Feature Representation and Manipulation Aid for a 3D Virtual Object by a Finger-Mounted Tactile Display*

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We have developed a tactile display that is attached to a user's fingertip. The display presents the touch status between the user's finger and a virtual spatial object by means of a vibratory stimulus. The display is equipped with ten vibratory pins, that are in contact with the surface of an index fingertip or of a thumb. By changing the pattern of vibration, the display presents the geometrical features of an object's surface such as a vertex, an edge, and a plane. An experiment was performed to confirm the user's ability to discriminate among the patterns. A pick-and-place model task in a virtual space was also performed to reveal the effectiveness of the tactile presentation during virtual object manipulation. The results showed that the tactile presentation improved the task completion time and the positional accuracy of the manipulated object.

Key Words: Human Interface, Human Engineering, Tactile Display, Three-Dimensional Object's Feature, Virtual Reality

1. Introduction

A three-dimensional virtual space is being introduced gradually into the machine design and evaluation environment. The period required by a design task and the cost of building a prototype would be decreased if a designer could use a virtual environment where he/she could view and evaluate a three-dimensional model generated directly from the CAD data of an object regarding its shape, color and even manipulation ability. However, only a CRT (cathode ray tube) display is provided in the current presentation environment; therefore, evaluation including a haptic point of view is hardly applicable although haptic evaluation is crucial in the evaluation of manipulation. A new virtual environment involving haptic presentation is expected to provide a novel tool for realizing agile and efficient design.

Regarding virtual reality haptics, newly designed devices with various configurations have been introduced and discussed recently [1–3]. These displays are classified into two categories: a force display and a tactile display. The force display principally represents a small number of net force vectors, for example, the weights of objects and repulsive forces from objects' surfaces. The tactile display represents a sensation of touch to the surface of objects, which involves information of shape and texture of the surface. This information imparted as a two-dimensional distribution is only conveyed effectively by the tactile display [4–5] which is in direct contact with the user's fingertip, while only the force display delivers constraints of a finger contacting a virtual fixed surface by applying a force via the device to the finger.

In this paper, we discuss a new method to aid the user of a virtual environment to manipulate a spatial object by using a tactile display that enables tactile perception of objects. For this purpose, a lightweight tactile display was developed [6,7] so that it could be
attached to the fingertip of the user. This display imparts a sensation of touch to the surface of a spatial object by adding a vibratory stimulus to the fingertip. In addition, a difference in surface status is also conveyed by using multiple vibratory pins and their activation patterns. First, we describe the structure of the display. This is followed by the evaluation of the display’s presentation based on a discrimination experiment of vibratory patterns prepared for different conditions of contact status. Moreover, a model task of object picking and placing is discussed to indicate the effectiveness of this tactile presentation in manipulation of spatial objects.

2. Finger-Mounted Tactile Display

Figure 1 shows a finger-mounted tactile display that has ten vibratory pins at a contact plate. The user places either the index finger or the thumb on a pin array and fastens it with straps to fix the display to the finger. The pins are arranged in a 5-row and 2-column matrix to form a display window. A schematic diagram of the device is shown in Fig. 2. This structure is made of photocured resin, which realized small dimensions of 56.0×23.5×23.6 mm³ and a light weight. The device weighs 30 grams without the cable to a control PC.

The pins are made of the same resin as the structures. The shape of the tip of the pin is a square of 0.5 mm on each side. The height of the pin’s tip is aligned to the plane of a finger contact plate. The ten pins are driven individually by a bimorph-like piezoelectric actuator (Megacera, Inc.) which measures 16.0×5.0 mm² and is a 0.6 mm thick. The actuator consists of a stainless steel substrate with piezoelectric ceramic layers on both sides. A 100 volt input was applied to drive the device. The vibration of the actuator is digitally controlled by a PC (80486, 66 MHz) which produces a square wave signal. The amplitude of vibration is altered by the duty ratio of the wave. Table 1 shows typical data of the pin amplitude. The input levels in the Table indicate a series of sensation intensities. The amplitude was measured by a laser displacement meter with no loading condition and indicated as peak-to-peak values. The trajectory of a pin tip is shaped almost like a sinusoidal wave.

3. Contact Pattern Presentation by Finger-Mounted Tactile Display

3.1 Presentation of finger contact status

The display is designed to present the features of objects’ surfaces such as microshape or texture. Although the information of objects’ surfaces observed by the fingertip is related to various physical properties, the most fundamental and perceivable element is the geometrical shape of the surfaces. If the geometrical feature of surfaces is discriminated by the fingertip, it is expected that efficiency of work in a virtual space will be improved owing to an increased accuracy in perceiving the object’s status during its manipulation.

The fundamental elements of geometrical features that are crucial for manipulation involve the distinction of vertices, edges and planes of objects. These features were presented approximately to the user’s fingertip by the tactile display with simplified vibratory-pin assignments, as shown in Table 2. These assignments were determined based on a contact status between the finger and the object; however, the tactile presentation with this assignment is not necessarily accurate as the feel of the assignments is sufficiently close to the real touch to these features of objects. Therefore, in a strict sense, this assignment should be regarded as a code. In the assignment, a vertex of an object is represented by a single

Table 1 Pin amplitudes for input levels

<table>
<thead>
<tr>
<th>Input Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>8</td>
<td>15</td>
<td>23</td>
<td>29</td>
<td>35</td>
</tr>
</tbody>
</table>

Fig. 1 Finger-mounted tactile display

Fig. 2 Structure of finger-mounted tactile display
Table 2 Vibration patterns for each contact status

<table>
<thead>
<tr>
<th>Contact Status</th>
<th>Surface Feature</th>
<th>Pattern Number</th>
<th>Vibration Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Contact</td>
<td></td>
<td>0</td>
<td>○○○○○</td>
</tr>
<tr>
<td>Contacting</td>
<td></td>
<td>1</td>
<td>○○○○○</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>•••••</td>
</tr>
<tr>
<td>Colliding</td>
<td></td>
<td>3</td>
<td>○○○○○</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>•••••</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>○○○○○</td>
</tr>
</tbody>
</table>

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Table 3 Correct answer ratios of Subject A using his thumb

<table>
<thead>
<tr>
<th>Displayed pattern no.</th>
<th>Answered pattern no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 2 3 4 5 6</td>
</tr>
<tr>
<td>1</td>
<td>100% 0% 0% 0% 0% 0%</td>
</tr>
<tr>
<td>2</td>
<td>0% 80% 0% 0% 0% 0%</td>
</tr>
<tr>
<td>3</td>
<td>0% 0% 100% 0% 0% 0%</td>
</tr>
<tr>
<td>4</td>
<td>0% 0% 0% 80% 0% 0%</td>
</tr>
<tr>
<td>5</td>
<td>0% 0% 0% 0% 100% 0%</td>
</tr>
<tr>
<td>6</td>
<td>0% 10% 0% 0% 0% 90%</td>
</tr>
</tbody>
</table>

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finger intruded the object.

(4) Look up a vibratory pattern in Table 2 based on the contact category. In the case of an edge contact, the most appropriate pattern is determined based on the angle between the axis of a finger and the edge of an object.

This display device alone presents only the stimulus to the skin sensation and does not include the effort of restricting the motion of the fingers of a hand which is provided as a force from virtual objects. Therefore, the user's finger intrudes into an object if the object is fixed to the ground and does not move even after the collision. Although it is possible to avoid the intrusion of a finger by introducing the slipping motion to the objects, in this present study it was assumed that the object was fixed in a virtual space.

3.2 Discrimination experiment

The tactile discrimination of the users was investigated experimentally to determine whether they could distinguish the six contact patterns (Patterns 1 to 6) which represent the different status between the user's finger and the object's surfaces. (Pattern 7 was eliminated from this experiment since it was used during manipulation after an object was pinched following a collision.) Four subjects (two novices and two experienced users) participated in the experiment in which these patterns were presented to the index finger and the thumb of a right hand, and they were asked to determine which pattern was on the fingertip. Each of the six patterns were randomly presented ten times, sixty in total, to one subject. The answer to the pattern number was reported on each presentation. Prior to the experiment, the subject examined all the six patterns presented to his/her finger by selecting arbitrarily each pattern with its number. The subjects wore headphones that provided a band-limited noise to prevent them from hearing the cue coming from the sound of the texture display.

Table 3 shows the correct answer ratios of Subject A who used his thumb. The ratios indicate a sufficiently high ability to discriminate among the patterns. As for the other four subjects, some
confusion was observed in cases where pin arrangements were similar to each other; however, the confusion of the subjects had different types of misjudgment. The difference between subjects was small, so that we could consider the average of correct answer ratios shown in Fig. 4. Given that the chance ratio (under random reports) is 17 percent, we think the average correct answer ratio of 83% is sufficiently high since the subjects were novice users who were allowed only a short time to practice prior to the experiment.

4. Manipulation Aid of Spatial Objects

4.1 Manipulation aid by tactile display

The tactile presentation discussed above was introduced to a manipulation task of a virtual object to evaluate the effectiveness of the device experimentally. The model task performed was a picking-and-placing of a plate (block) object. The completion time and the positional accuracy of the task were investigated under two conditions, with and without tactile presentation.

The experiment was performed as follows. One subject put on a head-mounted display (EyeGenius, Virtual Research Inc.) to capture a stereoview of a virtual work space. Figure 5 shows a virtual hand that allows limited rotation of the index finger. This simplified hand was approximately of the same size as a real hand. Three-dimensional position and rotation sensors (3Space Fastrak, Polhemus Inc.) were attached to the subject’s index finger, the back of the hand, and the head, which provided data to determine the rotation angle of the virtual index finger, the position and orientation of the virtual hand involving a thumb, and the viewing point. The nominal resolution of the sensor was 0.8 mm and 0.15 degree. These data were updated at about 10 Hz. The subject wore the two tactile displays at the fingertips of an index finger and a thumb.

The pattern of activated pins was determined according to the contact status between a spatial object and the two points for collision detection at the fingertips of the index finger and the thumb. The contact status was classified into seven types as shown in Table 2, which provided the activated pin pattern for each state.

The model task of picking an object was done by the index finger and the thumb. The completion of pinching was determined when both of the two collision detection points intruded an object. After the pinching, the tactile presentation continued unchanged according to the positions of collision detection points at the moment of pinching.

Figure 6 shows an experimental work space. The manipulated object is a green cuboid $100 \times 50 \times 30 \text{ mm}^3$ in size with one surface ($100 \times 30 \text{ mm}^2$) in red. The model task is to place this object on a target panel parallel to the depth direction. Four target panels indicated by #1 to #4 in Fig. 6 were used. The initial position of the object was randomized within plus or minus 10 cm from the center of the work space, along every three axes. The initial orientation was also randomized within plus or minus 10 degrees from the orientation at the target panel.

The target panel is a 300 mm square that was
fixed 200 mm away from the center of the work space, perpendicular to the horizontal axis or to the vertical axis. The panel was rendered checkered to indicate the center position and the right angle on the panel. The subject was allowed to change his/her viewing position arbitrarily, starting with an initial position 35 cm from the center. The subject pinched the object floating around the center and placed it at the center of an indicated panel, with the red surface facing the panel. The direction was such that the largest surface faced to the subject, as shown in Fig. 7. To place the object, the subject released the held object. The release of the object was acknowledged when the tip of the index finger detached from the object fixed to a base part of a hand involving the thumb by rotating the index finger. After the release the object came to rest at the position.

A single target panel is displayed in each session of the experiment. Figure 7 shows a subject's (monocular) view where a lower panel is used and the subject is placing the object. Since both the virtual hand and the object are not constrained to the surface of the panel, they intrude into the surface during the task and the object can be placed anywhere in the work space. When the object contacts the panel, the tactile presentation turns into pattern 7 to indicate the collision with the panel. Without tactile stimulation, the subject performed the task under only visual observation.

The procedure of the experiment was as follows. The target panels were presented in the order of #1, #2, #3 and #4. The next panel was presented immediately after the subject placed the object on the previous panel. Four trials with the four panels complete one run. Ten runs were performed consecutively; thus, forty trials makes one session. The subject performed four sessions in the following order; the first without-tactile session, the first with-tactile session, the second without-tactile session, and the second with-tactile session. The subject was asked to place the object rapidly and accurately. A 20-minute rest period was inserted in between sessions. Before the sessions, five practice runs for each of with- and without-tactile sessions were performed by the subject to become accustomed to the task. Four subjects (Subjects A through D) participated in the experiment. Subject B was slightly more proficient than the others.

4.2 Results

The subjective impression of the authors who participated in the experiment was that it was difficult to perceive visually both the exact distance of the object to the target panel and the contact condition between them when the object was very close to the target plane, although they could be viewed in a stereo-scopic image. In addition, pinching the object by rotating the finger in the depth direction was not necessarily easy only by visual observation as the index finger was occluded by the object. Introducing the haptic presentation appeared to facilitate the judgment markedly. Moreover, the tactile difference among the patterns associated with the position of the object was clearly observed when the fingertip deviated from the center of the object.

Figures 8, 9 and 10 indicate the mean elapsed time before picking the object, that of placing the object, and that of task completion, respectively. These results show that the time was shortened by introducing a tactile feedback. Since there was significant individual difference in the results, here we look into the task completion time of Subject B who achieved the highest proficiency among the subjects. It was 6.6 sec on average without tactile feedback and 6.0 sec with tactile feedback, which is approximately 10 percent shorter. The variance was cut by half as well. The ANOVA in terms of tactile contribution to the mean time of completion time indicated a highly significant difference of $F(1, 157) = 16.9, p < 0.01$.

Figure 11 shows the relationship between the positioning time (from picking to placing) and the error for Subject A with tactile feedback. Figure 12 is that without tactile feedback. The error indicates the largest penetration distance of a vertex to the back side of the panel. The average error in Fig. 11 (with tactile feedback) was almost zero while that in Fig. 12 (without tactile feedback) was $-5.13 \text{mm}$, which indicates the object was sinking into the panel. The dispersion is also smaller for the case with tactile feedback than that without it.

Table 4 shows the number of failures that occurred in the task. Failure means cases where the subject released the object accidentally while carrying it to the panel or an extremely long time was required.
before picking the object due to inappropriate pinching movement. The number of failures decreased by using tactile feedback for all the subjects, indicating the effectiveness of tactile feedback.

5. Conclusion

The structure and basic function of the finger-mounted haptic display developed by the authors were discussed based on the results of evaluation experiments to determine its field of application.

This display can present different tactile information depending on basic surface features of a spatial object, although it has a limited number of display pins for the purpose of portability. Moreover, the experiment of picking and placing an object, which modeled a manipulation task in a virtual space, revealed that the tactile presentation by the display decreased the task completion time and improved the accuracy of the task. It is considered that the use of both visual and tactile information during a manipulation task is a normal procedure; hence, the haptic cue provided here may be an equivalent of the real one at least partially to facilitate the manipulation. There was a subjective evaluation that stated that the observed facility of the task was augmented more than the amount of improvement of the completion time. This also supports the effectiveness of tactile presentation as a manipulation aid for spatial objects.

Regarding an interface for exploiting three-dimensional virtual space, a new form of interaction has been desired to reflect the affinity to real-space
interfaces. The presented display imparts to human somatic sensation information provided by the interaction with a spatial object. Although the effectiveness of this device has been confirmed in the above discussion, there must exist other types of configurations for conveying tactile information during a task in a virtual space. Thus, it is necessary to evaluate the system in more diversified environmental setups and tasks. In addition, a future research topic would be the new design of a tactile display that has a more number of pins and an even smaller size.

References

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