows the diagram of the proposed system called the Forehead Retina System (FRS) and Fig. 3 shows the appearance of the system during use. A CCD camera attached on a pair of sunglasses (Ajoka Corp., SunGlasses Camera) captures the view in front. A laptop PC (Pentium-M, 1.1 GHz) extracts the edges and converts it to a tactile stimulation pattern. The pattern is transmitted to the driver circuit via a standard serial port (128 kbps). 512 electrodes are driven sequentially to create the tactile pattern. The entire process is triggered by the image capture event, which occurs every 33 ms (30 fps).

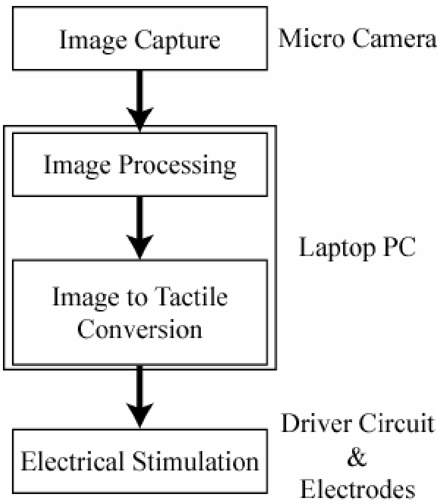

Fig. 2 Structure of the FRS.

Fig. 3 Appearance of the FRS during use.

Table. 1 Hardware specifications of the FRS.

Camera		Electrodes	
View Angle	45 deg	Number	512 (32 × 16)
Format	NTSC Color	Diameter	2.0 mm
Refresh Rate	30 fps	Interval	3.0 mm
Lens	Pinhole	Weight	100 g

2.1 Image processing

Fig. 4 shows how the image is converted to a tactile pattern when a cup or a hand is presented.

Every 33 ms, an NTSC format image is captured. First, it is converted to a 160 × 80 grayscale image. Second, the outline edge is extracted by a Laplacian of Gaussian (LOG) filter. Third, the image is scaled down to a resolution of 32 × 16. By allocating 1 or 0 to each pixel according to the following equation, we obtain a black and white binary image.

$$\begin{cases} 1 & (\text{pixel value} > \text{threshold}) \\ 0 & (\text{pixel value} \leq \text{threshold}) \end{cases}$$

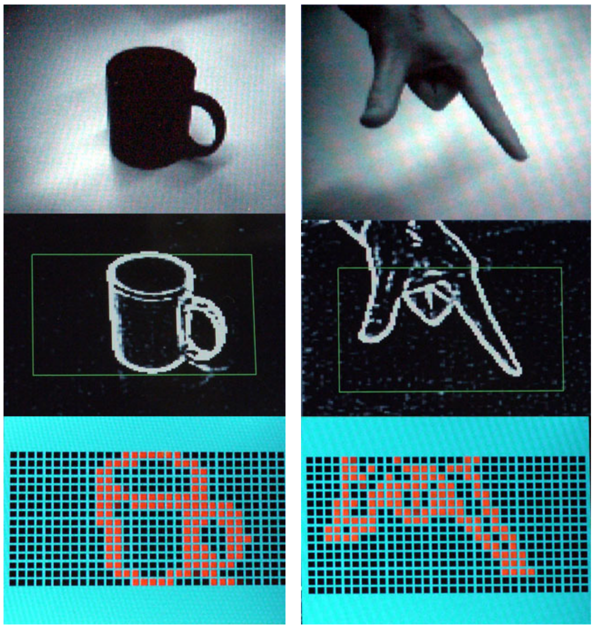

Fig. 4 The captured image is converted to a tactile pattern. (Top) Raw image. (Middle) Edge extraction. (Bottom) Tactile pattern.

The current system can only express a black and white image, which is definitely not sufficient. In the near future, the system will be expanded to provide the tactile presentation of a grayscale image, which is achieved by converting the image intensity to a stimulation pulse frequency.

2.2 Electrical stimulation

Although electrical stimulation has a long history, it was not applied for welfare devices for two reasons. One is that stable stimulation was difficult. The other is that spatial resolution was much worse than that of the mechanical stimulation.

However, in reality, these difficulties have already been solved by previous studies. Stable control of electrical stimulation is possible by using very short pulses [3], and the spatial resolution can be the same as that of mechanical stimulation by using anodic (positive current) stimulation, in contrast to conventional cathodic stimulation [6] [10]. Therefore, it can definitely be said that the use of electrical stimulation as a tactile display is already a well-established technology.

However, there still exist two problems for the FRS. One is forehead stimulation; the other is numerous electrodes.

2.2.1 Forehead skin stimulation

There are two groups of sensory nerves in the skin. One is the A-β fiber, which has a diameter of about 5 μm, connected to mechanoreceptors. The other is A-γ and C fibers, which have a diameter of less than 1 μm; they generate unpleasant sensations such as pain and heat.

In electrocutaneous stimulation, the electrical current from the surface electrode generates electrical potential inside the skin. The potential along the nerve generates membrane potential. If the potential becomes higher than the threshold, the nerve is activated and the associated sensation is generated.

If we stimulate the A-β fiber, the generated sensation is some type of mechanical sensation such as pressure and vibration; this is because the receptors that are connected at the tip of the nerve are mechanoreceptors (Merkel cell, Meissner corpuscle, Ruffini ending, and Pacinian corpuscle). The problem occurs when A-γ or C fibers are also stimulated because they generate an unpleasant sensation.

Two parameters determine the electrical current threshold. One is nerve depth, and the other is nerve diameter. The electrical current threshold is inversely proportional to the nerve depth or the square of the depth [18], while it is inversely proportional to the nerve diameter or the square root of the diameter [18].

The significant difference between the finger and the forehead is the skin thickness. While the finger skin has a horny layer that is more than 0.7 mm thick, the forehead skin has a horny layer that is less than 0.02 mm thick. The layer has high electrical impedance and can diffuse electrical current.

This is why the sensation elicited by fingertip stimulation is not unpleasant. In the fingertip, all the nerves are beneath the thick horny layer so that the distance between the nerves and the surface electrodes is relatively constant. Therefore, the A-β fibers for mechanoreceptors are stimulated while the other fibers are not activated (Fig. 5 top left).

However, if the horny layer is thin, the variance of the nerve depth greatly effects the stimulation. In many cases, thinner nerves reside in the shallower part of the skin, resulting in an unpleasant sensation such as pain and heat. Therefore, if we put the electrodes directly on the forehead skin, a severe pain sensation is elicited (Fig. 5 top right).

The general idea to prevent this problem is to put a conductive layer between the electrode and the skin. A hydrogel sheet is commonly used. The layer works as the equivalent of the horny layer so that the excitation of the thinner nerves by electrical current concentration is prohibited. We may regard the layer as a spatial low-pass filter, which diffuses electrical current.

There are four parameters for the design of the gel layer: electrode distance, gel thickness, gel impedance, and skin impedance. The relationships among these parameters are as follows.

If the gel is thin, the electrical current is concentrated, and thus, unnecessary nerves are activated.

If the gel thickness is relatively larger than the electrode distance, the electrical current mainly passes through the gel layer and cannot reach the skin (Fig. 5 bottom right). Therefore, most of the electrical power is wasted in the gel, which is a severe problem for a wearable device.

Similarly, if the gel impedance is relatively lower than the skin impedance, the electrical current only passes through the gel.

On the contrary, if the gel impedance is relatively higher than the skin, the electrical voltage drops mostly in the gel so that a large part of the energy is changed to Joule heat in the gel layer.

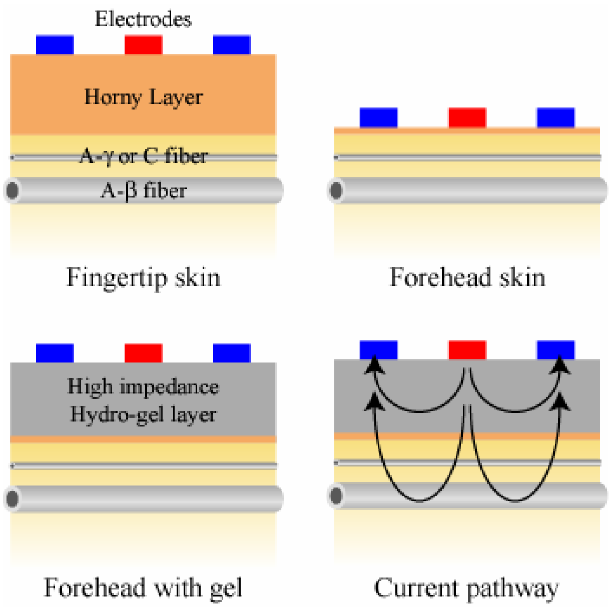

Fig. 5 The fingertip skin is covered with a thick horny layer, which contributes to stable sensation. Hydrogel layer works as the equivalent of the horny layer.

In conventional electrical stimulation, the electrode distance was quite large (typically about 3 to 10 mm); therefore, the above relationships 2 through 4 were negligible because the current pathway inside the gel can be ignored. Therefore, a thick gel with a fairly low impedance (10 to 50 kΩcm) was used. It seems that the gel layer is regarded as a convenient substitute for conductive paste, which stabilizes contact.

In contrast, we used a much denser matrix of electrodes, in which the interval was 3 mm; diameter, 2 mm; and distance, 1 mm. Therefore, the optimal gel characteristics should be designed based on the four relationships.

By trial and error, we found out that the gel thickness should be between 0.3 and 2.0 mm. The optimal thickness is around 0.5 to 1.0 mm. The gel impedance should be much higher than that of the conventional conductive gel for electrical stimulation. It should be around 100 to 1000 kΩcm. The optimal value is around 400 kΩcm. If these values are satisfied, electrical stimulation without any unpleasant sensation is achieved; simultaneously, power wastage is minimized.

Note that the optimal thickness is about the same as the electrode distance, and the optimal impedance of the gel and the impedance of the horny layer are matched.

2.2.2 Numerous electrodes

Compared to the presently used portable electronic devices, most of the proposed "portable" welfare devices are not portable in reality. They are bulky, heavy, and have a short operation time.

By adopting electrical stimulation, these problems have been partly solved. Nevertheless, driving N = 512 electrodes with more than 300 volts is quite a difficult task, and such a task normally requires a large circuit space.

We used a high-voltage switching integrated circuit. Fig. 6 shows the application of our technique. Rather than preparing N current sources, we used one current source and N switches called half-bridges. The half-bridge is composed of a high-side switch and a low-side switch. By switching, we selected an anodic electrode while all the other electrodes served as the ground [14].

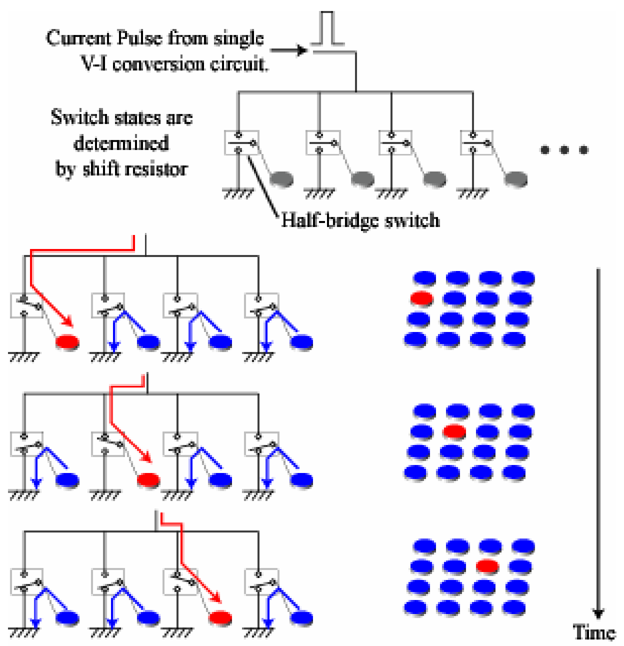

Fig. 6 2D information is presented by high-speed switching [14].

The same technique has commonly been used in motor drive circuits. This technique was previously proposed and utilized in cortical brain stimulation [15] and the cochlear implant [16] for electrical nerve stimulation. We utilized the same technique for electrotactile display to achieve both a very large number of stimulations and system portability.

We also used shift resistors so that the switch states are set by serial communication (Fig. 7). In this manner, although we drove 512 electrodes, we only used a few wires to connect the driving circuit and electrode module.

Note that in this switching method, only one point is stimulated at a time. Therefore, the refresh rate is limited by the number of stimulations. Currently the electrical pulse has been set to 50 μs. Therefore, it takes 25.6 ms to stimulate all the electrodes. It is barely shorter than the cycle time (33 ms).

One primitive but crucial problem is that of the shape of the forehead. It is spherical rather than cylindrical, and it varies from person to person. We divided 512 electrodes to eight units of 64 electrodes. Each unit is a square of about 30 mm. As the unit is small, it fits well on almost any adult person (Fig. 8).

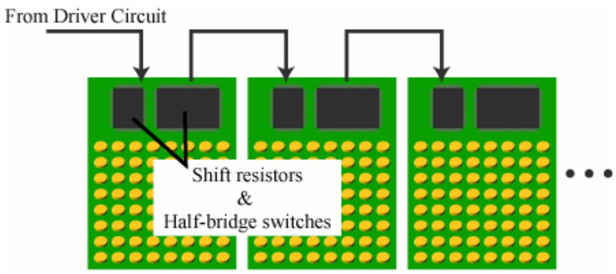

Fig. 7 Electrode board configuration. Each unit has 64 electrodes, shift resistors and half-bridge switches [14].

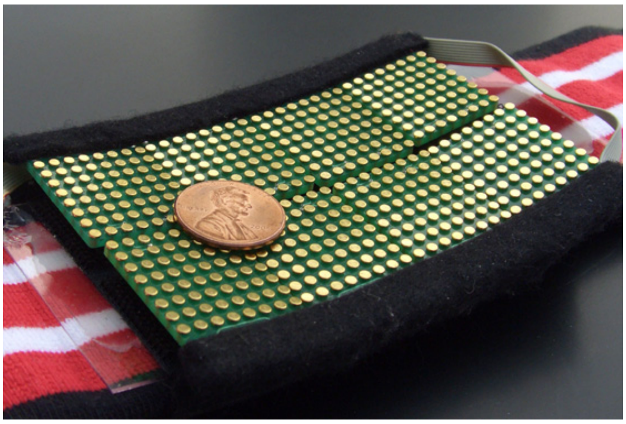

Fig. 8 512 (32 × 16) electrodes module for the forehead.

3 EXPERIMENT

3.1 Two point discrimination

Two point discrimination test was conducted to determine electro-tactile spatial resolution. Four points A-D were selected as SS (standard stimulation) points (Fig. 9). After 30 pps (pulses per second) electrical pulses were applied fore 1.0s and paused for 0.5s, the same pulses were applied to the other point as CS (comparison stimulation). The CS point was 1 or 2 electrodes away from the SS point, which means -6, -3, 3 or 6 mm displacement. The displacement was either horizontal or vertical.

In the horizontal case, participants were asked to answer whether the displacement was right or left (forced choice). 10 tests were conducted for each displacement at one SS point and answer rates were obtained. The same experiment was conducted for the vertical displacement case.

Fig. 10 shows the result of the experiment from one participant. Horizontal axis is the displacement, and vertical axis is the rate of the answer. In vertical displacement case, one electrode displacement (3 mm) was enough to answer the displacement direction correctly. It suggested that 3 mm interval electrodes are not unnecessarily dense for the forehead.

On the contrary, in horizontal displacement case, there are certain offsets according to the SS position. This offset becomes larger when the SS point becomes away from center. This phenomenon seems peculiar, because it means that although SS and CS are applied to the same location, one feels certain displacements. We are now trying to find out whether it is a particular phenomenon of the electrical stimulation or generally happens in mechanical stimulation.

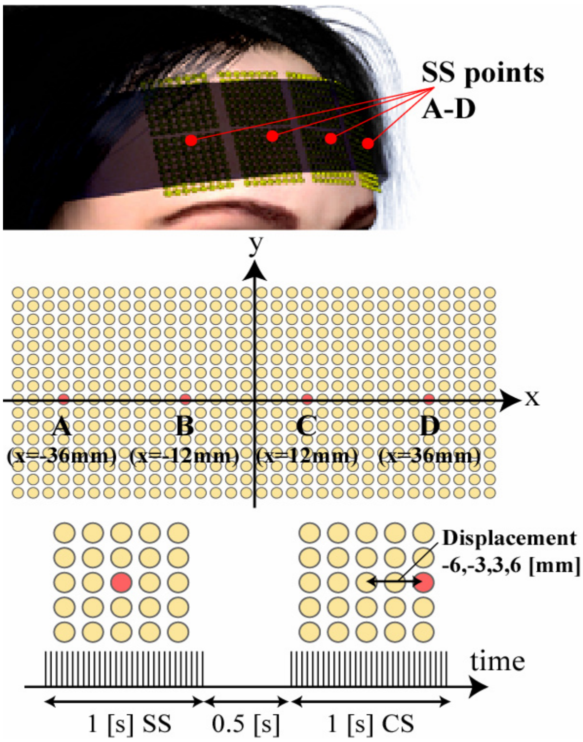

Fig. 9 Two point discrimination test setup.

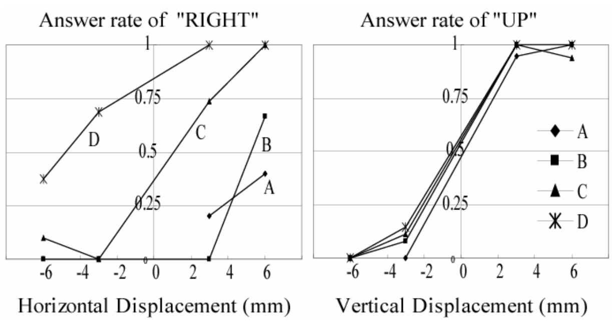

Fig. 10 Result of two point discrimination test. Horizontal and vertical displacements showed different behaviors.

4 CONCLUSION

We proposed the use of an electrotactile display on the forehead as a vision substitution system. Although the display has a large number of electrodes, the entire system is lightweight and compact. We tested the system and confirmed that problems regarding sensation quality rarely occurred. Two point discrimination test suggested that 3 mm interval electrodes are not unnecessarily dense for the forehead.

The paper showed only the static capabilities of the display. Other topics pertaining to the display include tactile recognition using head motion (active touch), grayscale expression using frequency fluctuation, and change in sensation after long-time use due to sweat. These will be the topics of our next study.

The current system uses only basic image processing to convert the visual image to tactile sensation. Further image processing, including motion analysis, pattern and color recognition, and depth perception is likely to become necessary in the near future.

We must note that although many useful algorithms have been proposed in the field of computer vision, we cannot always use them unconditionally. The processing must be performed realtime (at most 33 ms or one frame latency), and the system must be small and power efficient for portability. Therefore, we believe that rather than incorporating elegant but expensive algorithms, the combination of bare minimum image processing and training is practical. We are beginning to test the system with the visually impaired to determine the most appropriate balance as good human interfaces have always achieved.

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