16th IEEE International Conference on Robot & Human Interactive Communication
August 26 ~ 29, 2007 / Jeju, Korea

MA1-2

Electrotactile Display for Integration with Kinesthetic Display

Katsunari Sato[1], Hiroyuki Kajimoto[2], Naoki Kawakami[1] and Susumu Tachi[1]

[1]Information Science and Technology , The University of Tokyo, Tokyo, Japan,
e-mail : Katsunari_Sato@ipc.i.u-tokyo.ac.jp, (kawakami, tachi)@star.t.u-tokyo.ac.jp
[2] Department of Human Communication, The University of Electro-Communications, Tokyo, Japan,
e-mail:kajimoto@hc.uec.ac.jp

***Abstract*—The goal of this study is to develop a haptic interface for dexterous manipulation. To achieve this, we proposed electrotactile-kinesthetic integration. Our electrotactile display presents natural touch sensations of objects. In addition, this display is so small that it is considered to not affect the moving range of fingers. The haptic interface for dexterous manipulation is realized by mounting it on a kinesthetic display having a wide workspace. The electrotactile display on the integrated haptic interface is used actively. Therefore, we actively evaluated the performances of the electrotactile display on the single-fingered prototype system. The results revealed the present performance of the system. Subsequently, it also shows the possibility of further improving of the haptic interface by devising an electrotactile rendering method.**

I. INTRODUCTION

When we handle objects using telepresence or virtual reality systems, haptic feedback is necessary for dexterous manipulation [11][12]. This haptic feedback is divided into two types: kinesthetic (force) feedback and tactile (touch) feedback. The former improves the stability of hand movements [1][3] and the latter helps us perceive object properties [12]. The sensations from both types of haptic feedback should be available for dexterous manipulation. For example, when we handle a pen, we can stably pinch it by our fingertips and feel a reflecting force from the kinesthetic sensation; the position of the pen can be determined by the tactile sensations.

Thus far, several haptic interfaces have been developed [11][12].However, these are not suitable for dexterous manipulation because of inadequate tactile feedback. The tactile display on conventional interfaces presents only a symbolic "contact" sensation of an object. Therefore, we cannot feel the object on our fingertips. It is believed that handling small objects such as pens is difficult without position information. Nowadays, there are some researches that can present the distributed touch sensation of an object [9][10][13]. Unfortunately, the systems proposed by these researches are too large for use in dexterous manipulation. A large system limits the workspace of our fingers, i.e. the movement range of our finger to manipulate an object. This limitation of workspace complicates manipulations such as pinching.

Based on conventional studies, we set the goal of our study to be the development of a haptic interface for dexterous manipulation. First, we summarize the requirements for the touch feedback display intended for dexterous manipulations as follows:

1. It should present a highly realistic and intuitive touch sensation, i.e., it should present not only the "contact" sensation but also the distributed touch sensation that humans perceive.
2. It should be a compact body that does not invade the workspace of our fingers. Such a body also affords advantages in its implementation. It will simplify integration with the kinesthetic feedback display.

To fulfill these requirements, we used an electrotactile display [6] as the touch feedback display. We mounted the display on a kinesthetic display having a wide workspace. This integration provided a haptic interface that was suitable for dexterous manipulations (Fig. 1).

In this paper, we propose electrotactile and kinesthetic integration for dexterous manipulation. In section II, we introduce the concept of electrotactile-kinesthetic integration. Subsequently, we construct a single-fingered prototype and evaluate the basic performance of the electrotactile display in section III. In section IV, we discuss the results of the experiments and further improvements to our system.

II. CONCEPT OF SYSTEM

To achieve dexterous manipulation, we integrate the electrotactile and kinesthetic displays. We introduce their features and their integration in this section.

A. Haptic integration

The electrotactile display that we have developed can

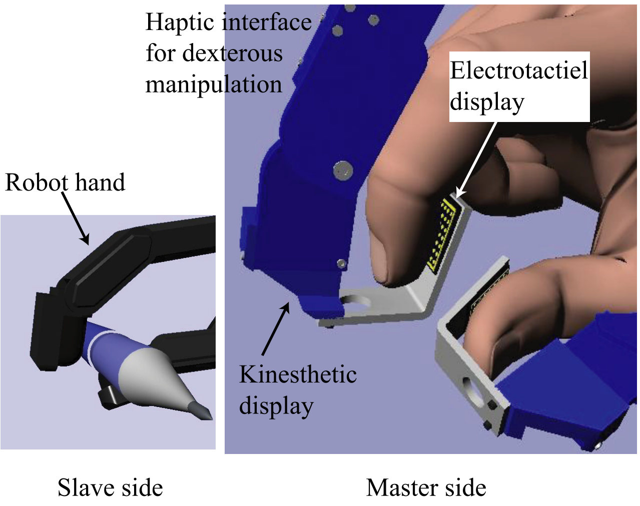
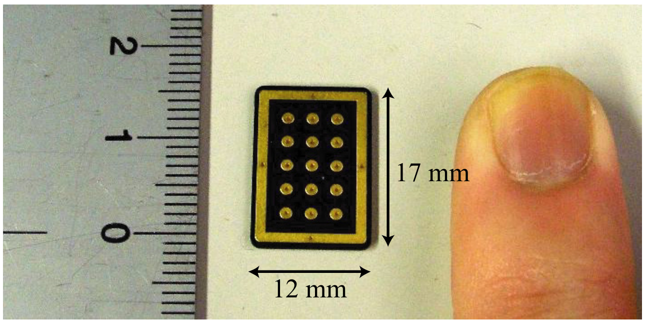


Fig. 1 Conceptual diagram of electrotactile and kinesthetic integration for dexterous manipulation. This is an example used for a master-slave system.

present intuitive tactile sensations. It comprises a pin electrode matrix. It directly activates nerve fibers within the skin surface by an electrical current from the surface electrodes (Fig. 2). The electrical currents flow from the electrode to adjacent electrodes through the skin. It can selectively stimulate each type of receptor and produce vibratory and pressure sensations with an arbitrary frequency. Some applications of this device include the Smart Touch [5] and Forehead Retina system [7]. They allow us to perceive the position, edge, and field sensation of an object. In addition, the electrode plate of this display is small and lightweight. Therefore, it is considered to not affect the workspace. Further, we can easily mount it on all types of kinesthetic displays.

The kinesthetic display presents the reaction and friction force of object surfaces. Nowadays, several types of kinesthetic displays are used [1]. In this study, we consider a small-sized display that has multiple degrees of freedom (DOFs) such as PHANToM (SensAble Tec.) and CyberGrasp (Immersion Tec.). Some of them provide a wide workspace and sufficient kinesthetic feedback to our hand.

When a user touches objects in a remote or virtual environment using our integrated system, he/she can perceive the distributed touch sensation and reaction force of objects. From these sensations, the user can easily recognize the object position, posture, and shape, i.e., he/she can easily recognize what object he/she is touching. For example, from the rounded kinesthetic sensation and the tactile sensation of concave-convex surfaces, we can recognize that we are touching a gear (Fig. 3). We believe that this haptic information will also help the user manipulate objects dexterously.



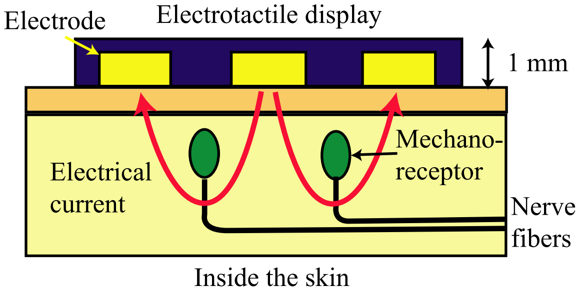


Fig. 2 (Above) Picture of electrotactile display (Electrode plate). (Below) Method of electrical stimulus (Reconstructed from [6]).

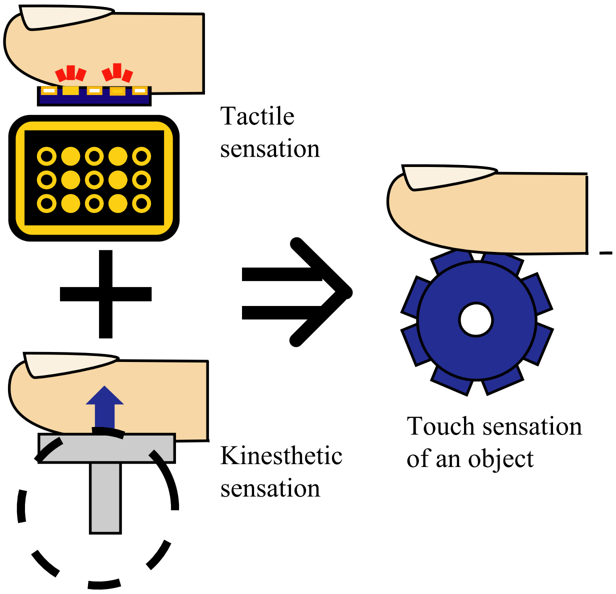


Fig. 3 Presentation of touch sensation by electrotactile and kinesthetic integration.

B. Electrotactile rendering

The electrotactile display presents distributed touch sensations. This implies that the electrostimulus is provided by the electrodes at the position corresponding to the contact position of a finger pad and an object. For example, when the finger pad contacts the face of the cube, all electrodes send a current to the finger. When the center of the finger pad touches the edge of the cube, the electrodes located in a line send the current.

In this tactile rendering method, it is necessary to be careful when deciding the strength of the electrostimulus at each electrode. We assume the case when we touch an object by our finger pad. The fingertip is elastic and thus it has the characteristic of a spatial band-path filter. Therefore, stress concentrates at the edge of a contact surface. It emphasizes the edge automatically. However, when we perceive touching sensation of an object using the electrotactile display, the sensation of this phenomenon cannot be produced.

To present the stress concentration on the fingertip by using the electrotactile display, we have to change the stimulus strength for every electrode responding to the contact surface. Therefore, we consider that the electrotactile display should present a stimulus by gradual strengthening it; it should have an adequate strength resolution for the electrical stimulus.

III. EXPERIMENT

When we manipulate an object using the abovementioned haptic interface, the electrotactile display will dynamically make contact with our finger pad. Therefore, we evaluate the basic performance of the electrotactile display when using it actively. We examine the space resolution of the electrotactile display by distance and width discrimination. Subsequently, we evaluate the strength resolution of the electrical stimulus by strength discrimination.

A. Material

We constructed the single-fingered prototype system of the electrotactile and kinesthetic integration for the experiment. Figures 4 and 5 show the overview and configuration of the system, respectively. This prototype comprises the electrotactile and kinesthetic displays, a laptop PC, and an H8 microcomputer (Akizuki, Coop.). The kinesthetic display is controlled by the PC and the electrotactile display is controlled by the PC and H8 microcomputer.

In this prototype, we used the PHANToM Omni (SensAble Tec.) as a kinesthetic display. The PHANToM has six DOFs and presents triaxial force feedback at 1 kHz. It allows us for a wide workspace and presents sufficient force for one finger. We mounted the electrotactile display on the end-effector of the PHANToM.

The electrotactile display we used comprises a 3 × 5 electrode matrix (Fig. 2). The size of the electrode plate is 12 × 17 × 1 mm. This small size does not affect the workspace of the PHANToM. The surrounding electrode is used as an electrical ground. The diameter of each electrode is 1.25 mm and the distance between the centers of the electrodes is 2.5 mm. The pulse width is 40 μs and the pulse frequency is 60 Hz. The maximum strength of the stimulus is 5.0 mA and the strength can be controlled by the user.

The position data of the user's index finger is captured by the PHANToM and translated to the PC. Then, the position of the cursor in the virtual environment is updated. Based on this cursor position, the reflection force and the electric current at the electrode pin are calculated. The reflection force is calculated from the spring-damper model. Current is passed through the electrodes based on the position of the contact field between the cursor and the virtual object. In this prototype, the strengths of the electrostimulus are the same at all electrodes, i.e., the electrotactile rendering method that we mentioned in section II was not implemented.

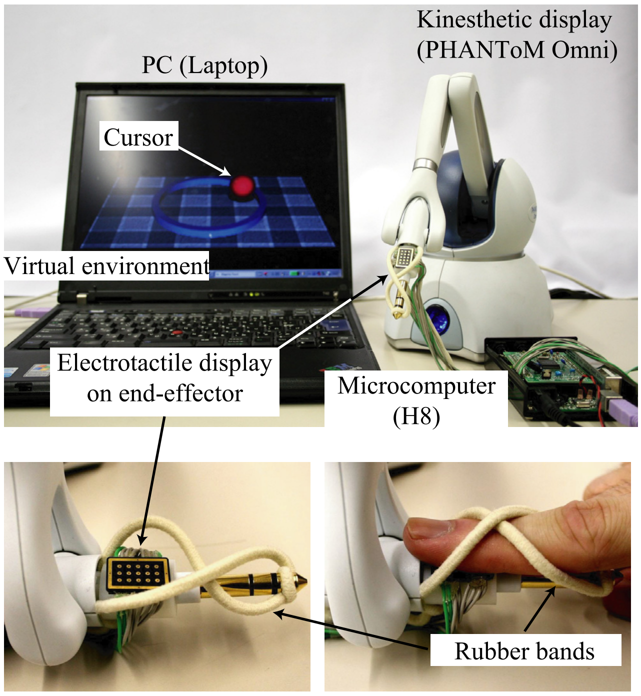


Fig. 4 (Above) Overview of the single-fingered prototype. (Below) Electrotactile display on end-effector of PHANToM.

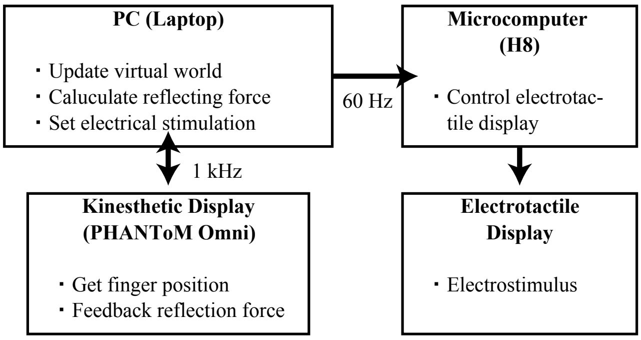


Fig. 5 Configuration diagram of prototype system.

B. Methods

The participants were volunteers in their 20's and comprised two males and two females. Before beginning the experiments, they were explained to the participants. The experiment was conducted using the system that is explained in section *A*. The participants placed the tip of their index finger on the electrotactile display and moved the end-effector of the PHANToM. They can control the cursor in the virtual environment using their fingertips. The fingertip was fixed on the end-effector by rubber bands.

There were three experimental conditions: 2-line, width, and strength conditions. In each condition, there was a floor, a cursor, and two lines (standard and comparison lines) in the virtual environment. In the dist 2-line condition, the participants touched the lines simultaneously and reported whether they were identical or not. In the width and strength conditions, the participants alternately touched the standard line and the comparison line. Subsequently, for the width condition, they determined whether the comparison line was wider than the standard line. In the strength condition, the participants evaluated whether the strength of the electrical stimulus in the comparison line was stronger than that in the standard line.

When we manipulate objects that are in contact with our finger, there are two types of relative movements between the finger and the object—static and dynamic. Therefore, we specified two modes of touching the lines—pushing and sliding (Fig. 6). In the pushing mode, the participants can only push and remain stationary on the line (down the cursor to the floor along the Y-axis). In the sliding mode, the participants push and slide their finger vertically along the lines (along the Z-axis).

In the experiment, the participants were able to view the floor, the landmarks for determining the location to touch, and the cursor that they controlled. In addition, they were able to feel the reflecting force from the floor and the electrotactile sensations from the lines. However, they were not able to view the lines and feel the reflecting forces from them. Therefore, they were not able to report on the visual and kinesthetic sensations.

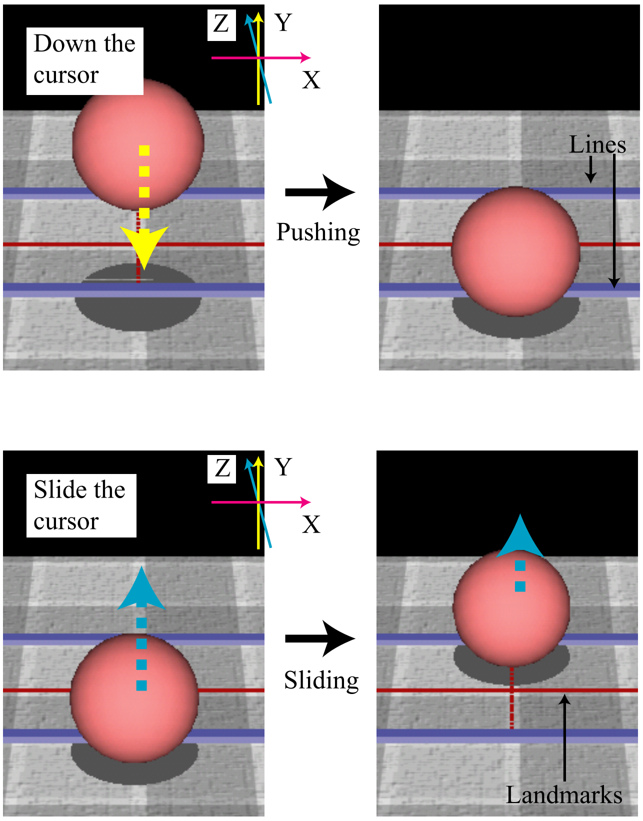


Fig. 6 Experiment 1: Two modes of touching lines.
(Note that participants were not able to view lines during experiments.)

C. Settings

The settings of each experimental condition are summarized in Tab. 1. In each condition, we recorded the participants' answers. We consistently used a constant method to examine a discrimination threshold on this experiment. The number of the parameter value was six. Each value was presented 20 times in one experiment.

In 2-line discrimination, the widths of the lines were 2.5 mm and the distances to their centers were varied according to the values 2.5, 4.0, 5.5, 7.0, 8.5, and 10.0 mm.

In width discrimination, the distance between the centers of two lines was fixed at 40.0 mm and the width of the standard line is 7.5 mm. The widths of the comparison lines were 2.5, 4.5, 6.5, 8.5, 10.5, and 12.5 mm.

In strength discrimination, the distance between the centers of two lines was 40.0 mm. The widths of the lines are 15.0 mm. The standard stimulus strength was decided by the participants. The comparison stimulus differed from the standard according to the values –0.25, –0.15, –0.05, +0.05, +0.15, and +0.25 mA.

Tab. 1 Experiment 1: Settings of experiment in each condition.
Con: condition, Dis: distance between centers of lines, Wid: width of line,
Str: strength of stimulus, Std: standard line, Cmp: comparison line

Con	Line	Dis (mm)	Wid (mm)	Str (mA)
2-line	Std	2.5, 4.0, 5.5, 7.0, 8.5, 10.0	2.5	Set by Participants
	Cmp			
Wid	Std	40.0	7.5	
	Cmp		2.5, 4.5, 6.5, 8.5, 10.5, 12.5	
Str	Std		15.0	
	Cmp			std ± 0.05, 0.15, 0.25

D. Results

The experimental results in each setting are shown in Figures. 7, 8, and 9. Each "circle" and "rhomboid" represents the average response ratio in the pushing and sliding modes, respectively. The straight and broken lines represent the fitting curve in each mode. The error bars represent the standard deviation.

In Fig. 7, the horizontal axis represents the distance between the centers of lines and the vertical axis represents the response ratio of "identical." From this figure, we can estimate that the threshold of 2-line discrimination (75% discrimination) is around 10.0 mm in the pushing mode. In the sliding mode, it is around 9.2 mm.

In Fig. 8, the horizontal axis represents the width of the comparison line and the vertical axis represents the response ratio of "wide." From this figure, we can estimate the lower and upper thresholds of width discrimination (25 and 75% discrimination) to the 7.5 mm width line. In the pushing mode, they are approximately 6.0 and 10.5 mm respectively. In the sliding mode, they are approximately 5.5 and 9.5 mm.

In Fig. 9, the horizontal axis represents the stimulus strength of the comparison line and the vertical axis represents the response ratio of "strong." From this figure, we can estimate the lower and upper thresholds of strength discrimination (25 and 75% discrimination) to the strength of the participants set. In the pushing mode, they are approximately –0.15 and +0.08 mA, respectively. In the sliding mode, they are approximately –0.10 and +0.05 mA.

Note that the strengths of the electrical stimuli set by the participants were approximately 2.0 mA. Based on the participant's feedbacks, they could comfortably feel electrical stimuli of around 1.25 to 2.75 mA.

IV. DISCUSSION

A. Physiological viewpoint

In the results of the 2-line discrimination, the threshold is approximately 9.5 mm. This value is large as compared to the two-point discrimination threshold of the index finger, which is approximately 2.0 mm [8]. On the electrotactile display, the electrical current flows from the electrode only to the adjacent electrodes. Therefore, the discrimination threshold should be around 5.0 to 7.5 mm. However, under practical conditions, the electrical current leaks to the surrounding electrodes. This leakage current causes a wide area of contact sensation. Therefore, we believe that it will complicate the identification of whether the lines are identical or not.

We believe that this space resolution will improve by increasing the density of the electrodes. However, this will

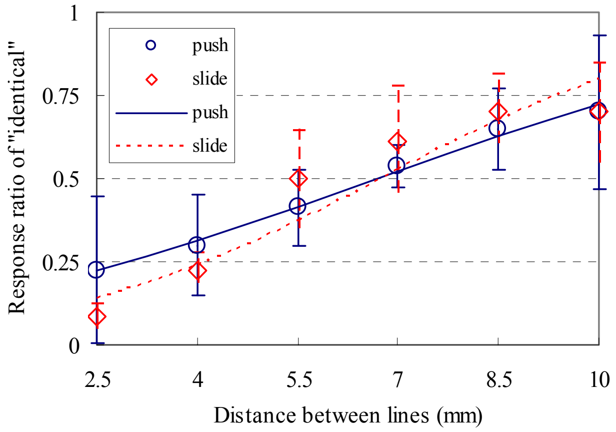


Fig. 7 Experiment 1: Result of 2-line discrimination.

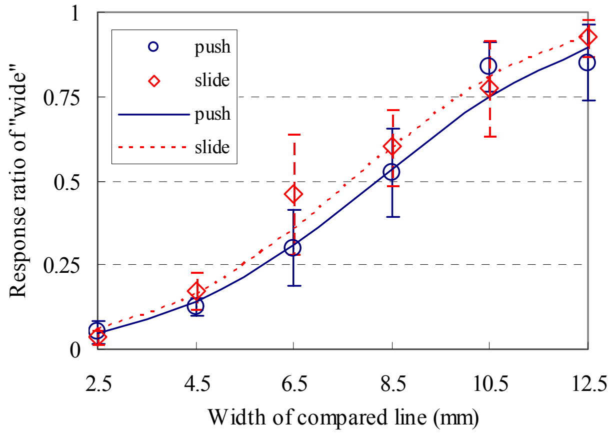


Fig. 8 Experiment 1: Result of width discrimination.

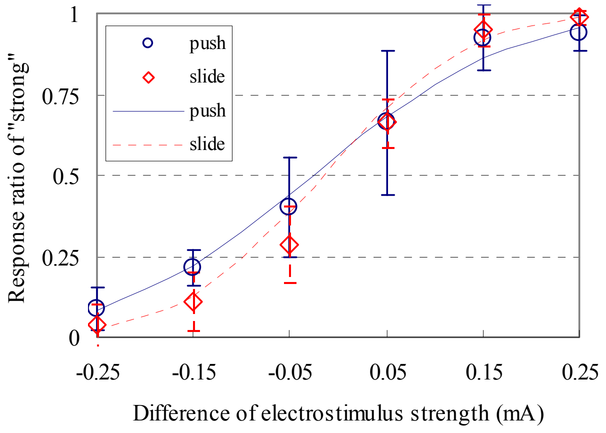


Fig. 9 Experiment 1: Result of strength discrimination.

cause an increase in the electrical current which in turn will cause an increase in the leakage current. We have to examine this trade-off relationship more closely and set the optimum density of the electrodes.

The width discrimination threshold for the 7.5 mm line is approximately 2.0 mm. Based on the distance of the center of the electrodes, the width discrimination threshold is considered to range from 0.0–2.5 mm. The result is considered to be sufficient from this theoretical value. Therefore, the abovementioned leakage current does not affect the width discrimination.

In all experiments, the results reveal the tendency of the slide mode to be more sensitive than the pushing mode. This agrees well with the knowledge about active touch [4]. The ability of tactile perception improves by moving the finger pad to the surface of an object. However, the difference is small as compared to the conventional results of active touching. This reveals that the tendency of the electrotactile stimulus to reduce the effect of active touching.

B. Viewpoint from application

The electrotactile display has sufficient space resolution in width. Therefore, it is considered that several contact field sizes can be presented. For example, we can perceive the difference in the touch sensation of a pen from a bat. Unfortunately, 2-line resolution is not sufficient and thus the perception of a fine slot is difficult. Therefore, we require further improvements in the electrotactile display in order to present fine features of an object surface.

At the strength discrimination, the upper and lower thresholds are approximately 0.12 and 0.06 mA, respectively. These thresholds are considered to be small as compared to the range of the strength of the electrical stimuli that the participants could feel comfortably (1.5 mA). Therefore, we believe that the electrotactile display has a high strength resolution. Based on this result, it is possible to implement the electrotactile rendering mentioned in section II. We believe that this implementation will improve not only the neutrality of the stimulus but also the space resolution.

Based on the results, the effect of the touching modes on the resolution is small. This is convenient. When manipulating an object, we sometimes cannot move the finger after the first contact. In this case, we have to recognize the size of the contact field. Therefore, we require a high space resolution at the static mode of touching, in a manner similar to the dynamic mode. The result shows that this requirement can be satisfied by using the electrotactile display.

V. CONCLUSION

In this paper, we proposed electrotactile-kinesthetic integration for haptic interfaces. We believe that this integration will enable us to manipulate objects dexterously. We constructed a single-fingered prototype. Subsequently, we dynamically evaluated the basic performance of the electrotactile display. The results revealed the present performance of the electrotactile display. Subsequently, they also showed the possibility of further improving the electrotactile display by devising an electrotactile rendering method.

In the future, we will enhance the system to enable users to perceive a more intuitive haptic sensation than that perceived currently. First, we will implement the electrotactile rendering method introduced in section II. Second, we will develop the electrodes in order to realize a higher space resolution. To achieve this, we will examine the effect of the electrical current and electrode density on the haptic perception. Finally, we will construct a multifingered haptic interface for dexterous manipulation.

VI. REFERENCES

[1] Y. Bar-Cohen, C. Mavroidis, M. Bouzit, C. Pfeiffer and D. Magruder, "Haptic Interfaces," Chapter in *Automation, Miniature Robotics and Sensors for Non-Destructive Testing and Evaluation*, Y. Bar-Cohen (Ed.), The American Society for Nondestructive Testing, Inc., 2000, pp. 461-468.

[2] J.V. Draper, J.N. Herndon, B.S. Weil and W.E. Moore, "Effects of force reflection on servomanipulator task performance," in *Proceedings of International Topical Meeting on Remote Systems and Robots in Hostile Environments*, 1987, pp. 654-660.

[3] H. Hanafusa and H. Asada, "Stable prehension of objects by robot hand with elastic fingers," in *Proceedings of 7th International Symposium Industrial Robots*, 1977, pp. 361-368.

[4] L.A. Jones and S.J. Lederman, "Human Hand Function," Oxford University Press, 2006, pp. 61.

[5] H. Kajimoto, M. Inami, N. Kawakami and S. Tachi, "SmartTouch: Augmentation of skin sensation with electrocutaneous display," in *Proceedings of11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003, pp. 40-46.

[6] H. Kajimoto, N. Kawakami, T. Maeda and S. Tachi, "Electro-Tactile Display with Tactile Primary Color Approach", in *Proceedings of International Conference on Intelligent Robots and Systems*, 2004.

[7] H. Kajimoto, Y. Kanno and S. Tachi, "Forehead Electro-tactile Display for Vision Substitution," in *Proceedings of EuroHaptics 2006*, 2006, pp. 75-79.

[8] E.R. Kandel, J.H. Schwartz and T.M. Jessell, "Principles of Neural Science (Forth Edition)," McGraw-Hill Medical, 2000, pp.436.

[9] Y. Kim, I. Oakley, and J. Ryu, "Combining Point Force Haptic and Pneumatic Tactile Displays", in *Proceedings of the EuroHaptics 2006*, 2006, pp. 309-316.

[10] N.S. Methil, Y. Shen, D. Zhu, C.A. Pomeroy, R. Mukherjee, N. Xi, and M. Mutka, "Development of supermedia Interface for Telediagnostics of Breast Pathology", in *Proceedings of IEEE International Conference on Robotics and Automation*, 2006, 3911-3916.

[11] K.B. Shimoga, "A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part 1. Finger Force Feedbackk" in *Proceedings of the IEEE Virtual Reality Annual International Symposium*, 1993, pp. 263-270.

[12] K.B. Shimoga, "A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part 2. Finger Touch Feedbackk" in *Proceedings of the IEEE Virtual Reality Annual International Symposium*, 1993, pp. 271-279.

[13] C.R. Wagner, D.P. Perrin, R.L. Feller, R.D. Howe, O. Clatz, H. Delingette, and N. Ayache, "Integrating Tactile and Force Feedback with Finite Element Models", in *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1–10, Barcelona, Spain, 2005. pp. 3942-3947.