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A Novel Braille Display Using the Vibration of SMA Wires and the Evaluation of Braille Presentations*

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Abstract

In this study, a new Braille display is constructed based on the vibration of a Shape Memory Alloy (SMA) wire. To present Braille information, a vibration actuator is used instead of conventional Braille dots. According to the temperature-dependent characteristic shrinkage and the vest ration to the initial length of an SMA wire, a vibration actuator which can be driven by several [Hz]-100 [Hz] pulse signals has been developed. A method for presenting Braille information is proposed by the application of the developed actuator to a Braille display. In this research, multiple actuators constructed by using metal pins (0.7 [mm] in diameter, 3 [mm] in length) and SMA wires (50 [um] in diameter, 3 [mm] in length), are placed as to form standard Braille. The actuators are vibrated by PWM signals with different frequencies and appropriate timings, and the effectiveness of the proposed method for Braille display is verified by experiments. From the experimental results, the highest recognition rate of 100 [%] was achieved under the conditions of 50 [Hz] vibration frequency and 500 [ms] time delay. This means the vibration patterns effectively stimulated the Meissner corpuscles, and helped the subjects properly discriminate Braille characters presented by the developed display. Good evaluations were received from the subjects who are visually-impaired.

Key words: SMA, Braille, Braille Display, Vibration, Vibration Actuator

1. Introduction

Humans communicate with each other using the five senses such as the vision, audition and olfaction, together with the sensations through their bodies. Information transmitted through non-verbal media directly affects emotions and feelings, and touch sensations especially play an important role in the perception of an object and its surrounding environment. For visually impaired people, auditory and tactile information is the primal communication media, and computerized devices and equipment have been introduced to help with their communication in daily life. Recently, accompanying the popularization of personal computers, the digitization of information through E-book and E-mail has developed rapidly. In the current information age, methods to make such types of information easily and conveniently accessible to the visually impaired have become important. The purpose of this study is to develop an energy-efficient and easily-portable Braille display which can be mounted on any mobile electronic media.

The visually impaired usually get the information through Braille and speech

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synthesizers [1]. Since Braille is currently the most widely used communicative tool by visually impaired people, electronic Braille displays with actively sliding surface, consisting of 20 - 40 characters per line as shown in Fig.1 [2], have been widely used. Such displays have been developed by researchers and developers to replace traditional Braille printed on the paper, and information in Braille can be easily accessed using these devices. For a normal Braille display, the user has to move their fingers on top of each dot in a Braille cell in order to read the Braille character. This method is called active touching.

The developed Braille displays are made by small solenoid electromagnetic vibrators [3], small motors [4], piezoelectric actuators [5], pneumatic actuators [6], Phase-Change Microactuators [7], ultrasonic actuators [8] and electrostatic actuators [9]. Small motors can easily be adapted as vibration actuators, and have been applied to mobile phones [10], PDAs, and Braille displays for visually impaired people in previous studies. By attaching an eccentric mass, a vibrating force is produced, however, it is not easy to precisely control the vibration frequency and amplitude. Another disadvantage is that the electromagnetic device is large, but the power consumption is greater than the energy provided by a mobile battery. To solve these problems, piezoelectric actuators have been developed. An array of multiple piezoelectric actuators can be used to present the Braille patterns, and the driving principle is based on generated mechanical strain due to piezoelectric effect in such devices. The simplicity of the structure does not require the coil windings, and enables to present plural mechanical vibrations in a small space. However, the driving voltage of the piezoelectric actuators need about several tens volts, and due to the influence of mechanical components, it is difficult to apply them to mobile devices. In addition to that, due to the high power consumption and large size, is difficult to combine existing Braille displays with portable mobile devices. The high cost is also one of the shortcomings.

Considering the above problems, we are developing a Braille display which has low power consumption, small size, passively touched and can easily be combined with portable mobile devices. A Shape Memory Alloy (SMA) wire is employed to develop a vibration actuator which is driven by a low voltage supply in this research. By using the vibration actuators, a compact Braille display with 4 Braille cells has been constructed. Since the size of each Braille cell is just 2.0 [mm] x 4.5 [mm], the developed compact Braille display is portable. The cost of the developed compact Braille display is quite low, because each vibration actuator is made using only a 3 [mm]-long SMA wire. Furthermore, through the vibration the users are able to read the Braille character without even moving their fingers to feel each dot in a Braille cell. The user just has to put their fingertip on top of the Braille cell in order to read the presented character. For the purpose of verifying the effectiveness of the developed device, experiments were conducted with the support of the students from Kagawa Prefectural School for the visually impaired.

In this research, it is assumed that the target of the Braille recognition rate would be 90 [%]. The target of the reading speed is still assumed to be 60 characters/minute which is less than 1/3 of the usual 200 characters/minute. The recognition rate of Braille attained in this experiment is 100 [%] when the speed is 60 characters/minute. In previous studies, the vibration pin type tactile display (Braille display) Ino [11 ~ 13] required a recognition time of 2 seconds for each Braille cell and that the recognition rate is not as good (about 60 [%]) as we achieved. Shimizu [14] found that the Braille recognition rate changes with the number of vibrations (#1 ~ # 6) of Pins from 95 [%] to 0 [%].

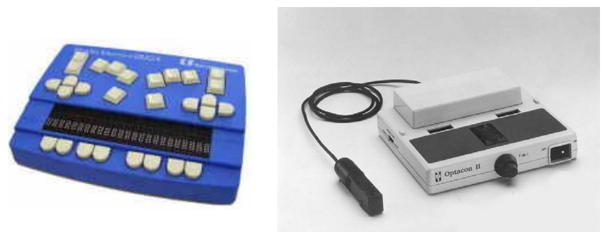

Fig.1 Braille Display

The rest of this paper is organized as follows. In Section 2, the structure of the vibration actuator and the Braille display system configuration are introduced. The preliminary experiment to determine the optimal parameters of pulse signal is described in Section 3. In Section 4, the results and analysis of experiments on the practicability of the developed Braille display are presented. Finally, the conclusion and our plans for future research are described in Section 5.

2. Vibration Actuator and Braille Display System

2.1 Tactile Receptors

According to the previous studies, we know that the human fingertip has many tactile receptors which could sense vibration, pressure, deformation and temperature, and the tactile receptors could sense many kinds of external stimuli (15). Tactile receptors are found at the epidermis-dermis border down to the subcutaneous tissues. Tactile receptors can be categorized according to specific morphologies and functions. The tactile receptors in the glabrous skin include four different types; Meissner corpuscle, Pacinian corpuscle, Merkel disc, and Ruffini endings. The Meissner corpuscles and the Merkel disc have small well-defined receptive fields with a diameter of a few millimeters. Conversely, the Pacinian corpuscles and Ruffini endings form large and diffuse fields. The Meissner corpuscles and the Pacinian corpuscles respond to mechanical vibration, while the Merkel disc and the Ruffini endings respond to pressure or deformation of the skin. The Ruffini endings sense stretching of the skin or bending of the fingernails as these stimuli compress the nerve endings. Mechanical information sensed by the Ruffini endings contributes to our perception of the shape of objects held in our hands. The Meissner corpuscles detect vibration stimuli in the range up to 10 ~ 150 [Hz], and the minimum threshold frequency is 40 [Hz]. The Pacinian corpuscles which have large receptive fields detect frequency components greater than 100 ~ 300 [Hz], and the minimum threshold frequency is about 150 ~ 200 [Hz]. The Merkel discs respond to vertical displacement and detect vibrations with the frequency of less than 2 [Hz]. The two-points discrimination threshold of the Meissner and Pacinian corpuscles is between 1.3 [mm] and 2.4 [mm] (16). That is, if the distance between two vibrating points is beyond the threshold, a human can feel two points. Otherwise, a human just feel a smooth surface instead of two points.

Because of the characteristics of the various tactile receptions, in this study we focused on the Meissner corpuscle, the Pacinian corpuscle and the Ruffini endings that respond to the vibration stimuli to the fingertips.

2.2 Vibration Actuator

In order to produce a vibration stimulus which can be sensed by tactile receptors, we developed a Braille display using filiformed shape memory alloys (SMA) (17). The filiformed SMA wires (Toki Corp, BioMetal BMF50) respond to the specific temperatures, *T1* and *T2*, which are 68 [℃] and 73 [℃] respectively. By applying a weak current to the SMA, heat is generated by the internal resistance, and the SMA shrinks up to 5 [%] lengthwise at the temperature *T2*. When the current stops and the temperature drops to *T1*, it returns to the original length. Fig.2 shows an outline drawing that explains the relationship between the temperature of the SMA wire and its length. The SMA wire is so thin that it rapidly cools after the current stops, and returns to its original shape when the temperature shifts from *T2* to *T1*. This means that the shrinkage and the return to initial length of the SMA wire can be controlled by the pulse current as shown in Fig.3. By applying a pulse current to the SMA wire, the body temperature instantly rises due to the generated heat inside the body, and shrinks from its initial length. When the pulse current stops, the body instantly cools down, and recovers its initial length. The process of shrinkage and return to

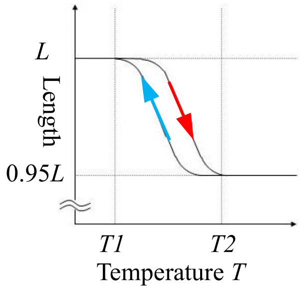

Fig.2 Temperature Characteristics of SMA Wire

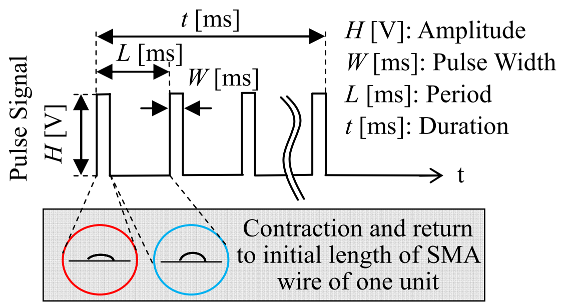

Fig.3 Pulse Signal for Driving SMA

the initial length of the SMA wire synchronizes completely with the ON/OFF pulse current. To control the magnitude of the vibration when presenting Braille information, the amplitude of pulse signals H and the duty ratio W/L should be determined based on the calories exchanged. At the same time, the SMA temperature needs to be maintained between $T1$ and $T2$ so as to initial length and contract most efficiently. A pulse-width modulated (PWM) rectangular wave signal with arbitrary frequency, amplitude and duty-ratio is generated in a PC, which is amplified to drive the actuators. The current amplifier was specially designed for driving SMA actuators in variable frequencies and variable voltage amplitude with current control. A small vibration can be generated by continuous initial length and shrinkage of the SMA wire while the continuous pulse current flows through SMA wire. In this study, the diameter of the SMA wire is 50 [μm], and the length is 3 [mm]. The length of the SMA shrinks about 1 ~ 2 [μm] by a current pulse with the frequency of several tens of hertz. Since this vibration displacement is almost the same as the size of the human tactile receptors such as the Meissner and Pacinian corpuscles, the physical stimuli given by the vibration are perceived as various tactile sensations [(18)], and the micro-vibration actuators have been applied to the research of the presentation of various textures[(19)]. However, the micro vibration for the purposes of this study is too small to present Braille.

In order to amplify this micro vibration to make it usable as a Braille pin, we employ a round-head pin, which is fixed on the SMA wire. Fig.4 illustrates the structure of the vibration actuator consisting of a 50 [μm] (diameter) x 3 [mm] (length) SMA wire and a 1.4 [mm] (diameter) x 3 [mm] (length) round-head pin. The SMA wire generates continuous synchronization with the state of the ON/OFF pulse current, causing the process of SMA wire to shrink and return to its initial length. This vibration is transmitted to the round-head pin. With this structure, the round-head pin successfully amplifies the vibration of a SMA wire, so that a user can recognize the Braille pins through the vibration, when he/she lightly touches the vibration actuators with his/her fingertips as shown in Fig.5.

In this study, we confirmed that the mechanical vibrations were strong enough to present tactile stimuli when a person touched the vibration actuator. Fig.6 shows the Braille display employing the vibration actuators. Braille characters are presented by cells of six raised dots arranged in a grid of two dots horizontally by three dots vertically. The dots are numbered 1, 2, and 3 from the top of the left column and 4, 5, and 6 from the top of the right column. The presence or absence of dots gives the coding for the Braille. Japanese Braille is conventionally regulated that the dot height is approximately 0.5 mm, the horizontal and vertical spacing between dot centers within a Braille cell is approximately 2.0 mm, and the blank space between dots on adjacent cells is approximately 3.2 mm horizontally. Vibration actuators are allocated in the same manner as a conventional Braille character, two columns of three dots each. Furthermore, a rubber sheet with the thickness of 0.5 [mm] is set on the display surface to absorb vibration interference from other actuators.

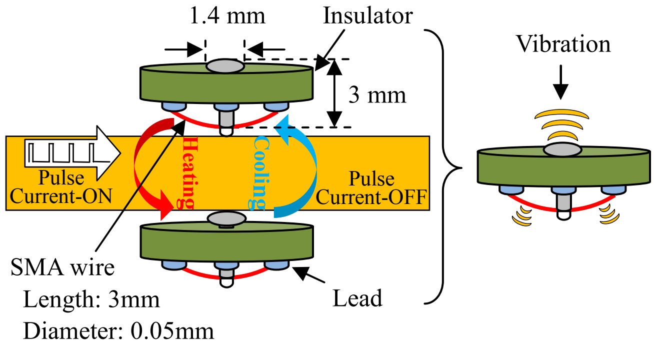

Fig.4 Structure of Vibration Actuator

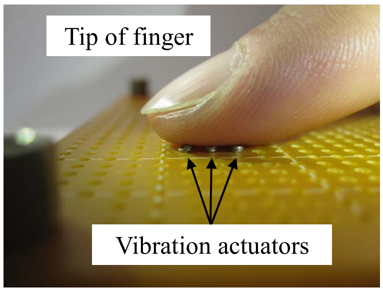

Fig.5 Figure Contact Site

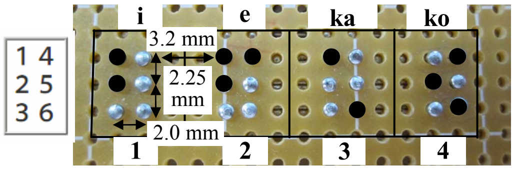

Fig.6 Braille Display with 4 Cells

2.3 Configuration of Braille Display System

By using the designed vibration actuators, a Braille display system is constructed in this study to transmit Braille information. The developed system is shown in Fig.7. The generated pulse signal is transmitted to the Braille display through a DIO board. In order to make the vibration of the actuators strong enough to be recognized, the transmitted signal should be amplified by using a current amplifier. The amplifier is specially designed for driving vibration actuators in variable frequencies and variable voltage amplitudes with current control. The current amplifier has 24 channels, and it is possible to control each channel independently (one Braille cell has 6 Braille dots, and one dot corresponds to one channel). Fig.8 shows the control interface for generating a pulse signal to a Braille display for each channel by using a conventional computer.

In this study, the vibration frequency (see Fig.3) of each actuator is 2 [Hz] ~ 50 [Hz], the amplitude of voltage (see Fig.3) is 2 [V], and the ON-OFF duty ratio of pulse signal is suitably controlled in the range between 1:250 and 1:20. The above parameters can be varied to modify the strength of vibrations according to each person's ability to feel the vibrations. The maximum power consumption of each actuator is approximately 80 [mW], when the actuator with its resistance 2.4 [Ω] is driven by a pulse signal with the amplitude of voltage 2 [V], and the duty ratio 1:20. The battery of the mobile device is enough to drive these actuators. When the shape memory alloy shrinks, the temperature becomes about 70 [℃]. Since the length of the SMA is quite short and the diameter is also small, users do not feel the heat conducted through the pin.

3. Selection of Parameters to Test Drive

In this study, the preliminary experiment was conducted by using pin-type vibration actuators to determine the optimal parameters of the pulse signals. The Braille display with 4 characters used in the experiment is shown in Fig.6. The display is composed of 24 vibration actuators, which can be driven independently. The parameters to be determined in the experiment are as follows [20].

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Subjects A and D, who were students in the Kagawa Prefectural School for the Visually Impaired, took part in the experiments. Their profiles are shown in Table 1. Subject A is male and is congenitally visually impaired, and Subject D is female who lost her sight at the age of 10. Ten Braille characters */a, i, u, e, o, ka, ki, ku, ke, ko/* were randomly presented to the two subjects, and they gave the answers by telling which pins were vibrating. The subjects read each Braille cell from left to right on the Braille display by using their index fingertip with their preferred speed. Vibration duration (see Fig 3) of actuators was 50 ~ 900 [ms].

The experiment was done in 2 steps:

(1) Vibration duration experiment of the vibration actuator

We believed that the Meissner corpuscle responded well to vibration stimuli. Therefore, in this experiment, we chose 50 [Hz] as the reference vibration frequency for stimulation of the Meissner corpuscles and Ruffini endings.

(2) Vibration frequency experiment of the vibration actuator

We applied the experimental results obtained from the vibration duration experiment to this vibration frequency of experiment. In this experiment, considering the different responses to vibration frequency of the four kinds of tactile receptors, we chose 20 [Hz] and 30 [Hz] for the Meissner corpuscle, 50 [Hz] for the Meissner corpuscle and Ruffini endings [17], [20 ~ 23]. These vibration frequencies were used in the Japanese Braille recognition experiment.

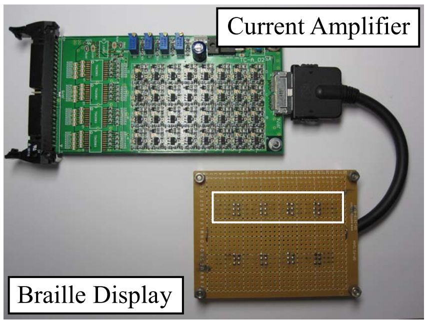


Fig.7 Braille Presentation System

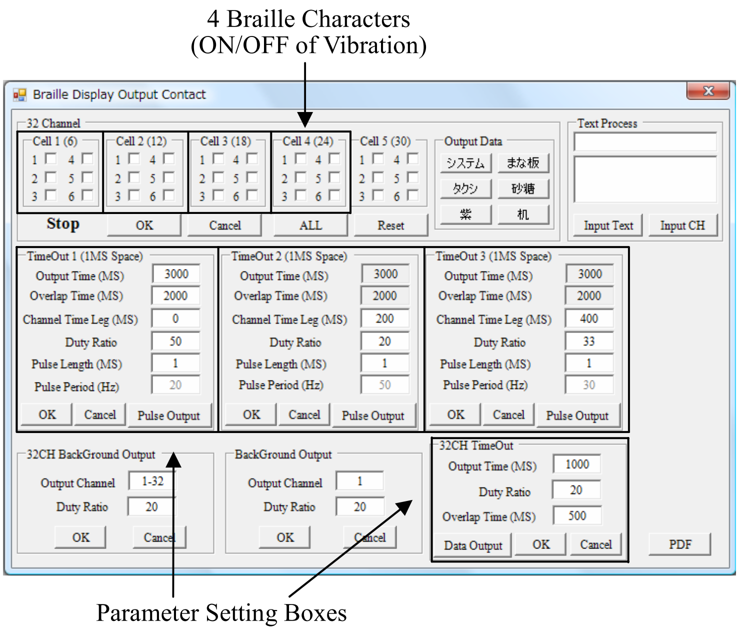


Fig.8 Dialog Interface for Parameter Settings

The results of the experiments are shown in Fig.9 and Fig.10. In Fig.9 the recognition rate of each Japanese Braille cell with different vibration durations is shown. High recognition rates are obtained at 500, 700, 900 msec. By considering the recognition time, 500 msec interval is adopted in the following experiments, because the 500 [ms] vibration duration gives the shortest reading time when compared to the other vibration durations such as 700 [ms] and 900 [ms]. In Fig.10 the recognition rate of each Japanese Braille character at different frequencies is shown. From the experimental results we can find that the driven frequencies of vibration actuator to 30 [Hz] and 50 [Hz] used for this study is fully possible, and it is the number of years that the subject had used Braille that cause individual differences in the recognition results. Subject A who is congenitally visually impaired could read Braille better. The recognition time of the Braille characters was around 8 ~ 9 seconds for the 20 [Hz] and 30 [Hz], and less than 6 ~ 7 seconds for the 50 [Hz].

In the experimental results, when the number of vibrating pins in one cell was one or two, the Braille letters were well recognized. However, as we had anticipated, the recognition rate decreased when the number of vibrating pins increased. There was an interference of vibrations among the pins, which caused the difficulty in discriminating the dots. To solve these problems, we propose two driving modes as seen in the next section.

Table 1 Profile of Visually impaired People by 5 Subjects

Subjects \ Profiles		Age	Years of using Braille	Visually impaired Status
males	A	14	12	congenital
	B	16	10	congenital
females	C	21	9	congenital
	D	15	5	lost the sight at the age of 10
	E	15	4	lost the sight at the age of 10

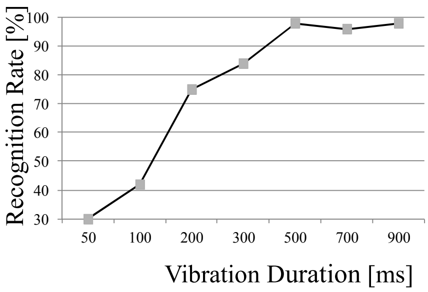


Fig.9 Braille Recognition Rate by different Vibration Durations

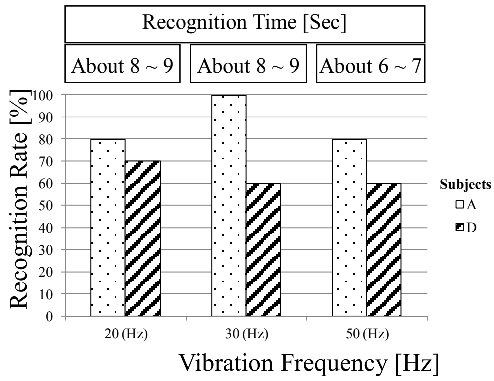
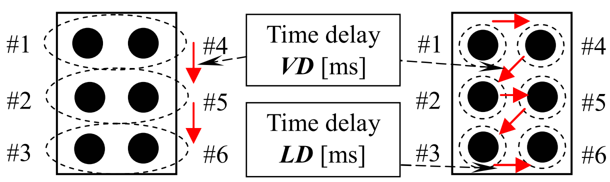


Fig.10 Braille Recognition Rate by different Frequencies



(a) Three-stage mode (b) Six-stage mode

Fig.11 Vibration actuator Driven Mode

4. Braille Display System and its Evaluation

In order to reduce interference from each vibratory stimulation of the actuators, we considered putting a time delay between the rising time of the vibration actuators to make the actuators' vibration rhythmic so that the vibrations can be more easily sensed. The rhythmic vibration can be produced by controlling the parameters of the driving signal of each actuator. In this section, two Braille presentation experiments, one with a three-stage mode and the other with a six-stage mode are described, and according to the obtained experimental results, the comparison between these two modes is given. Subjects A ~ E who were students in the Kagawa Prefectural School for the Visually impaired took part in the experiments. All subject profiles are shown in Table 1. The Braille display presents 4 Braille characters simultaneously. During the experiments, the subjects used the same method to read Braille presented by our developed device as to read traditional Braille. The reading method is to use both index fingers to read Braille character one by one from left to right. When the subject reads the Braille character, they can extrapolate the meanings of the character string. We managed to acquire the permission to conduct the experiment using their pupils after explaining our intention to the person in charge of the Kagawa Prefectural School for the Visually Impaired. In addition to that, we got the consent from each individual subject after giving them a proper explanation regarding the experiment. A teacher from the school was present as an overseer during the experiments.

4.1 Two Different Driving Modes of Braille Display

The three-stage mode and the six-stage mode which add the time delays are used in experiments on the Braille recognition systems.

In Fig.11 (a), six dots in one Braille character are divided into three groups and driven with time delays (three-stage mode). Using this method, the actuators are driven in the order of (#1, #4) → (#2, #5) → (#3, #6), where the numbers indicate the actuator's number. The time delay between the two groups is presented by *VD* [ms] (Time-Delay of Vertical Direction), which is added as a parameter between the groups.

Fig.11 (b) shows the other method that drives actuators one by one with a time delay (six-stage mode). Using this method, the actuators are driven in the order of #1 → #4 → #2 → #5 → #3 → #6. The time delay between #1 → #4, #2 → #5, #3 → #6 actuators is presented by *LD* [ms] (Time-Delay of Lateral Direction), and time delay between #4 → #2, #5 → #3 actuators is presented by *VD* [ms]. The vibration actuators generate rhythmic vibrations which can be easily recognized by the tactile receptors in the fingers.

4.2 Experiments for Braille Presentation (Three-Stage Mode)

In this experiment we can validate using the combination of the vibration frequency for Braille recognitions. We could analyze the recognition rate and time delay to evaluate the recognition difficulty for the Braille vibrators. Since this experiment uses a three-stage mode for improving the recognition rate of Braille, we believe that each stage can use a different frequency to drive the vibrators in order to help the visually impaired distinguish different tactile sensation from the different frequency vibrations. Considering the characteristic responses of tactile receptors to mechanical vibration frequency, 20 [Hz], 30 [Hz] and 50 [Hz] were chosen to provide vibrating stimulation to the recognition of the position of each vibrator easy.

The driving schematic diagram and the driving signal of Braille */ke/* are shown in Fig.12, where Braille dots #1, #2, #4 and #6 were divided into three groups by three different frequencies 20 [Hz], 50 [Hz], and 30 [Hz]. In order to help people easily discriminate between each group, three frequencies were selected. Actuators #1 and #4 which were in the first group were driven simultaneously by the same frequency of 20 [Hz], and the time delay *VD* between the first group and second group was presented by 300 [ms].

The #2 actuator, which was in the second group was driven by the frequency of 50 [Hz], and the time delay *VD* between the second group and the third group was presented by 300 [ms]. Actuator #6 which was in the third group was driven by the frequency of 30 [Hz]. The vibration duration *t* [ms] of each actuator was set to 500 [ms]. In the above example, we used 20 – 50 – 30 (300) to indicate its parameter settings.

In this experiment, we chose 16 conditions (see Table 2) which were combined with different *VD* and vibrating frequency to present Braille to the subjects. In addition, the amplitude of voltage was set to 2 [V], the width of the pulse was set to 1 [ms]. 18 Japanese Katakana characters which are shown in Fig.13 were regarded as the test content. Five visually impaired subjects (A ~ E, two males, and three females) took part in the experiment and gave their results for the selected characters under 16 different conditions.

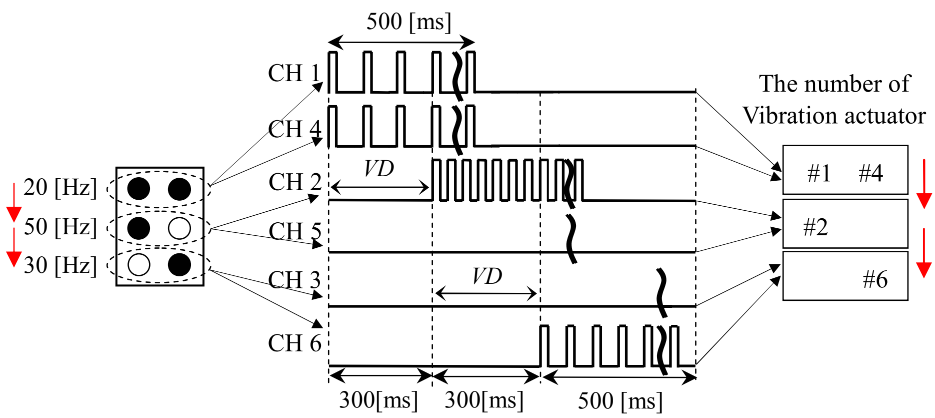


Fig.12 Vibration Actuator Driving of Three-stage mode /*ke*/

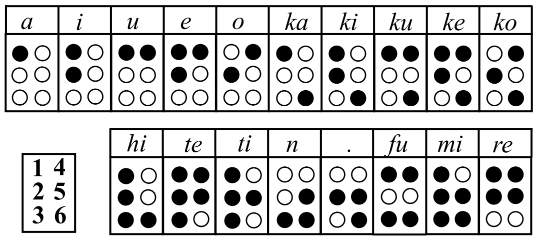
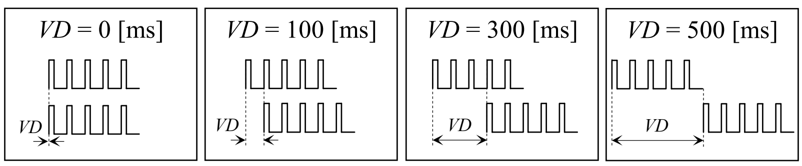


Fig.13 Japanese Braille

Table 2 Combination of Vibration Frequency and Time Delay

Vibration duration *t* [ms]	500															
Experimental selection	1				2				3				4			
* Vibration Frequency *VF* [Hz]	20-30-50				20-50-30				50-30-50				50-50-50			
** Time - Delay of *VD* [ms]	0	100	300	500	0	100	300	500	0	100	300	500	0	100	300	500



* *VF*: Vibration Frequency
** Time – Delay of *VD*: Time – Delay of Vertical Direction

The average recognition rates and dispersion value under the different conditions are shown in Fig.14. From this figure, it can be observed there are large variations in the subjects' Braille recognition rates. One reason for the big variation in the subjects' recognition rates was the differences in the period of time they had been using Braille. Some subjects have more experience than others. Therefore, the margin of error of the Braille recognition rates occurred.

An analysis of the vibration characteristics of tactile mechanical receptors shows that the recognition rate of Braille obtained when using the same vibration frequency to drive the vibrators on three stages is better than the results obtained when using different vibration frequencies on three stages. According to Miyaoka's research on recognition thresholds for vibratory stimulation [16], the holding vibration stimulation with the same vibration frequency can make the recognition threshold of tactile mechanical receptors stable. With the stable recognition threshold the subjects could feel regular vibration stimulation, and could distinguish whether the vibrators were vibrating or not. So the recognition rate for Braille can be improved. This was also proven in our experimental result for the 50 – 50 – 50 [Hz] combination when compared with other frequency combinations as illustrated in Fig.14. In addition, the pin-type vibration actuator used in this study was driven by a 50 [Hz] vibration stimulation which could produce a continuous deformation of the skin. That means the vibration on the skin produces a tension, which caused the Ruffini endings to become stimulated to reach the active state. So, the subject could improve the positioning accuracy of each vibrator [15] to recognize the Braille better.

On the other hand, when using several frequency combinations, the recognition threshold of the tactile mechanical receptors is decided based on the highest vibration frequency. That means the subjects could not easily recognize the vibration whose frequency is lower than the threshold. In fact they found it difficult to distinguish whether the vibrators are vibrating or not. The more different the frequencies used, the worse recognition rate for Braille became. Furthermore, since the capacity field area of the Ruffini endings is larger than that of the other tactile receptors, and the location of Ruffini endings is deeper than the others, Ruffini endings can not position each vibrating actuator well although skin deformation can be produced by different vibration frequencies. From our experimental results under the conditions of 20 - 30 - 50 (0), 20 - 50 - 30 (0), 50 - 30 - 50 (0) and 50 - 50 - 50 (0), we noticed that the increase of the use of 50 [Hz] vibrations the recognition rate of increases.

With reference to time delay, we discovered the effect from four different time delays on the Braille recognition rate. According to Kikuchi's analysis [24] on time and spatial characteristics of point vibration stimulation, we found that the recognition rate of Braille is different when using different time delays. If the time delay is too short (vibration duration is 500 [ms]), the subjects cannot distinguish the vibration of the vibrators well because of the interaction between the vibrations. From the experimental results obtained using 100 [ms] time delay, we can see the recognition rate of Braille, under the conditions of 20 – 30 – 50 (100), 20 – 50 – 30 (100), 50 – 30 – 50 (100) and 50 – 50 – 50 (100) are not good.

If the time delay is too long, when the next vibrator begins to vibrates, the subjects will forget the position of the last vibrating vibrator, which causes difficulties in distinguishing the Braille. This is determined by the human's physiology, psychology, and nervous system. So we set the time delay not longer than the maximum vibration duration 500 [ms]. From the experimental results, we could see that the recognition rate of Braille became higher along with the increase in the time delay. We speculated that the increase in the time delay could reduce the interaction between the vibrators, and enhanced the subjects' ability to recognize the vibrations produced by each vibrator, thereby the recognition rate of Braille improved. Table 3 shows the relationship of the Braille reading times, for each *VF* and *VD*. We can see although the *VD* time increased, the total recognition time of Braille is shortened. In other words, by adding the appropriate time delay, Braille identification becomes easier, and the recognition time becomes shorter. With a vibration frequency of 50 – 50 – 50 [Hz], the average reading speed was about 15 characters/minute.

There are some exceptions to the results shown in Fig.14, which are 20 – 30 – 50 (500), 20 – 50 – 30 (300), 50 – 30 – 50 (0), and 50 – 50 – 50 (100). Two reasons are considered to the occurrence of the exceptions. The first reason is that there are individual differences in tactile sensation. Even though we used the same parameters, each subject's tactile sensations are different. The second reason is, that in Japan the percentage of people using Braille amongst the visually impaired is low (about 20%), and we were unable to find many subjects for the experiment in our region. In addition, among the subjects the variability in the number of years using Braille is large (from 4 years to 14 years).

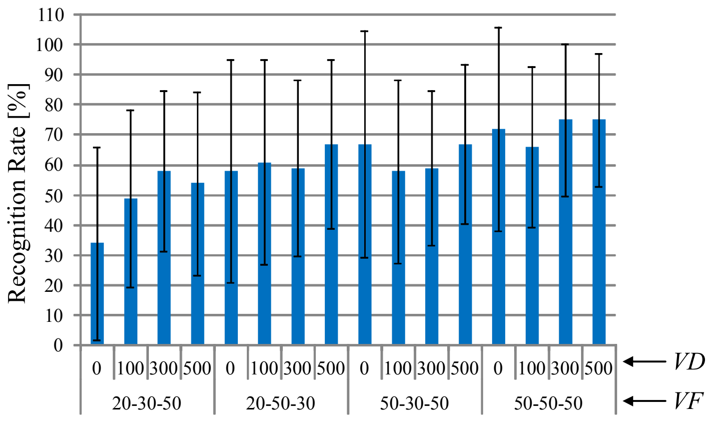


Fig. 14 Average Recognition Rate of Five Subjects

Table 3 Braille Recognition Time by *VF* and *VD*

t [ms]	500															
VF [Hz]	20-30-50				20-50-30				50-30-50				50-50-50			
VD [ms]	0	100	300	500	0	100	300	500	0	100	300	500	0	100	300	500
**PT* [s]	0.5	0.7	1.1	1.5	0.5	0.7	1.1	1.5	0.5	0.7	1.1	1.5	0.5	0.7	1.1	1.5
***TRT* [s]	7	6.6	5.8	5.2	7.1	6.7	5.5	4.9	6.8	6.1	5.1	4.5	6	5.1	4.2	3.8
****RT* [s]	6.5	5.9	4.7	3.7	6.6	6	4.4	3.4	6.3	5.4	4	3	5.5	4.4	3.1	2.3

* *PT*: Maximum Presentation Time of each Braille cell ($t + 2VD$)
** *TRT*: Total Recognition Time ($RT + PT$)
*** *RT*: Recognition Time Only

4.3 Experiments for Braille Presentation (Six-Stage Mode)

In the above experiment, we used the three-stage mode to drive the vibration actuators, and analyzed the effect of the vibration frequency and time delay on the recognition rate of Braille based on the vibration characteristics of the tactile senses. The above experimental results showed that using the same vibration frequency on vibrators and rationalizing the time delay can improve the subjects' recognition rate. In this section, we used a six-stage mode to drive the vibrators and conducted a more detailed division of the vibration frequency and time delay. The parameters are shown in Table 4. We used the parameters with good experimental results from the three-stage mode and continued using these vibration frequencies (*VF*) in this experiment. The experiment content and the subjects are the same as those used in the three-stage mode. The randomly selected 180 patterns were presented to the subjects in one trial. Based on the parameters of *VD* time delay, we added the *LD* time delay (time delay of lateral direction, for example, between #1 and #4, between #2 and #5 and between #3 and #6), and made the vibration time of each vibrator in each Braille cell completely independent. That is, there is never more than one vibrators vibrating at the same time. In Fig.15, the presentation of the Japanese Braille */ke/* is shown as an example, where the parameter is set to 50 – 50 – 50 (300) (300). In this figure, we used steps to describe the vibration process of the vibrators. The CH1 vibrator was vibrated for 500 [ms] at 50 [Hz] (*i*). After waiting for 300 [ms] *LD* time delay (*ii*) from the end of CH1 vibration, the CH4 vibrator was vibrated for 500 [ms] at 50 [Hz] (*iii*). Then a 300 [ms] *VD* time delay (*iv*) is added before the vibrator of CH2 begins to vibrate (*v*). The vibrators of CH5 and CH3 did not need to vibrate, but the interval should include all the time from (*vi*) to (*x*). Finally, the CH6 vibrator was vibrated for 500 [ms] at 50 [Hz] (*xi*).

Fig.16 shows that by using parameters which combine the vibration frequency and the time delay, the average recognition rate and the dispersion value of Braille improved after adding the *LD* time delay. This shows that based on *VD* time delay the *LD* time delay can improve subjects' recognition rate of Braille. Furthermore from the figure it is observable that the dispersion values of 50-50-50 (500) (300), 50-50-50 (300) (500), 50-50-50 (500) (500) variability show the decreasing influence of individual differences. Therefore, we can know the versatility of parameter settings for the Braille display and can help the subjects with less experience achieve high recognition rates. Table 5 shows the relationship between the Braille reading times and each *VF*, *VD* and *LD*. We can see that although the *VD* and *LD* time increased, the total recognition time of Braille shortened. In Table 5 the recognition time is negative. That means the average of the actual total recognition time is shorter than the standard Braille characters presentation time which was set as the longest time among

Table 4 Combination of Vibration Frequency and Time Delay

Vibration duration *t* [ms]	500									
Experimental selection	1		2							
* Vibration Frequency *VF* [Hz]	50-30-50		50-50-50							
** Time - Delay of *VD* [ms]	300	500	300				500			
*** Time – Delay of *LD* [ms]	0	0	0	100	300	500	0	100	300	500

* *VF*: Vibration Frequency
** Time – Delay of *VD*: Time – Delay of Vertical Direction
*** Time – Delay of *LD*: Time – Delay of Lateral Direction

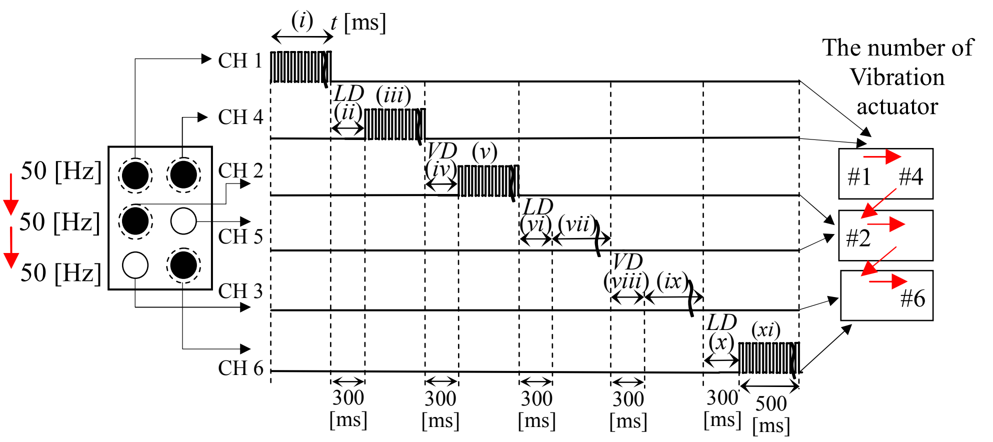


Fig.15 Vibration actuator Driving of Six-stage mode /*ke*/

18 Braille character presentation time. Although 50 – 50 – 50 (500) (500) took a longer time than the other cases, the recognition rate of Braille is better.

For this experiment, we made sure that these 4 Braille characters have no semantic association with each other (exp. */mi/, /ku/, /hi/, /u/; /te/, /e/, /re/, /o/*). In this case, the reading speed is 14 characters/minute. Here, we should mention that in real life Braille characters usually have a semantic association with next one (exp. */fu/, /ku/, /o/, /ka/; /ko/, /u/, /e/, /n/*). Therefore, readers can guess the meaning according to semantic association. The reading speed when semantic associations were allowed, was observed to be faster than when there was no semantic association with the characters. It illustrates the authors point of view that using the same vibration frequency on the vibrators and rationalizing the time delay can improve the recognition rate.

Furthermore, we found that individual difference can have a significant impact on the recognition rate. Subject A who is a congenital visually impaired, began to learn Braille from the age of two. He has about 12 years experience of reading Braille. Subject D whose visual acuity declined from the age of 8 began to learn Braille as a 10 – year – old. Her experience in reading Braille is just 5 years. From the results in Table 6, subjects A (a) made fewer mistakes (marked in gray) than subjects D (b). This shows that the length of years reading Braille can have an impact on the Braille recognition rate.

From the above experimental results we can conclude that after adding the *LD* time delay, the recognition rate of Braille is improved and more accurate than that of the three-stage mode. However, the reading time also becomes longer than the reading time of the three-stage mode. In order to improve the practicality of our system, we will shorten the subjects' reading time and keep the higher recognition rates in our future research.

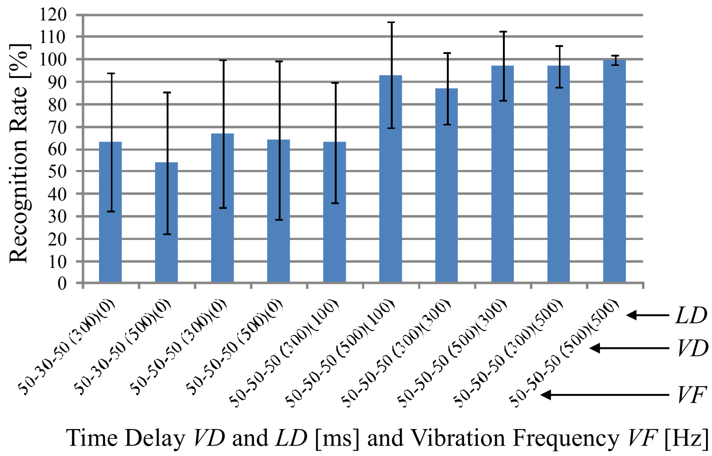


Fig. 16 Average Recognition Rate of five Subjects

Table 5 Braille Recognition Time by *VF*, *VD* and *LD*

t [ms]	500									
VF [Hz]	50-30-50		50-50-50							
VD [ms]	300	500	300				500			
LD [ms]	0	0	0	100	300	500	0	100	300	500
**PT* [s]	3.6	4	3.6	3.9	4.5	5.1	4	4.3	4.9	5.5
***TRT* [s]	6.8	6.2	6.5	6.0	5.2	4.8	5.5	5	4.5	4.2
****RT* [s]	3.2	2.2	2.9	2.1	0.7	-0.3	1.5	0.7	-0.4	-1.3

* *PT*: Maximum Presentation Time of each Braille cell ($6t + 2VD + 3LD$)
** *TRT*: Total Recognition Time ($RT + PT$)
*** *RT*: Recognition Time Only

Table 6 Recognition Results of Each Character by two Subjects A and D

(a) Subject A

Braille Data / *VF* (Hz) *VD* and *LD*(ms)	/u/ 14	/e/ 124	/ki/ 126	/ku/ 146	/ke/ 1246	/ti/ 1235	/te/ 12345	/hi/ 1236	/fu/ 1346	/mi/ 12356
50-30-50 (300)(0)	14	124	126	146	126	1356	1235	136	1346	1236
50-30-50 (500)(0)	14	124	126	146	1246	1235	1345	13	1346	1236
50-50-50 (300)(0)	14	124	126	146	1246	135	134	1236	1346	12356
50-50-50 (500)(0)	14	124	126	146	1246	1235	12345	1236	1346	12356
50-50-50 (300)(100)	14	124	126	146	1246	1235	12345	1236	1346	12356
50-50-50 (500)(100)	14	124	126	146	1246	1235	12345	1236	1346	12356
50-50-50 (300)(300)	14	124	126	146	1246	1235	12345	1236	1346	12356
50-50-50 (500)(300)	14	124	126	146	1246	1235	12345	1236	1346	12356
50-50-50 (300)(500)	14	124	126	146	1246	1235	12345	1236	1346	12356
50-50-50 (500)(500)	14	124	126	146	1246	1235	12345	1236	1346	12356

(b) Subject D

Braille Data / *VF* (Hz) *VD* and *LD*(ms)	/u/ 14	/e/ 124	/ki/ 126	/ku/ 146	/ke/ 1246	/ti/ 1235	/te/ 12345	/hi/ 1236	/fu/ 1346	/mi/ 12356
50-30-50 (300)(0)	1	24	16	46	146	1356	1235	136	136	1236
50-30-50 (500)(0)	14	24	126	16	16	13	13	13	136	136
50-50-50 (300)(0)	145	124	1236	16	1236	135	134	13	1346	12356
50-50-50 (500)(0)	14	123	126	46	126	1356	1235	136	136	1236
50-50-50 (300)(100)	1	12	16	146	126	135	134	13	13	12356
50-50-50 (500)(100)	14	124	126	146	1246	1235	12345	126	1346	12356
50-50-50 (300)(300)	14	124	126	146	1246	12345	12345	123	1346	12356
50-50-50 (500)(300)	14	124	126	146	1246	1235	12345	123	1346	12356
50-50-50 (300)(500)	14	124	126	146	1246	1235	12345	1356	1346	12356
50-50-50 (500)(500)	14	124	126	146	1246	1235	12345	1236	1346	12356

4.4 Analysis of Experiments

In this study, a vibration actuator using SMA was developed and applied to a new Braille display for the visually impaired. In order to verify the effectiveness of the developed Braille display, experiments on Braille presentation with a three-stage mode and a six-stage mode were conducted. The conditions including vibration frequency, vibration duration and time delays on both the vertical and lateral directions affected recognition results.

We found that when the vibration frequency was 50 – 50 – 50 [Hz] the recognition rate was higher than those with other vibration frequencies. The reason for the good recognition rate is that Meissner corpuscle and Ruffini endings could easily sense the vibration stimulus at 50 [Hz] [21 ~ 23]. The vibration generated by the vibrators could produce a continuous deformation of the skin which stimulated the Ruffini endings. The subjects could improve the positioning accuracy of each vibrator, and as a result could recognize the Braille better.

Moreover, by changing the time delay from 0 [ms] to 500 [ms], the recognition rate increased. From the results shown in Fig.14 (Three-stage mode), Fig.16 (Six-stage mode), Table 3 and Table 4, it can be shown that the recognition rate increased after adding time delays between the vibration actuators. The reason is that the Ruffini endings are located deep in the skin, and slowly adapt to change [16] [25]. Therefore, that is to say since the time and spatial resolution of the Ruffini endings for vibration stimulation is poor, it leads to a low recognition rate of Braille with a 0 [ms] time delay.

While more than one vibration actuators can produce stimulus at the same time, the nerve impulse from the tactile receptors simultaneously arrive at the brain through the nerve fibers. It is difficult for the brain to classify the stimulation sources. This is the reason why the recognition rate of the six-stage mode is higher than that of the three-stage mode. So, to reduce the interference of each vibration actuators, adding time delays on the vertical and lateral direction is necessary and regarded as important parameters in improving the recognition rate. The longer the time delays are, the higher the recognition rate is. However, the speed of reading Braille will still be slow. In the future work, shortening the reading time while keeping a high recognition rate is our target.

5. Conclusion and Future Work

A compact Braille display which is driven by a PWM current was developed using Shape Memory Alloy wires. The merits of the developed Braille display are low power consumption, high-speed response, clear presentations of vibration stimuli, and can be fitted to mobile phone or other devices which would allow visually impaired people to always carry it. In this study, the vibration actuator was used to construct the Braille display. From the experimental results, the recognition rates were the highest under the conditions of 50 [Hz] vibration frequency. This means the vibration patterns effectively stimulated the Meissner corpuscles, and helped the subjects discriminate the Braille characters more easily and accurately. In addition, the use of the same vibration frequency gave a better performance. By considering the time delay, which was the most important parameter for the recognition rate, the highest performance was obtained when using a 500 [ms] time delay with each vibration actuator. The results of this experiment show that the recognition rate of Braille characters was higher compared with the results for recognition rates in previous studies. The effectiveness of using the developed Braille display to present Japanese Katakana characters for the visually-impaired was verified by using the above experimental results. To make the Braille display more practical and keep the high recognition rate, the recognition time should be further considered for the instant recognition. In the near future, we will try to study the optimal parameters to shorten the recognition time so that users can read smoothly.

References

(1) *Nuance TALKS*, http://www.nuance.com/talks, 2008.

(2) *KGS Ltd*, http://www.kgs-jpn.co.jp/eindex.htm

(3) Frisken-Gibson, Sarah F.; Bach-y-Rita, Paul; Tompkins, Willis J.; Webster, John G: “A 64-Solenoid, Four-Level Fingertip Search Display for the Blind”, *IEEE Transactions on Biomedical Engineering*, Vol.BME-34, No.12, pp.963-965, 1987.

(4) Nagano, Kanno, Ashihara, Nagahasi: “ Communication aid for deaf-blind due to the vibration motor”, *IEICE Technical Report*, HCS96-09, 1996.

(5) Masafumi Uchida, Hisaya Tanaka, Hideto Ide, Shuichi Yokoyama: “Vibration tactile display using 16 different modulation wave of a single PZT transducer”, *IEEJ C*, Vol. 120-C, No. 6, pp. 825-830, 2000.

(6) Xiaosong Wu, Haihong Zhu, Seong-Hyok Kim, Allen, M.G.: “A Portable Pneumatically-Actuated Refreshable Braille Cell”, TRANSDUCERS & EUROSENSORS ’07, *The 14th International Conference on Solid-State Sensors, Actuators and Microsystems*, Lyon, France, June 10-14, pp.1409-1412, 2007

(7) Green, S.R. Gregory, B.J. Gupta, N.K.: “Dynamic Braille Display Utilizing Phase-Change Microactuators”, *IEEE SENSORS 2006, EXCO*, Korea, October 22-25, pp.307-310, 2006.

(8) Hermes Hernandez,Enrique Preza, Ramiro Velazquez: “Characterization of a Piezoelectric Ultrasonic Linear Motor for Braille Displays”, *Electronics, Robotics and Automotive Mechanics Conference, 2009, CERMA ’09*, pp.402-407, 2009.

(9) Vincent Lévesque: “Virtual Display of Tactile Graphics and Braille by Lateral Skin Deformation”, *Ph.D. Thesis, McGill University*, August 2009

(10) Tsuneo KANNO, Hidehiro NAGANO, Osamu ASIHARA, Hiroshi NAGAHASHI: “A Communication Aid for Deaf-Blind People Using Vibration Motors”, *The Transactions of the Institute of Electronics, Information and Communication Engineers. A.* Vol. J80-A, No. 9, pp. 1509-1516, 1997.

(11) Chikamune Wada, Shuichi Ino, Hisakazu Shoji, Tohru Ifukube: “A study on uses of tactile stimulation for hearing substitutes : usage of quality of tactile sensation”, *Technical report of IEICE*. HCS 97(262), pp.71-76, 1997.

(12) Homma. T, Ino. S, Kuroki. H, Izumi. T, Ifukube. T: “Development of a piezoelectric actuator for presentation of various tactile stimulation patterns to fingerpad skin”, *Engineering in Medicine and Biology Society, 2004. IEMBS '04. 26th Annual International Conference of the IEEE,* Vol.2, pp.4960-4963, 2004.

(13) Ino. S, Homma. T, Izumi. T: “Psychophysical Measurement of Multiple Tactile Sensations Using a Broadband Vibrotactile Display”, *Universal Communication, 2008. ISUC '08. Second International Symposium on,* pp.274-280, 2008.

(14) Tadashi Kikuchi, Yutaka Shimizu: “Tactile point identification”, *The Japanese Journal of Psychology*, Vol.57, No.3, pp.163-170, 1986.

(15) Tetsu Miyaoka: “Basis of human tactile sensation information processing”, Fundamentals and Applications of Haptic Technology, *The Japan Society of Mechanical Engineers*, No.08-34, pp.3-6, 2008.

(16) T. Miyaoka, T. Mano, and M. Ohka: “Mechanisms of fine-surface-texture discrimination in human tactile sensation”, *Journal of the Acoustical Society of America*, Vol.105, pp.2485-2492, 1999.

(17) Yosuke Mizukami and Hideyuki Sawada: “Tactile information transmission by apparent movement phenomenon using shape-memory alloy device”, *International Journal on Disability and Human Development*, Vol.5, No.3, pp.277-284, 2006.

(18) Hideyuki Sawada, Yohsuke Mizukami, Keishi Fukuyama, Keiji Uchida and Makoto Kaneko: “micro-vibration actuator using Shape Memory Alloy fiber and their characterization”, Proceedings of *the 8th Conference of SICE System Integration Division SI2007*, pp.76-68, 2007.

(19) Keishi Fukuyama, Hideyuki Sawada: “A Texture Presentation System that Stimulates Visual and Tactile Sensations and its Evaluation”, *Journal of Information Processing of Japan*, Vol.52, No.4, pp.1562-1570, 2011.

(20) Feng Zhao, Keishi Fukuyama, Yohsuke Mizukami and Hideyuki Sawada: “Compact Braille display using SMA wire array”, Proceedings of *the 18th IEEE International Symposium on Robot and Human Interactive Communication Toyama*, pp. 28-33, 2009.

(21) K. Shimoga: “A survey of perceptual feedback issues in dexterous telemanipulation: Part II”, in *Virtual Reality Annual International Symposium*, pp. 271-279, 1993.

(22) C. Youngblut, R. Johnston, S. Nash, R. Wienclaw, and C. Will: "Review of virtual environment interfaces technology", Institute for Defense Analyses (IDA), Tech. Rep., 1996.
(23) V. G. Macefield, *Neural Aspects of Tactile Sensation*. Elsevier Science, 1998, ch. The Signalling of Touch, Finger Movements and Manipulating Forces by Mechanoreceptors in Human Skin, pp. 89-130.
(24) T. Kikuchi, Y. Shimizu: "Identification of the position in a tactile sense", *Japanese Psychological Research*, Vol.57, No.3, pp.163-170, 1986.
(25) Vallbo, A. B. & Johansson, R. S.: "Properties of cutaneous mechanoreceptors in the human hand related to touch sensation", *Human Neurobiology*, 3, pp.3-14, 1984.