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RESEARCH AND DEVELOPMENT OF VISION BASED TACTILE DISPLAY SYSTEM USING SHAPE MEMORY ALLOYS

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Abstract. *In this paper, an innovative vision based tactile display system is presented. Using common web camera to get visual information, the developed system captures and recognizes the shape of an object by proposed method which combines basic algorithm of the active contour and Harris corner detection. In order to let people sense the shape of the captured object, the developed system transforms visual information of the shape to tactile sensation. To represent the obtained tactile sensation, a tactile display panel is designed with 25 compact pin-type actuators to provide stimulation sources by using shape memory alloys. By employing higher-level perception, the resolution of the designed tactile display panel increases more than three times. Therefore, the shape of the captured object can be represented accurately. For verifying the effectiveness of the developed vision based tactile display system, experimental results are shown.*

Keywords: Vision based tactile display system, Shape memory alloys, Tactile display panel, Shape recognition, Higher-level perception

1. **Introduction.** Humans usually use the five senses (vision, audition, tactile, taste, olfaction) to obtain information from around environment, and especially use vision, audition and tactile to communicate with each other. For visually impaired people, auditory and tactile information is the primal communication media. Since auditory information is easy to be affected by noises from environment, it is reliable for visually impaired people to get information by tactile sensation. Another benefit with tactile sensation is that it is private unlike audio which can be overheard by others. Visually impaired people can identify material and texture of the touched things by tactile sensation [1, 2]. The most common tactile presentation method used by visually impaired people is Braille. The traditional Braille is printed on the paper, and embossed dots in each cell are used to represent each Braille character. Recently, accompanying the popularization of personal computers, the digitization of information through E-book has developed rapidly. Many researchers have paid attention on developing electronic Braille displays. The developed Braille displays are classified into two categories which are mechanical stimulating device and electrical stimulating device [3]. Electrical stimulating device is a tactile device that directly activates nerve fibers within the skin with electrical current from surface electrodes thus generating sensations of pressure or vibration [4]. Due to the invasive

nature of the electrical stimulating device, more researchers focus on researching mechanical stimulating devices which were constructed by using piezoelectric actuator [5], electromagnetic actuator [6], small servomotors [7].

In order to represent pictorial information for visually impaired people, researchers used the same kinds of actuators which were mentioned in the above to construct tactile display instead of traditional raised paper diagrams. In [8], a tactile-display device which was relying on lateral skin-stretch stimulation was described. It was constructed from an array of 64 closely-packed piezoelectric actuators connected to a membrane. The deformations of this membrane caused programmable lateral-stress fields in the skin of the finger pad. In [9], the design of a haptic texture display consisting of fifty vibratory pins that evoke a virtual touch sensation of textured surfaces contacted to the users' fingerpads is presented. Although these devices are widely used, poor portability because of large size is the drawback of them. In order to make tactile display device smaller, portable devices were designed by the authors of [10, 11]. However, requirements of high-voltage supplies and low response existed in these devices.

Considering the above problems, shape memory alloys (SMA) wire (Toki Corp., BioMetal, BMF50) is used to make actuators for tactile display [12, 13, 14, 15] because of its low voltage supplies. In [13], a refreshable Braille display was developed by using SMA wire. In [12], a portable Braille display was proposed based on the type of [13]. In [14], tactile information transmission by apparent movement phenomenon was discussed by using SMA device. Since the diameter of the SMA wire is 50μm, it can respond instantly and shrink within less than millisecond. This character overcomes the drawback of the low response of general SMA and makes the above applications successful. Due to the advantage of this SMA wire, it is employed to make 25 compact pin-type actuators to construct tactile display panel in this research. The designed tactile display can be used as Braille display as [13], and also be used to show some characters as [14]. For providing real-time information (shape of the captured object) to visually impaired people and making them able to sense the object without directly touching it, visual information should be captured with a camera [15]. Since the visual information cannot be directly encoded by visually impaired people, the transformation from visual information to tactile sensation is indispensable. In this research, this problem is solved by using our proposed method which is based on higher-level perception. For guaranteeing the accuracy of the visual information, shape recognition method combines basic algorithm of the active contour and Harris corner detection is proposed. The experiments are done by using the developed vision based tactile display system. According to the experimental results, the effectiveness of the developed system is verified.

The rest of this paper is organized as follows. In Section 2, tactile receptors and higher-level perception are introduced to provide an understanding of how humans sense things with tactile sensation. In Section 3, the structure and the functions of vision based tactile display system are presented. Experimental results are shown in Section 4. Finally, conclusion and future work are drawn in Section 5.

2. **Preliminaries of Tactile Sensation.**

2.1. **Tactile receptors.**

The skin can sense vibration, pressure, deformation and temperature since it has many tactile receptors which are found at the epidermis-dermis border down to the subcutaneous tissues. The tactile receptors can be categorized into four different types according to specific morphologies and functions. They are Merkel cell, Meissner corpuscle, Ruffini ending and Pacini corpuscle. As shown in Figure 1, Merkel cells are located in the epidermis approximately 10μm in diameter, and they can sense

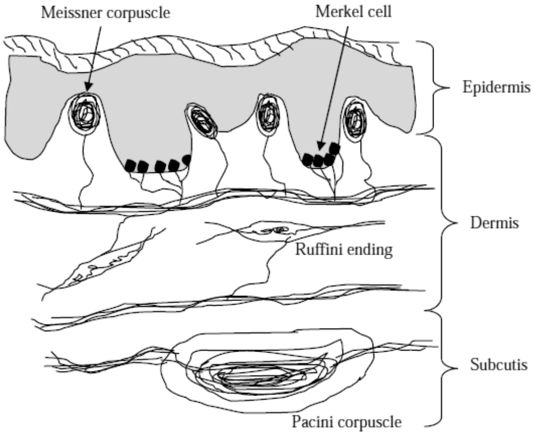


Figure 1. Tactile receptors under skin

Table 1. Characters of the receptors

Receptor	Class	Sense modality	Frequency range
Merkel cell	SAI	Pressure, texture	0.4 – 100Hz
Ruffini ending	SAII	Skin stretch	7Hz
Meissner corpuscle	FAI	Stroking, fluttering	10 – 200Hz
Pacini corpuscle	FAII	Vibration	40 – 800Hz

pressure and texture. Meissner corpuscles are primarily located just beneath the epidermis within the dermis and between $30 - 140\mu$m in length and $40 - 60\mu$m in diameter. They can sense stroking and fluttering. Ruffini endings are also located in the dermis around $0.5 - 2$mm in the length, and they can sense skin stretch. Pacini corpuscles are located in the subcutis, and they are about $0.5 - 2$mm in the length and 0.7mm in the diameter. According to the response speed and size of the receptors, the four receptors can be classified into four categories: fast adapting I and II (FAI and FAII) and slow adapting I and II (SAI and SAII). The relationship between these four categories and the four tactile receptors is summarized as Table 1 [3].

The tactile receptors are distributed with different density in different regions of human body. Since most tactile sensation is obtained by human hands, tactile display panel is considered to be touched by palm in this research.

2.2. **Higher-level perception.** In order to convey the tactile information about the shape of the object, higher-level perception of tactile sensation is adapted in this research. *Phantom sensation* is known as one of the higher-level perception of human tactile sensation [16]. A variable sensation appears between two locations when they are stimulated simultaneously with arbitrary intensity. If two stimuli have the same intensity, the phantom sensation is perceived in the middle of them. If one stimulus is stronger than the other, the illusory sensation appears at the closer location to the stronger one, according to the strength ratio. Figure 2 shows the schematic figure of the phantom sensation which appears between two mechanical stimuli. Using the phantom sensation, the resolution of tactile display with limited stimuli can be improved.

Apparent movement is also one of the higher-level perception of tactile sensation [17]. When two locations on skin surface are excited by two mechanical vibratory stimuli with transient time delay, an illusory sensation can be perceived, that continuously moves from first location to the other, as shown in Figure 3. Using apparent movement, location-fixed stimuli can represent dynamic object with limited stimuli.

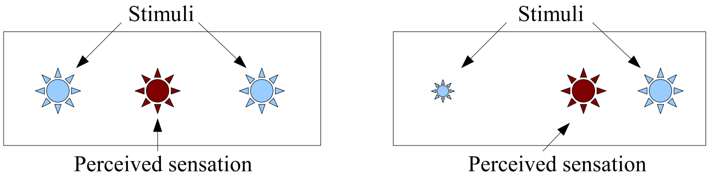


FIGURE 2. Phantom sensation

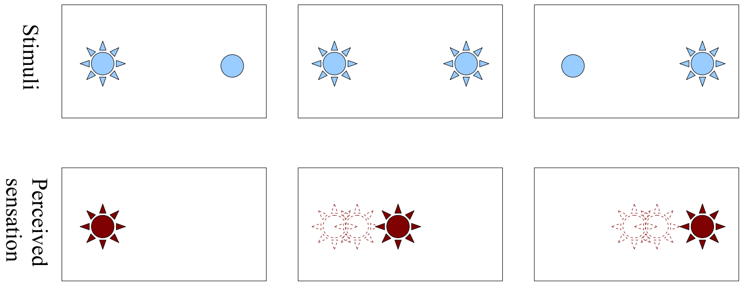


FIGURE 3. Apparent movement

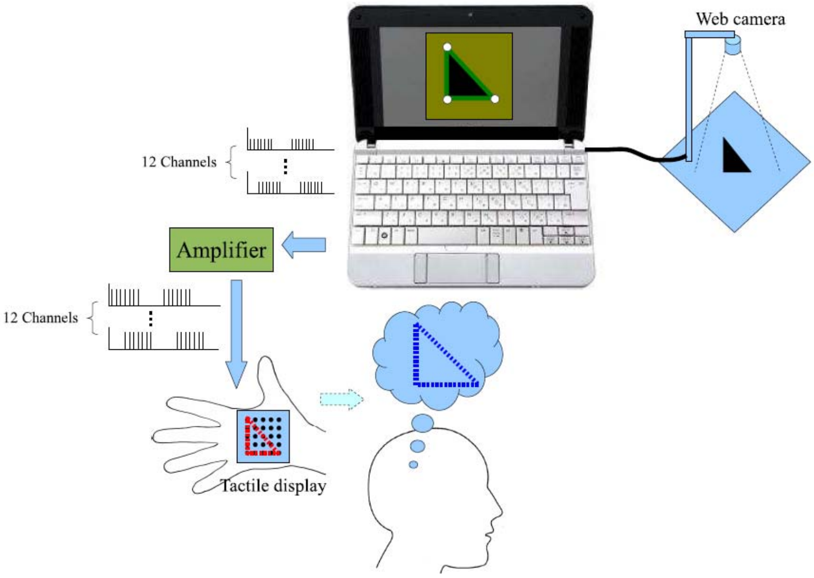


FIGURE 4. Schematic figure of vision based tactile display system

3. **Vision Based Tactile Display System.** Employing the above mentioned higher-level perception, vision based tactile display system is developed in this research. In this section, the structure and functions of the system are discussed. Figure 4 shows the schematic figure of the developed vision based tactile display system. The target of the system is to let people sense the shape of the object by using the tactile display. That is, the following functions should be included in the system:

- ⋆ Capturing the shape of the object by using a web camera.
- ⋆ Recognizing the shape of the object by an image processing technique.
- ⋆ Transforming visual information to tactile sensation.
- ⋆ Providing stimulation sources by a device.

In order to realize the above main functions, the solutions will be discussed in detail in the following subsections.

3.1. **Shape recognition of object.** In this research, a common web camera is chosen to capture visual information instead of professional one because of considering to improve the portability and to reduce cost of the system. In this subsection, a method to recognize the shape of the object is introduced.

In order to recognize the shape of object by using an image processing technique, the edge information of the object is indispensable. In this research, the active contour is employed to capture the edge information of the object. The active contour was proposed as an energy-minimizing parametric closed curve guided by external forces [18]. Energy function is associated with

$$E = E_{int} + E_{ext} \tag{1}$$

where E_{int} is the internal energy formed by the active contour configuration, E_{ext} is the external energy formed by external forces affecting the active contour. They are described as follows [19]:

$$E_{int} = E_{cont} + E_{curv} \tag{2}$$

$$E_{ext} = E_{img} + E_{con} \tag{3}$$

where

- E_{cont} is the contour continuity energy
$$E_{cont} = \left|\bar{d} - \|p_i - p_{i-1}\|\right|$$
- E_{curv} is the contour curvature energy
$$E_{curv} = \|p_{i-1} - 2p_i + p_{i+1}\|^2$$
- E_{img} is the image energy
$$E_{img} = -\|grad(I)\|$$
- E_{con} is the energy of additional constraints.

In this research, E_{con} is not considered. $p_1 \dots p_n$ is a sequence of points used to represent an active contour on an image plane. $\bar{d}$ is the average distance between all pairs $(p_i - p_{i-1})$. I is the image intensity. According to (1), the total energy of the active contour can be described as follows:

$$E = \sum_{i=1}^{n} E_i = \alpha \sum_{i=1}^{n} E_{cont,i} + \beta \sum_{i=1}^{n} E_{curv,i} + \gamma \sum_{i=1}^{n} E_{img,i} \tag{4}$$

Equation (4) is the kernel of the function *cvSnakeImage* of OpenCV, where E_i is the energy on every point, α, β and γ are the weights of every kind of energy. For minimizing the energy of the active contour, the greedy algorithm [20] is employed in the *cvSnakeImage*. It is efficient to accelerate the convergence of the active contour to the object.

The merit of the active contour is that it is easy to capture the information of object's contour and able to track the object even if the object moves. However, the details information of the corners is difficult to obtain by the active contour. In order to compensate this shortcoming, Harris corner detection method is considered to combine with the active contour. According to the commonly used definition of a corner [21, 22], the matrix of the second-order derivatives ($\partial^2 x$, $\partial^2 y$, $\partial x \partial y$) of the autocorrelation matrix ($M(x, y)$) of the image intensities ($I(\cdot, \cdot)$) should be described as (5) and (6).

$$R = \begin{bmatrix} \frac{\partial^2 M(x,y)}{\partial x^2} & \frac{\partial^2 M(x,y)}{\partial x \partial y} \\ \frac{\partial^2 M(x,y)}{\partial x \partial y} & \frac{\partial^2 M(x,y)}{\partial y^2} \end{bmatrix} \tag{5}$$

$$M(x,y)=\begin{bmatrix} \sum\limits_{-K\le i,j\le K} w_{i,j} I_x^2(x+i,y+j) & \sum\limits_{-K\le i,j\le K} w_{i,j} I_x(x+i,y+j) I_y(x+i,y+j) \\ \sum\limits_{-K\le i,j\le K} w_{i,j} I_x(x+i,y+j) I_y(x+i,y+j) & \sum\limits_{-K\le i,j\le K} w_{i,j} I_y^2(x+i,y+j) \end{bmatrix} \tag{6}$$

where $I_x(\cdot,\cdot)$ and $I_y(\cdot,\cdot)$ denote the partial derivatives in x and y, respectively. $w_{i,j}$ is the weighting parameter. The corners can be obtained by comparing the smallest value of two eigenvalues of (5) with the designed threshold. In this research, according to (5), a shape recognition function is designed by combining *cvSnakeImage* and *cvGoodFeaturesToTrack* of OpenCV. In the designed function, the detected corners are used to assist the active contours to capture the most proximate shape of the object. By using the designed shape recognition function, recognition results of four objects with different shape are shown in Figure 5.

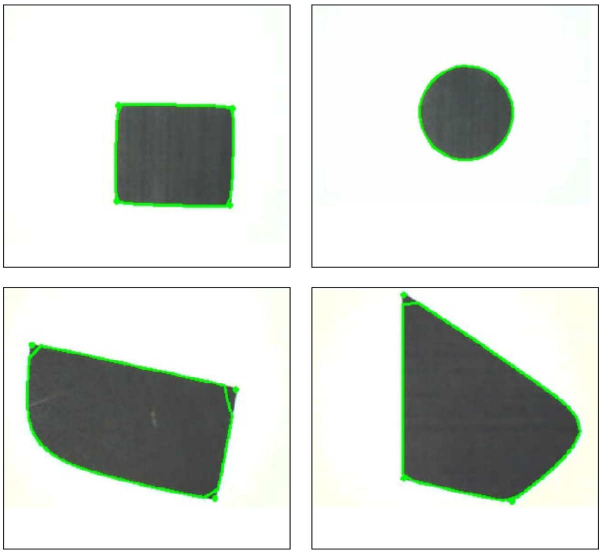


FIGURE 5. Recognition results of four objects

In Figure 5, we can see that if we only used *cvSnakeImage*, we could just capture the contour of each object without the information of the corners. Using this captured visual information, we cannot describe the accurate shapes of the considered objects except of the circle. By using our proposed method, the above problems can be solved because the information of the corners of each object can be obtained precisely. Therefore, any shape of the object can be captured and recognized accurately by using our proposed method. It guarantees the reliability of the source of the information which will be transformed to tactile sensation.

3.2. **Tactile display panel.** In this subsection, a tactile display panel used to represent the captured object is introduced. In order to generate stimuli to let people sense the shape of the object, shape memory alloy (SMA) wire is employed to make tactile display panel in this research.

Within typical operating temperature range, SMA has two phases, each with a different crystal structure and therefore different properties. One is the high temperature phase called Austenite phase and the other is the low temperature phase called Martensite phase. When temperature of SMA increases beyond critical values, the phase of SMA will be varied from Austenite phase to Martensite phase and vice versa. Since the crystal structure of SMA is changed corresponding to different phase, the shape of SMA is changed simultaneously. This unique behavior of SMA has made it popular for actuation and

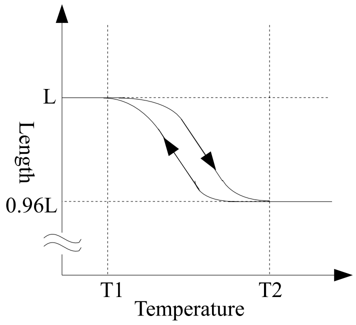


FIGURE 6. Characteristic of SMA wire

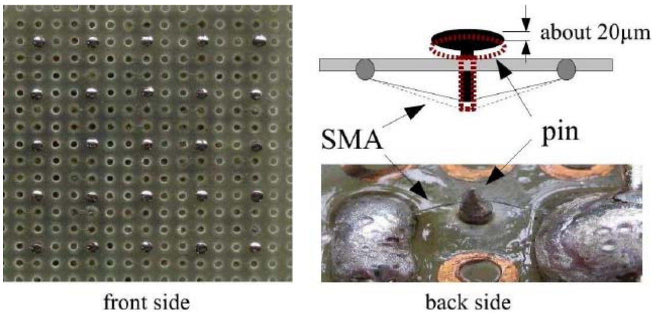


FIGURE 7. Tactile display panel

sensing and be applied in many industrial sectors such as aerospace, automotive and biomedical.

According to the unique characteristic of SMA, an SMA wire (Toki Corp., BioMetal, BMF50) is selected to make tactile display panel, and its characteristic is shown in Figure 6. When the temperature of the SMA wire arises beyond T1, the wire begins to shrink till the temperature is over T2. When the temperature of the SMA wire reduces back to T2, the wire begins to expand back to original length till the temperature is below T1.

Using this SMA wire, a compact pin-type actuator is constructed as shown in Figure 7. The diameter, length and resistance of SMA wire are 50μm, 6mm and around 3Ω, respectively. If current is added on the wire, heat is generated by the internal resistance of the SMA wire, and then the SMA wire shrinks (solid line in Figure 7). If the current is removed, the wire will become cool and expanded (dot line in Figure 7). Therefore, pulse signal is used to control the current for SMA wire's shrink and expansion. As we know, the general SMA has quite slow time-response. However, BMF50 can respond instantly and shrink within less than a millisecond. This is the reason that we adopted BMF50 to make a vibration actuator. Since the used BMF50 wire is thin and short, 1.5V can drive the actuator, and the energy consumption is less than 100mW. In order to let people sense the stimuli from the SMA wire, a pin is fixed at the middle of the SMA wire to transform the movement of the SMA wire to vibration of the pin. The displacement of the pin is about 20μm and is enough to be sensed by people. Since the SMA wire is short and thin, when it is driven by current in short time, the produced heat cannot make people feel hot. Therefore, according to the above merit, the designed compact pin-type actuator is suitable to be applied into the tactile display panel.

As shown in Figure 7, there are 25 compact pin-type actuators on the tactile display panel. They construct the matrix to show the shape of the object by using their vibration. That is, the active contours which are captured to describe the shape of the object can be mapped to the 25 compact pin-type actuators (see Figure 8). Since the resolution of

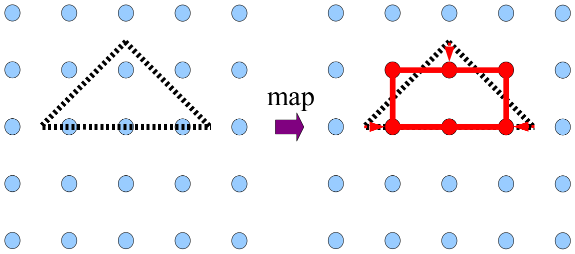


Figure 8. Tactile display panel without phantom sensation

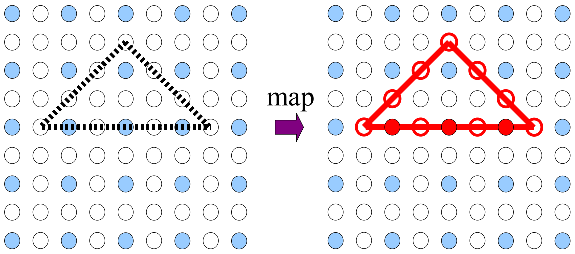


Figure 9. Tactile display panel with phantom sensation

the designed tactile display is low, after mapping process, the shape of the object maybe changes. For example, we regard a triangle as capturing object. After the mapping process, the shape of the object is changed from the triangle (dot line in Figure 8) to the rectangle (solid line in Figure 8). For solving this problem, common method is to increase the numbers of the actuators for improving the resolution. That is the reason that the size of the existing tactile displays is large. In order to make the tactile display portable, we adopted the phantom sensation which was mentioned in Section 2.2 to extend 25 stimuli to 81 stimuli based on 25 compact pin-type actuators instead of increasing the number of compact pin-type actuators. In Figure 9, phantom sensation can be perceived at the positions which are shown by hollow circles. Considering the same case as Figure 8, since the active contours can be mapped to the phantom sensation points, the most proximate shape of the object (solid line in Figure 9) can be described.

4. **Experiments.** In the above section, basic functions of vision based tactile display system were realized. In this section, experiments are done by using the developed system. Firstly, in order to verify the effectiveness of higher-level perception (Phantom sensation (PS) and Apparent movement (AM)), a whirlpool is represented without and with PS as shown in Figure 10. Pulse signals in Figure 11 are used to produce phantom sensation and apparent movement. Parameters of pulse signals are shown in Table 2.

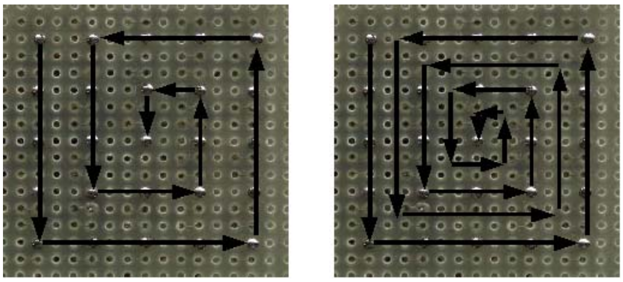
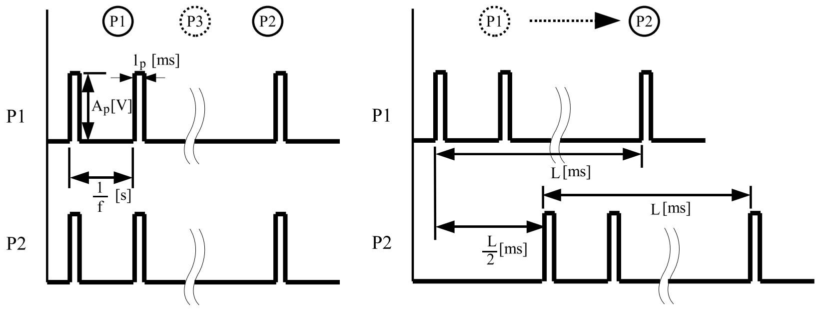


Figure 10. Chart of whirlpool



PS AM

Figure 11. Pulse signals for producing phantom sensation and apparent movement

Table 2. Parameters of pulse signals

Amplitude A_p	Frequency f	Pulse length l_p	Vibration Time L
2 [V]	25 [Hz]	1 [ms]	200 [ms]

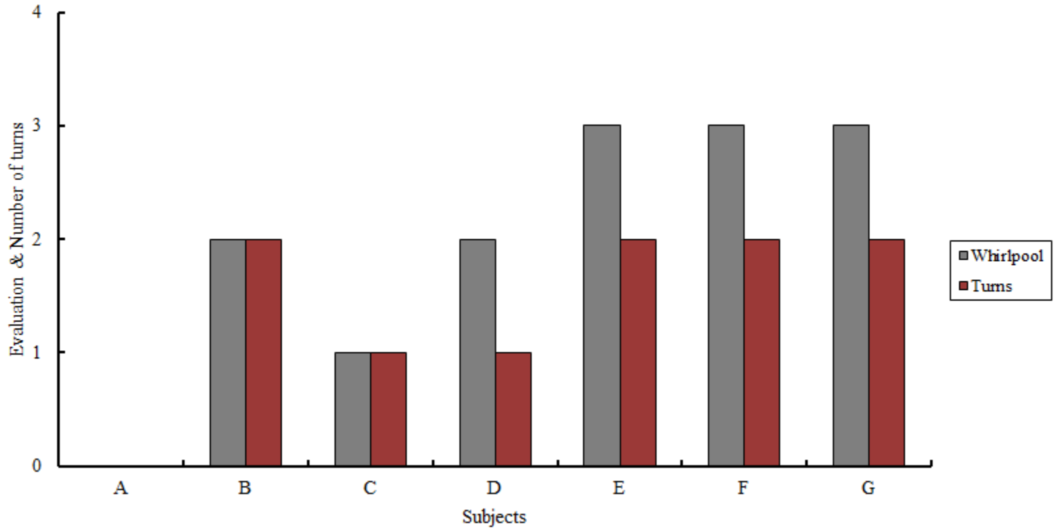


Figure 12. Results without phantom sensation (25Hz)

Seven subjects (five males and two females, without dysaphia) joined the experiments, and were required to give evaluation of whirlpool and the number of turns depending on their sensation. Evaluation of whirlpool includes: 0 – No feeling; 1 – Vibrating but not moving; 2 – Feeling a movement; 3 – Moving; 4 – Whirlpool. Experimental results are shown in Figures 12 and 13. Without phantom sensation (see Figure 12), most of subjects could sense the movement and know the moving direction. It proved that the apparent movement could help people to sense the movement. However, since there is not enough tactile information from the display, no one knew that was whirlpool or how many turns it had. Figure 13 shows the results of the experiments using the phantom sensation. Comparing it with the one in Figure 12, recognition of whirlpool was improved obviously. Since the tactile information was increased by using the phantom sensation, all the subjects could sense the number of turns more than three even though not all of them knew that was whirlpool. Therefore, high evaluation values and the number of turns verified that it was effective to represent the shape of object with the phantom sensation and the apparent movement.

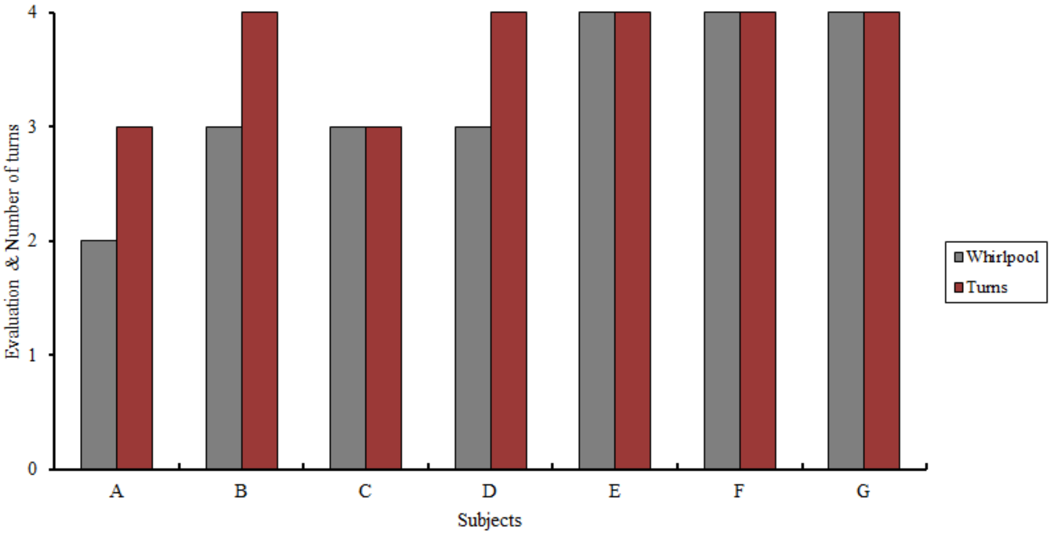


Figure 13. Results with phantom sensation (25Hz)

Table 3. Parameters of pulse signals

Amplitude A_p	Frequency f	Pulse length l_p	Vibration Time L
2 [V]	40 [Hz]	1 [ms]	200 [ms]

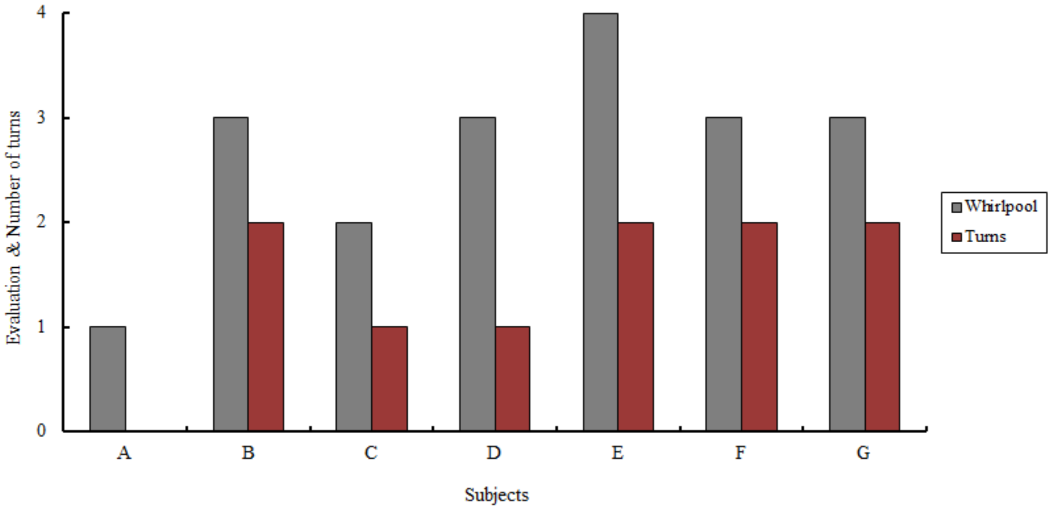


Figure 14. Results without phantom sensation (40Hz)

After changing the frequency of the pulse signals (see Table 3), the same experiment was done. The experimental results (see Figures 14 and 15) verified the effectiveness of representing the shape of object with the phantom sensation and the apparent movement further. Comparing the results in Figure 13 with the ones in Figure 15, we can find that the subjects sensed the movement under 40Hz better than the one under 25Hz. In [12], 25Hz was employed to drive six compact SMA actuators which were settled in ring-like bandage to present Braille one by one. The recognition was high under 25Hz, because this frequency could let people sense the single vibration source well. In this case, we can know that evaluation under 40Hz is higher than 25Hz to present the movement. The

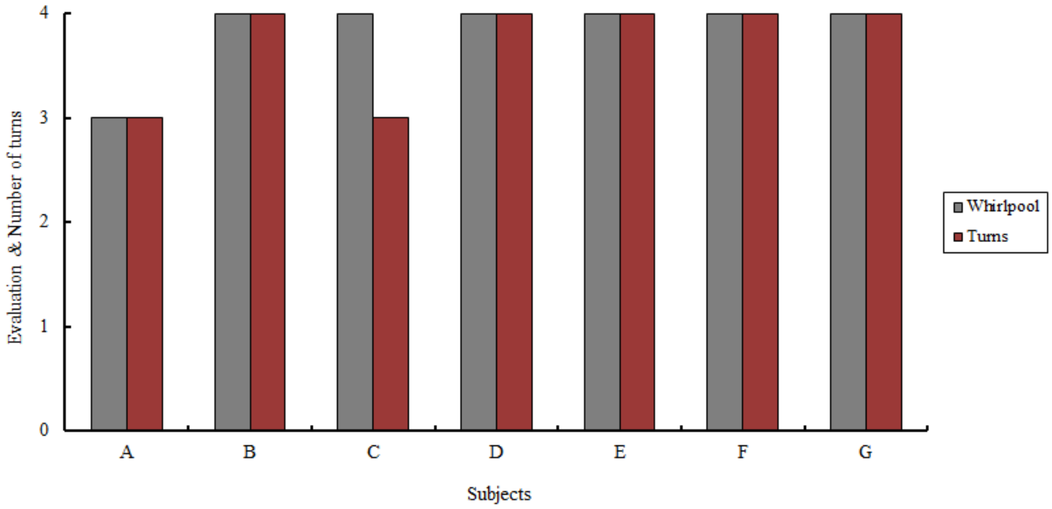


Figure 15. Results with phantom sensation (40Hz)

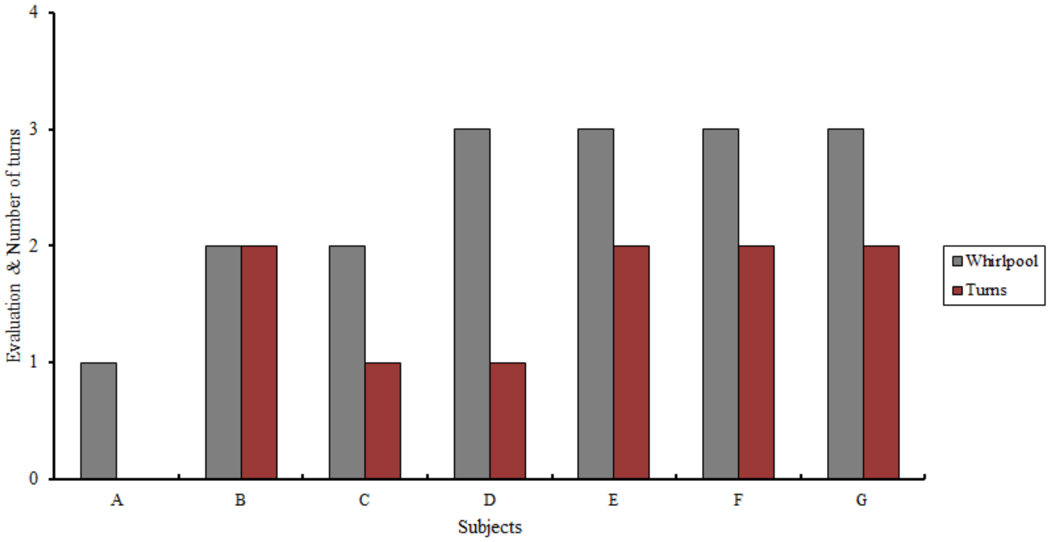


Figure 16. Results without phantom sensation (50Hz)

reason is that higher frequency can make the vibration stimuli become smooth and can make people easy to sense the movement. We also did the same experiment under 50Hz and obtained the results in Figures 16 and 17. Comparing the results in Figure 17 and Figure 15, we can know much higher frequency cannot get much better evaluation, and on the contrary, it made evaluation decrease. Therefore, the frequency 40Hz will be adopted in the next experiment.

Then, a further experiment was conducted to show the effectiveness of the developed vision based tactile display system. In this experiment, one circle and one rectangle were selected as detecting object, and a web camera (VF0470, CREATIVE) was used to capture visual information. The prototype of the developed system is shown in Figure 18.

Seven subjects (five males and two females, without dysaphia) joined the experiments, and were required to give evaluation depending on their sensation. The definition of evaluation value is: −2 – rectangle; −1 – like rectangle; 0 – unknown; 1 – like circle; 2 – circle. We used the same parameters of pulse signals as Table 3 to drive compact pin-type

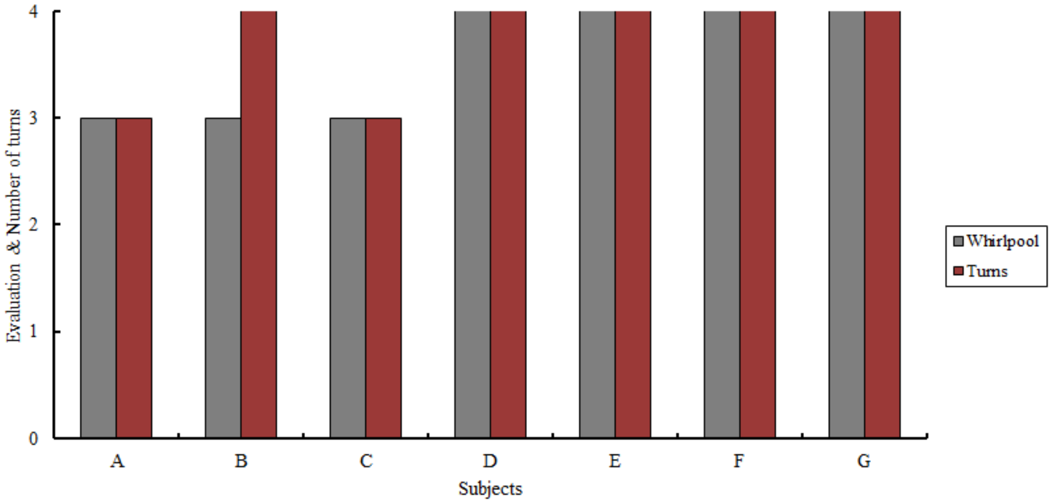


Figure 17. Results with phantom sensation (50Hz)

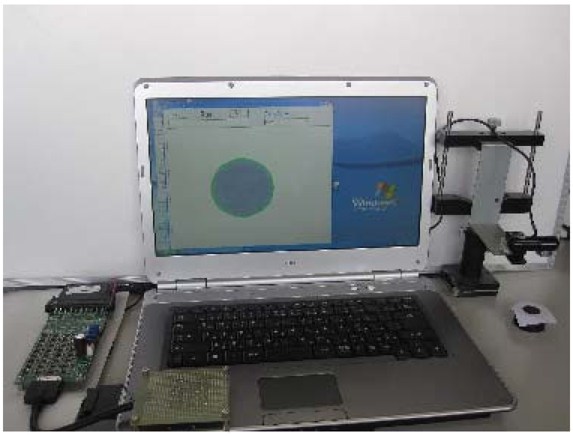


Figure 18. The prototype of vision based tactile display system

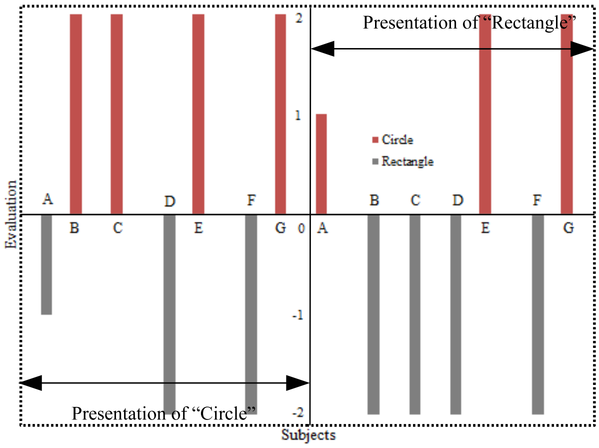


Figure 19. Results of distinguishing circle and rectangle

actuators of the tactile display panel. The experimental results are given in Figure 19. We can see that some subjects could not distinguish the circle and rectangle well. After experiment, they said that it was difficult to sense whether there were corners or not.

TABLE 4. Parameters of pulse signals at the corners

Amplitude A_p	Frequency f	Pulse length l_p	Vibration Time L
2 [V]	40 [Hz]	1.5 [ms]	400 [ms]

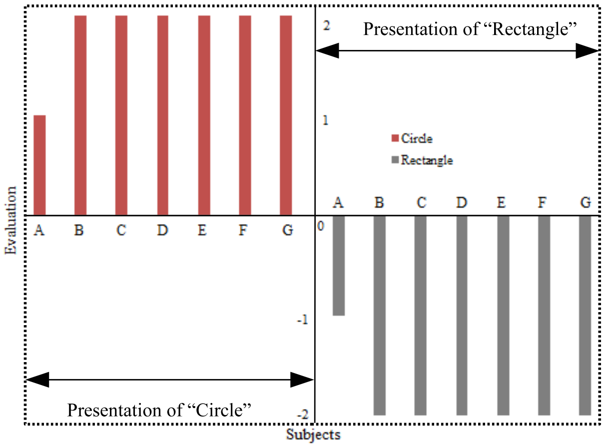


FIGURE 20. Results of distinguishing circle and rectangle

According to the comments from the subjects, we modified parameters of pulse signals to emphasize corners. The detailed parameters at the corners are given in Table 4, and the experimental results are given in Figure 20. The results showed that the circle and the rectangle could be distinguished by subjects well. Further, they verified that the developed system could capture the shape of object, transform visual information to tactile sensation by using higher-level perception and let people sense the shape of the object through the developed tactile display which just has 25 compact pin-type actuators.

5. Conclusion and Future Work.

Vision based tactile display system was developed to let people sense the shape of object. In order to capture the shape of object with common web camera, shape recognition method which combined basic algorithm of the active contour and Harris corner detection was proposed. For representing the shape of the captured object, 25 compact pin-type actuators were designed to construct tactile display panel by employing the ability of expansion and shrink of SMA under different temperature. After mapping visual information to tactile display panel by using phantom sensation and apparent movement, people could sense the shape of the captured object. Experimental results were given to verify the effectiveness of the developed system. In order to represent the shape of more complex objects, transforming visual information to tactile sensation will be further researched in our future work.

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