SICE-ICASE International Joint Conference 2006
Oct. 18-21, 2006 in Bexco, Busan, Korea

Design and Psychophysical Evaluation of Pneumatic Tactile Display

Yeongmi Kim[1], Ian Oakley[2] and Jeha Ryu[1]

[1] Department of Mechatronics, Gwangju Institute of Science and Technology , Gwangju, Korea
(Tel : +82-62-970-2425; E-mail: kym,ryu@gist.ac.kr)

[2] Electronics and Telecommunications Research Institute, Daejeon, Korea
(Tel : +81-3-000-0000; E-mail: ian@etri.re.kr)

Abstract: This paper presents a novel pneumatic tactile display. The air-jet display forms 5 by 5 arrays and features air nozzles with an external diameter of 2.4mm and internal diameter of 1.5 mm. In comparison with other tactile displays such as vibrotactile, electrotactile displays there is little concrete psychophysical data relating to pneumatic displays. This paper addresses this challenge, and presents brief psychophysical studies examining localization rate, the two point threshold, stimulus intensity and the temporal threshold of cues produced by pneumatic air jets. Two groups of subjects were used in these studies, subsequently termed groups A and B. Both were comprised of eight participants. In the case of localization study we obtained 58.13% and 85.9% of localization rates each for dense display and sparse display. Two-point threshold test showed the length of gap between two air-jet stimuli which subjects can detect. However, it was formidable to find out precise temporal resolution of the proposed pneumatic tactile display owing to the limited capability of the pneumatic valves. Lastly, the results of stimulus intensity study suggest that by varying the size of a pneumatically created tactile stimulus, we can effectively vary its perceived magnitude.

Keywords: pneumatic tactile display, psychophysical experiments, haptic interface

1. INTRODUCTION

We sometimes judge the situations relying on tactile information. As an example, finding a switch for lamp in a dark room and eating pop corns while watching a movie mainly use the sense of touch. In other words, people manipulate and explore an object haptically in a daily life.

Many researchers have studied haptics for both virtual and real environment applications and there were also many attempts to understand psychophysics of different events. Various kinds of tactile displays have been developed such as vibrotactile display, electrotactile display, piezoelectric display and pneumatic tactile display. Among these tactile displays, pneumatic tactile display delivers tactile sensation by blowing jets of air on a user's skin; however, there was a little study on pneumatic tactile display. The AirGlove [4] can apply an arbitrary point force to the user's hand so that this system provides the sensation of weight of a virtual object. Next example of pneumatic tactile display is Air Jet which helps to perceive the local shape sensation of virtual cube [1]. The other work was applied for teletaction for sensing of texture, local shape, and local compliance in tele-surgery.

In addition, there is little concrete psychophysical data relating to pneumatic displays. In the case of vibrotactile display, there were many studies depending on the type of vibrating motors, parts of body, and so on [2]. Amemiya and Tanaka tried to determine the two point threshold of thumb and forefinger for their pneumatic display, but complexity of variables such as air-pressure, air-jet nozzle diameter, and interspacing caused difficulty of concrete conclusion from this study. This paper addresses this challenge, and presents brief psychophysical studies examining localization rate, the two point threshold, stimulus intensity and the temporal threshold of cues produced by pneumatic air jets.

We present our pneumatic device and describe design of multi-element pneumatic display in Section 2. Then, we discuss the several psychophysical experiments in Section 3 in order to understand the relation between the air-jet stimulation and sensation. In section 4, we conclude our work and discuss the remaining task for the future work.

2. HARDWARE FOR PNEUMATIC TACTILE DISPLAY

2.1 System architecture

Our system possessed a relatively simple configuration. Fig.1 shows the overall system architecture of the proposed pneumatic device which consists of air supplier, regulator, interface and control board, battery and pneumatic valves. A PC used an RS232 serial connection to communicate with a dedicate ATMega 128 microprocessor which controlled the state of the 25 valves which formed the array. Since one microprocessor has 48 I/O port, the pneumatic element can be extended up to 48 air-jets with this system. We used a similar communications protocol to that adopted by other authors investigating tactile arrays and updated the array state 500 times a second. In all the studies described here we used an industrial air accumulator and regulator which ensured that the air pressure presented to users was a constant 1.034 bar. The valves used to control the flow of air were Yonwoo Pneumatic YSV10s. These are binary devices (either on or off) with a switching latency of approximately 20 ms. Also, AQV214 was used as a driver in order to control the valve individually.

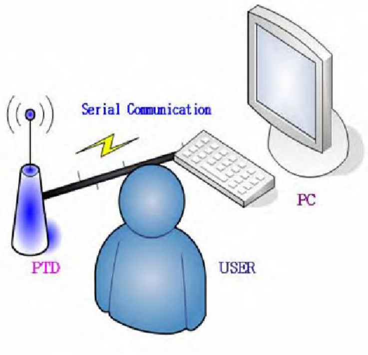

Fig. 1 System configuration

2.2 Design of pneumatic tactile display

For the purposes of the psychophysical studies, we constructed a pneumatic array consisting of 25 individual air jets arranged in a 5 by 5 grid. The array was a resin based pad designed to be mounted on the base of the index finger and held in place by an elastic sheath attached to its sides and running over top of the finger. It featured air nozzles with an external diameter of 2.4mm (and an internal diameter of 1.5mm). In each row of the array (running across the short axis of the finger pad) the air jets were mounted directly against one another, yielding an inter-stimulus distance of 2.4mm. However, small structural supports with a width of 0.8mm were placed between the columns of the array (running down the long axis of the finger pad) resulting in a distance of 3.2mm between pairs of adjacent jets. The overall array size was 12mm by 15.2mm. Fig.2 illustrates our device and middle figure shows the cross section of display design. In order to combine commercial kinesthetic feedback device such as PHANToM^{TM} in VR applications end part of the display was shape like fingertip to fit into the thimble by using resin as shown in the in last figure.

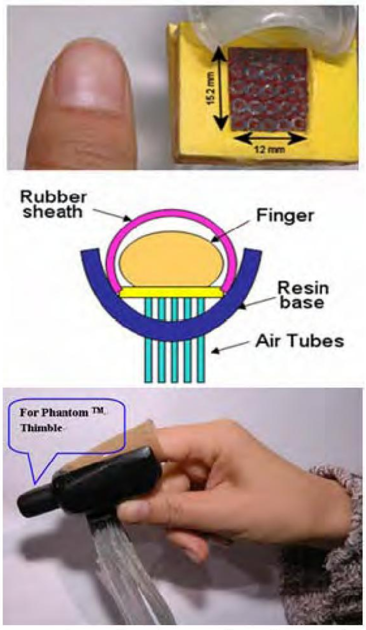

Fig. 2 Photograph and schematic of initial prototype of pneumatic array

3. PSYPHYSICAL EXPERIMENTS

In order to gain an understanding of the kinds of tactile cue that can be effectively displayed on our pneumatic hardware platform, we engaged in a battery of brief tests. Although conducted with the rigor of psychophysics in mind, the overall goal of these studies was more focused on the rapid production of reasonable approximations than on the adoption of impeccable procedures. Consequently, a number of experimental liberties were taken, as reported in the experimental procedures. We are aware of the limitations such an approach conveys to the validity of our data, and believe, in the absence of a suitable substitute, that it remains a useful and valuable contribution.

3.1 Experiments and participants

Two groups of subjects were used in these studies, subsequently termed groups A and B. Both were comprised of eight participants, four men and four women. The average age of the members of each group was 22 and 29 respectively. No participant has been studied haptics and experiences haptic devices. Group A completed four brief experiments, two investigating localization performance and two examining the two-point threshold. Group B completed a study looking at the perception of stimulus intensity and one investigating temporal resolution. All experiments have similar procedures. First of all, a participant reads instruction of experiments and then has the opportunity to ask question about their task. Then, the participant sits down in front of computer screen and puts the left index finger into the pneumatic tactile display. In order to get more reliable data, practice session is performed before the test session and it is not used for data analyzed. The participant stays in the room alone and puts the head phone which delivers white noise to mask any sound from the tactile interface.

3.2 Localization studies

The two localization studies shared a similar interface and procedure, and could be differentiated solely by the distance between the stimuli sites used in each. The intention was to contrast user performance with these different levels of inter-stimulus spacing. Each study included the presentation of 9 stimuli in the form of individual air jets and arranged in a square pattern. In the first study, these stimuli were formed by the 9 jets in the central 3 by 3 square of the 5 by 5 array (subsequently termed the dense study). In the second study, 8 of the stimuli fell on the rim of the array (the four corners and the four mid-points between them) and the 9th remained in the center (subsequently termed the spread study). This is illustrated in Fig. 3. The horizontal and vertical distances between stimuli centers in the dense study were 2.4mm and 3.2mm respectively. In the spread study these values were 4.8mm and 6.4mm. In each study, each stimulus was presented a total of 20 times (leading to a total of 180 trials) and in a random order.

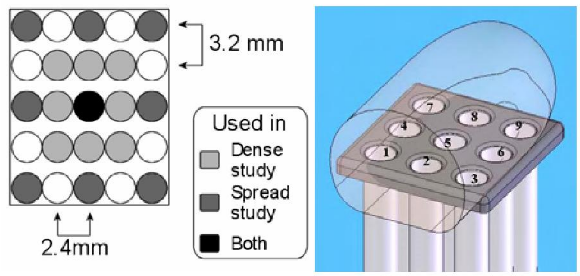

Fig. 3 diagram of pneumatic array showing stimuli used in localization studies

Each trial commenced with a screen instructing participants to press a key to begin. Upon completion of this action there was a 1 second pause, followed by 500 ms of stimulus presentation. Participants then had to press a key on the numeric keypad (the square arrangement typically situated on the right of a keyboard) to indicate the location of the displayed stimuli [Fig.3]. The bottom left of this keyboard (the key marked with the number 1) corresponded to a stimuli on the bottom left of the fingertip array. Similarly, the number 9, at the top right of the keypad, indicated a stimuli at the top right of the fingertip. The graphical interface to the study matched the spatial layout of the numeric keypad (and featured appropriate numbering) and after each trial graphical highlighting took place to indicate both the user's response and the correct answer. After this stage, a new trial began. Prior to each experimental session participants completed a practice session which was identical in structure, but consisted of only half the number of trials.

3.2.1 Localization Results

The localization rates for each air-jet in each study are presented in Fig. 4. ANOVAs revealed significant differences in these data in the case of the spread study ($F(8, 7) = 2.247$, $p<0.05$), but not in the case of the dense study ($F(8, 7) = 2.01$, $p=0.06$). Post-hoc t-tests showed the only significant difference in the spread study was between the air-jets one and nine. A t-test comparing localization performance between the two studies showed a significant difference ($p<0.001$).

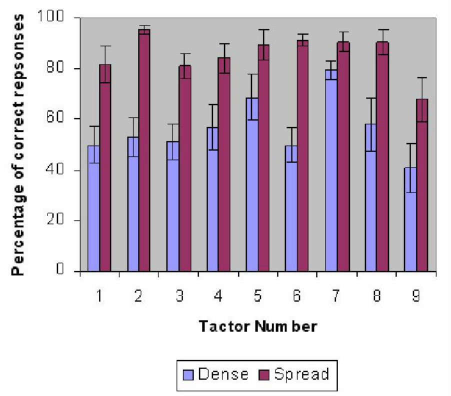

Fig. 4 Localization results

Generally speaking, these results indicate that perception of air-jet stimuli from our array is relatively homogenous across the finger pad. This serves more to confirm the usefulness of our simple hardware design than offer new psychophysical insight. One caveat is the significant drop in performance observed in one of the air-jets positioned on the extremity of the array in the spread study. A likely interpretation of this result is that this air-jet was located sufficiently far under the curved edge of the finger that the gap between its outlet and the skin of the finger became large enough to impair perception in some participants. Consequently, we suggest that to ensure consistent perception it may be advisable to use an array with smaller overall dimensions than that employed in our spread study. However, this is likely to be a tradeoff, as the jets in such an array would have to spaced more closely together, potentially reducing user performance (as seen from the results achieved in our dense study). An alternative solution might be to design a more sophisticated array that is curved to better fit the contours of the finger.

Relating these results to prior finger pad localization studies, typically conducted with pressure stimuli generated by pressing pins against the skin and in which localization rates of as low as 0.15mm have been reported [6], we can conclude that air-jet cues are not perceived with the same high levels of accuracy. In our dense study, featuring stimulus sites several mm apart, the error rate hovered around the 50 percent mark, suggesting users experienced considerable difficulty with the task. One possible reason for this is that the feel of the air-jet stimuli may be dependant on the position of the user's finger pad on the array. Small movements laterally or, perhaps more significantly, vertically away from device may cause considerable variations to the cues, and are challenging to measure or control for. An alternative explanation lies with the size of the pneumatic cues. The inner diameter of the tubing we used was 1.5mm, considerably larger than the point of a pin, and yielding effective inter-stimulus spacing (measured from the extremities of the air nozzles) of as little as 0.9mm. It is also possible that upon exiting the tubes, the jets of air immediately began to spread out causing a still larger stimulus footprint on the skin. These issues remain unresolved at this time and warrant further investigation.

3.3 Two-point studies

Two studies were conducted to gauge the two point threshold for air-jet stimuli. They were intended to complement one another, with the second examining smaller scale inter-site distances than the first. Both experiments shared a similar task and procedure. In each, participants tapped a key to begin a trial, and after a 1 second pause were presented with a stimuli which they then had to judge as either consisting of one or two separate jets of air. Feedback was given regarding their response but not as to its correctness. Both studies were preceded by practice sessions with half the duration of the experimental sessions.

The first study consisted of 5 different stimuli: a single jet, and four pairs of two jets. All the stimuli were situated on the centre column of the array (positioned along the centre of the long axis of the finger). The stimuli composed of pairs of jets featured either adjacent jets, or those separated by 1, 2 or 3 spaces. This corresponds to distances (as measured from the centers of the jets) of 3.2, 6.4, 9.6 and 12.8 mm. Each of the 5 stimuli was presented 20 times (leading to a total of 100 trials), and the position of each in the central column was randomized within the physical limits of the design (for instance, there are 5 possible display sites for the stimuli consisting of a single jet, but only 1 for the stimuli consisting of 2 jets separated by 3 spaces).

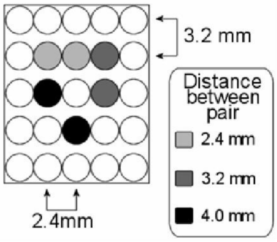

Fig. 5 diagram of pneumatic array showing sample set of stimuli used in second two-point studies.

The second two-point study examined a set of somewhat closer points, and took advantage of the physical constraints of our array. It consisted of four stimuli, one of which was generated by a single air jet, the remaining three generated by a pair of jets. The pairs of stimuli were all adjacent, but differed in the directionality of this adjacency. As our array is not uniformly spaced along its axes (as illustrated in Fig. 2, and due to the presence of structural supports between its rows, but not its columns), it features different inter-jet spacing between horizontally, vertically and diagonally adjacent jets and this fact was used to generate stimuli pairs with centers which were 2.4, 3.2 and 4.0 mm apart. This is illustrated in Fig. 4. To control for possible response biases in this study, each of the stimuli pairs was presented 30 times, while the single jet stimulus was presented a total of 90 times. This equalized the number of times participants were exposed to individual and pair stimuli, and led to a total of 180 trials. All stimuli were presented on the central 3 by 3 portion of the array, and randomized for the physical limits of this configuration. This led to 9 possible locations on which to display the single jet, 6 for each of the horizontal or vertical pairs, and 8 for the diagonal pair.

3.3.1 Two-point Results

Fig. 6 and 7 illustrate the accuracy with which participants correctly judged the stimulus in each trial as being composed of one or two points. As we were attempting to determine the two point threshold we discarded the data related to stimuli generated by a single point from our formal analyses. From the remaining data, ANOVA's showed significant effects (at $F(3, 7) = 128.751$, $p<0.001$ for the first, larger scale study, and $F(2, 7) = 11.052$, $p<0.001$ for the second). Post-hoc t-tests (with Bonferroni confidence interval adjustments) on the data from the first study revealed that when two points were adjacent performance was considerably lower than with any of the other configurations, where accuracy rates approached or exceeded 90 percent (all at $p<0.01$). Similar t-tests on the data from the second study confirmed significant differences between the most distantly separated pair of cues and both of the other two pairs (at $p<0.05$).

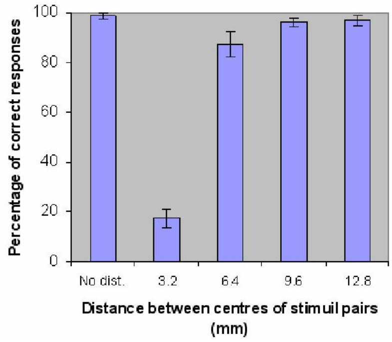

Fig. 6 Data from first two-point study

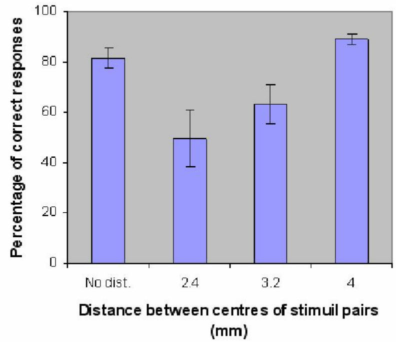

Fig. 7 Data from second two-point study

It is worth briefly discussing the differences in accuracy rates between the two studies. In the first study, subjects achieved greater levels of accuracy when presented with a single stimulus and much worse when presented with two reasonably proximal (3.2 mm apart) stimuli than they did in the second study (where they performed well below chance). The reason for this disparity is probably due to a response bias in the design of the first study: as subjects were presented with two response options to each trial, they most likely attempted to choose each one approximately 50% of the time. Needless to say, as the presence of a single cue occurred in only 20% of the trials, the data is skewed to reflect the expectations of the participants. Half the trials in the second study consisted of a single stimulus, avoiding this bias, and therefore providing a more accurate measure of the two-point threshold for pneumatic cues generated by air-jets.

The two-point threshold for pressure stimuli generated by pin-pricks to the skin has been reported to be as low as 1mm [5]. The data from our second study indicates that when the pneumatic cues are positioned 2.4mm apart users achieve an accuracy rating of approximately 50 percent, effectively equivalent to chance. Although somewhat better with a 3.2mm cue separation, participants were only able to reliably determine the presence of two separate cues when they featured a 4mm gap between them. This result is in line with those of our localization studies, supporting that data and further suggesting that the sensory thresholds for pneumatic cues are considerably greater than those for the more commonly studied pressure cues.

3.4 Stimulus intensity

Unlike many forms of tactile display, one current technological limitation of most air-jet displays is that they are unable to present stimuli of different intensities. This is largely due to the fact that most valves (which are used to control the airflow), and especially those that are small, reasonably priced and quiet, are binary. They are either off or on and consequently so are the stimuli that they can create. However, delivering cues that have the capability to grow or shrink in magnitude remains an attractive goal. One way this can be achieved with a display composed of binary elements is by changing the size of the skin area to which a stimulus is applied by changing the number of array elements used to display it. At threshold levels, a relationship between the size of skin contactor and the perceived magnitude of a displayed vibrotactile cue has been established by Verrillo [9], more recently investigated by Oakley *et al.* [11] and similar effects are well documented in other sensory modalities, such as vision [7].

Reflecting this work, we conducted a study intending to gauge whether participants can effectively discriminate between stimuli composed of different numbers of simultaneously active air jets. In fact, given our previous localization and two-point threshold results, it is reasonable to suggest that by activating groups of adjacent air-jets, we can in fact stimulate different sized areas of the skin. Based on this perceptual assumption we conducted a study in which participants experienced a pair of stimuli, each created by activating between 1 and 9 air jets, and then had to judge which of these two was of greater magnitude, or if they were the identical. The air-jets used in this study were drawn from the central 3 by 3 portion of the array and we twice compared each of the 9 possible magnitudes against all this entire set. This led to a total of 162 trials (9 magnitudes times 9 magnitudes times 2 presentations). Each stimulus was always produced by a single arrangement of one or more adjacent tactors (unlike in the studies on two-point localization which explicitly varied which jets stimuli were displayed on).

In this study, each trial consisted of a subject depressing a key to begin, a 1000 ms pause, followed by a 500 ms stimulus presentation, another 1000 ms pause and a final 500 ms stimulus presentation. Participants were required to respond by pressing keys corresponding to whether they thought the first stimulus was greater than the second, that they were the same, or that the second was greater than the first. An on-screen interface reinforced these instructions, and highlighted user responses, but not their correctness. Immediately prior to the experimental session, participants completed an 81 trial practice session.

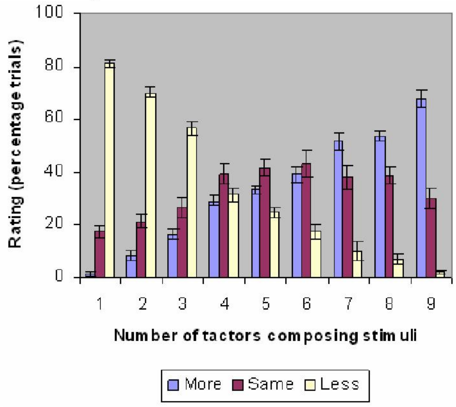

Fig. 8 Rating data from intensity study

3.4.1 Stimulus Intensity results

The data recorded in this study consisted of pair wise judgments comparing the perceived intensity of each individual stimulus against the full set of stimuli. The simplest way to analyze data in this form is to simply tally the number of times a given stimulus was rated as being greater, the same or less than another. As perceived intensity increases or decreases, these three counts should similarly increase or decrease. These data are shown in Fig. 8. We confined our analyses to the number of times each stimulus was rated as greater than another. An ANOVA indicated the variations in this statistic attained significance ($F(8, 7) = 129.65$, $p<0.001$), while post-hoc t-tests incorporating Bonferroni confidence interval adjustments revealed a large number of significant differences, summarized in Table 1. These results strongly suggest that by varying the size of a pneumatically created tactile stimulus, we can effectively vary its perceived magnitude. This finding is made especially valuable in light of the fact that the individual jets within our array are only capable of producing a stimulus of a single magnitude. By demonstrating the viability of an alternative mechanism to vary the intensity of a cue, we open the door to the production of a whole new range of dynamically changing stimuli.

Table 1 P values from t-test in intensity study

Number of air jets in other stimuli	Number of air jets in one stimuli							
	2	3	4	5	6	7	8	9
1	0.08	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2		0.46	0.01	0.01	0.01	0.01	0.01	0.01
3			0.01	0.01	0.01	0.01	0.01	0.01
4				1.0	0.64	0.01	0.01	0.01
5					1.0	0.01	0.01	0.01
6						0.07	0.14	0.01
7							1.0	0.12
8								0.20

3.5 Temporal resolution

An important aspect to consider in the design of any display is the temporal resolution of the relevant human perceptual system. Such knowledge informs us about the quality of the stimuli we can effectively display; we need only be capable of displaying stimuli at a speed which they can be easily perceived and discriminated. With regards to the human tactile system, temporal resolution is a complex issue. Due to the presence of different types of mechanoreceptor in the skin (each of which responds best to different types and frequencies of stimuli, up to peak sensitivities of 250 Hz for vibration) it is hard to use the existing literature to determine what the appropriate temporal resolution will be for pneumatic cues. This issue is further complicated by the fact that the kind of pneumatic display we are considering in this paper exhibits a rather complex, and not fully classified, temporal behavior. Not only do the valves that control the airflow have a relatively substantial latency (in the order of 20 ms), but there is also the issue of the physical delay between the activation of a valve and the corresponding arrival of a stimulus on the skin (due to the simple fact that the air is routed down lengths of tubing).

To investigate how these factors impact on the kinds of cues we are capable of creating, we designed a study examining the perception of pairs of temporally proximate stimuli. The goal of this investigation was to (within the limits of our display hardware) determine the perceptual threshold relating to the temporal spacing between pneumatic cues. Each trial in the study involved the display of either a single cue or a pair of consecutive cues, and participants were required to press a key to make a judgment as to which of these eventualities they felt had taken place. They received graphical highlighting about their choice but not about its accuracy. The total duration of each trial was kept at a constant 100 ms. 50 trials were administered in total. Half were composed of a single stimulus, the other half by 2 stimuli separated by 2ms, the minimum duration that our software is capable of presenting and considerably under the mechanical latency of the valves used in our hardware. All stimuli were displayed on the central jet of the array. Prior to the experimental session, participants completed a short practice session with a similar structure but composed of only 10 trials.

3.5.1 Temporal Resolution Results

The accuracy rate approaches one hundred percent for stimuli in both conditions, and a t-test indicated there was no significant difference between them ($p = 0.43$). From this result we can conclude that the temporal abilities of the human perceptual system considerably outperforms that of our display hardware, and that we can not expect to be able to effectively present high frequency information.

4. CONCLUSION AND FUTUREWORKS

The pneumatic tactile display which can deliver useful information for users has been developed and through a series of psychophysical studies, we developed a basic understanding of the perceptual characteristics of pneumatic stimuli. We gained insights into localization rates, the two-point threshold, and how intensity is perceived. We also discovered that the limits of tactual temporal perception considerably exceed that of our display hardware. For the future work, jet dynamics of pneumatic display will be studied and we will improve our hardware in order to overcome the limitation which the existing device has. Also, we will suggest useful application by using our device for VR or realistic broadcasting area.

Acknowledgement

This research was supported by the Republic of Korea's Ministry of Information and Communication (MIC) through the Realistic Broadcasting IT Research Center (RBRC) at the Gwangju Institute of Science and Technology (GIST).

REFERENCES

[1] Amemiya, K. & Tanaka, Y. "Portable Tactile Display Using Air Jet," In the International Conference on Artificial Reality and Telexistence, 1999.

[2] Cholewiak, R.W., J.C. Brill, & A. Schwab, "Vibrotactile localization on the abdomen: Effects of place and space," Perception & Psychophysics, 66(6): pp. 970-987, 2004.

[3] G. Moy, C. Wagner, R.S. Fearing "A Compliant Tactile Display for Teletaction," ICRA, 2000.

[4] Hakan G., Benjamin P., Sankar J., Uma J., "Design of a Haptic Device for Weight Sensation in Virtual environments," ASME, pp 1-9, 2002.

[5] Johnson, K.O. & Phillips, J.R. "Tactile spatial resolution - I. Two point discrimination, gap detection, grating resolution and letter recognition," Journal of Neurophysiology, 46(6):1177-1191, 1981.

[6] Loomis, J.M. "An investigation of tactile hyperacuity," Sensory Processes, 3:289-302, 1979.

[7] Oakley, I, Kim, Y., Lee, J. & Ryu, J. "Determining the Feasibility of Forearm Mounted Vibrotactile Displays," In Proceedings of the Haptics Symposium 2006, Arlington, VA, 2006.

[8] Sekuler, R. & R. Blake, Perception. Mcgraw-Hill College, 2002.

[9] Verrillo, R.T., "Effect of Contactor Area on the Vibrotactile Threshold," Journal of the Acostical Society of America, 35(12):1962-1996, 1963.