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Ungrounded Kinesthetic Pen for Haptic Interaction with Virtual Environments

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***Abstract*—We proposed a pen-shaped handheld haptic display that provides kinesthetic sensations to the fingers of a user without the use of mechanical linkages. The user's movements are not restricted since the device does not have mechanical linkages, and the user can enjoy haptic interactions with virtual environments. In order to downsize the device, we designed our device on the basis of a hypothesis that kinesthetic sensations on the user's fingers alone are sufficient to represent the sensations of touch. We implemented a prototype device and performed an experiment to confirm the representational ability of our device. We also developed a prototype haptic augmented reality system, using which the user can see and touch a computer graphics object.**

I. Introduction

VARIOUS haptic displays that provide the sensations of touch to enable interactions with virtual objects have been developed. However, simple and user-friendly haptic displays that produce realistic sensations of touch and can be easily applied to conventional virtual reality systems for haptic augmentation still need to be developed.

CyberGrasp [1] is a typical wearable haptic display, which is worn by a user, and it provides kinesthetic sensations to the fingers of a user. The user feels as if he/she is directly touching virtual objects with his/her hand. However, most wearable haptic displays are cumbersome and their use requires extra effort since users have to wear them. Handheld haptic displays are another type of haptic displays, which are more easy to use than wearable haptic displays, because the user needs to merely grasp the device to start using it. PHANTOM [2] is a typical pen-shaped handheld haptic display, which provides kinesthetic sensations to the hand of a user who is grasping the pen-shaped interface. The sensations provided by PHANTOM represent intimate kinesthetic sensations, which are provided with the help of mechanical linkages driven by multiple motors. However, this device must be grounded so that it restricts the user's movements to a range of mechanical linkages. Recently developed portable handheld haptic displays such as wUbi-Pen [3] and Senstylus [4] are capable of providing haptic sensations without the use of mechanical linkages. Although such ungrounded devices do not impose restrictions on the user's movements, there are other problems associated with the use of these devices; in order to effectively use wUbi-Pen, it is essential to maintain a physical contact between the device and the screen surface, and this device does not function if it is used in mid-air; on the other hand, Senstylus can be used in mid-air; however, it can only produce vibrations, which do not satisfactorily represent the realistic experience of touching objects. Although there are a number of ungrounded devices that provide kinesthetic sensations on the basis of a characteristic feature of human beings [5], these devices are capable of providing only periodic kinesthetic sensations. Moreover, the development of an ungrounded haptic display that can provide continual kinesthetic sensations has not been reported thus far.

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In this study, we propose a method to provide kinesthetic sensations to the fingers of a user without the use of mechanical linkages and develop a pen-shaped haptic display using this method (Fig. 1). The results of our experiment using a prototype device show that our proposed method can successfully provide kinesthetic sensations. We also develop a prototype haptic augmented reality system using this device.

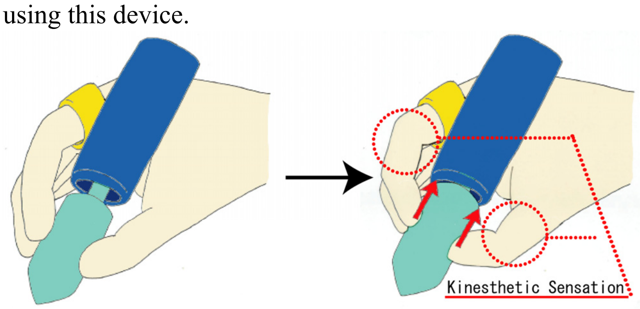

Fig. 1. Conceptual drawing of our proposed device

II. Proposed Method

Human haptic sensation includes cutaneous sensation of the skin and kinesthetic sensation produced at the joints of the fingers and arms. As mentioned in the previous chapter, conventional portable haptic displays, which do not restrict the user's movements, provide only cutaneous sensations or periodic kinesthetic sensations. In general, it is essential to use a large device to provide kinesthetic sensations to the user's arms; however, such large devices are seldom portable. On the other hand, it is possible that providing continual kinesthetic sensations only to the fingers will represent better sensations of touch than cutaneous sensations or periodic kinesthetic sensations.

Therefore, we propose a haptic display on the basis of a hypothesis that kinesthetic sensations on the user's fingers alone are sufficient to represent the sensations of touch. This hypothesis is efficient because we don't need to provide kinesthetic sensations to the arms; therefore the device can be downsized. Fig. 1 shows a conceptual drawing of our proposed device. The device is pen-shaped, which is easy to grasp. To apply a force using an ungrounded device, it is essential to place the point of support of force on some part of the user's body so as to set the sum of internal forces to zero. Therefore, we have to design our portable haptic display in such way that the point of support and the point of application of force are enclosed within the hand itself. We fixed the supporting point of force as a point on the base of the index finger, and we applied force to the fingertips of the index finger, middle finger, and thumb by changing the length of the pen-shaped device. Fig. 2 shows the schematic of the mechanism of our proposed device. The device consists of the following two parts: a part from where the pen is held (grip part) and a base part that is fixed to the hand. When a user grasps this device, the base part is fixed to the base of the user's index finger, which is inserted in the ring attached to the outside of the base part. The user grasps the grip part by the tips of his/her index finger, middle finger, and thumb. When the grip part moves toward the base part with the help of multiple motors in the base part, kinesthetic sensations are provided to the three fingers that grasp the grip part. Inside the base part, three motors and strings are fixed, which pull each connecting point in the grip part and control its 3-DOF motion, as shown in Fig. 2. When all the three motors wind the strings and pull each connecting point, the grip part moves parallel to the central axis of the pen as it is pulled into the base part. On the other hand, when only one or two motors are driven, the grip part moves perpendicular to the central axis as it is moved away from the axis. The motion parallel to the central axis generates the sensations of "pushing" or "pecking" virtual objects, and the motion perpendicular to the central axis generates the sensation of friction or the sensation of touching an object using the side of the pen.

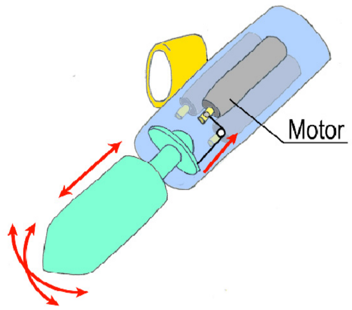

Fig. 2. Schematic of the mechanism of our proposed device

III. PROTOTYPE DEVICE

To confirm the availability of our proposed method, we developed a prototype device. Fig. 3 shows the outer appearance of the device, and Fig. 4 shows the dimensional drawing of the inner structure of the device. As mentioned above, our device is composed of the base part, which is fixed to the hand, and the grip part, which moves toward the base part. The body of the device was cast using a rapid prototyping system (Dimension BST 768, Stratasys Inc.). As shown in Fig.2, although the motors are placed inside the base part parallel to the central axis of the pen, we placed three motors (Maxon Motor Corp., RE 10, 1.5 W, gear ratio = 1:16) at the bottom of the base part perpendicular to the central axis in order to simplify the implementation of the device. Strings are fixed to brass pulleys (6 mm across) using screws. These strings are laced through holes present in the base part, and they are tied at the connecting points in the grip part. The 3-DOF motion of the grip part is controlled by pulling up the connection points using the motors. The maximum force applied to the user using one motor is 4.9 N. A spring is also placed in the base part, which pushes back the grip part when there are no input powers to the motors.

We also set up a holding fixture outside the base part using paper clay that covers the base of the user's thumb and index finger so that the user can hold the device firmly. The ring for the fixation of the hand and the base part is attached outside the base part. Fig. 5 shows the prototype device that is held by user in his/her right hand.

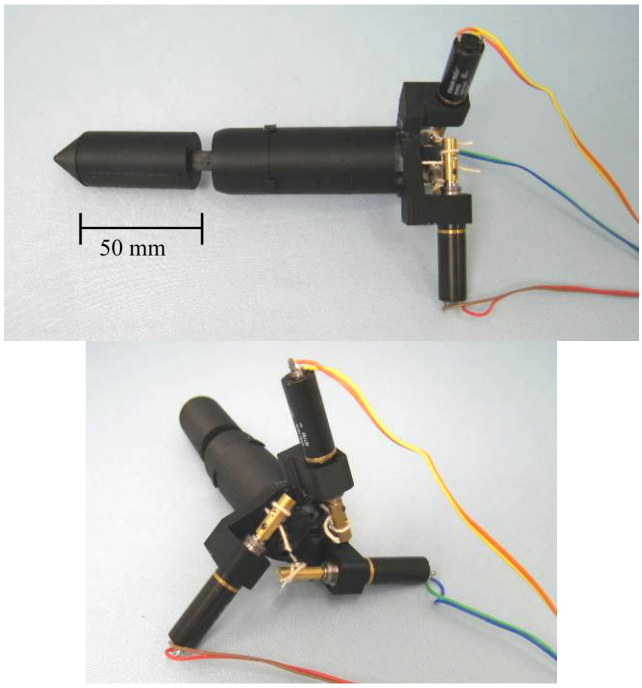

Fig. 3. Implemented prototype device

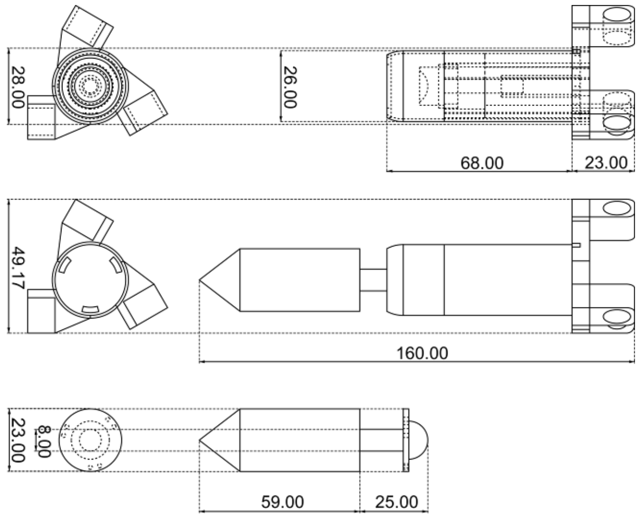

Fig. 4. Dimensional drawing of prototype device. The unit of measurement is mm.

Fig. 5. Prototype device grasped by hand

IV. Experiments

A. Hardness Detection Experiment

In order to confirm whether kinesthetic sensations can be provided by our proposed method and validate the representational ability of our prototype device, we performed an experiment to measure the difference limen (DL) of the hardness detected using the prototype device.

In this experiment, the subject touched two virtual walls using the prototype device and mentioned which wall was harder. Fig. 6 shows the experimental setup, and Fig. 7 shows the coordinate system used in the experiment.

Since the position of the center of gravity moved toward the bottom of the device due to the motors placed at the bottom of the pen, we cancelled the gravitational bias by suspending a weight through a sheave with a string attached to the bottom of the base part. The weight was 70 g, which was nearly equal to the total weight of the three motors and pulleys. We also placed a double-sided tape on the grip part in order to prevent slipping between the grip part and the user's finger tips. An infrared LED (IR LED) was attached to the tip of the device, and the position of the device was measured by capturing the IR LED with a Bluetooth IR camera (WiiRemote, Nintendo Co., Ltd.). Position sensing was performed at a resolution of 0.3 mm and a frequency of 200 Hz. The virtual wall and the position of the tip of the device were drawn on the display of a laptop, and the subject could touch the virtual wall while looking at the display. When the position of the tip of the pen is expressed as x (mm) and the position of the edge of the virtual wall is expressed as x_0 (mm), the force F (N) applied by the device is calculated using the following equation. In this equation, k (N/mm) is a factor that corresponds to the hardness of the virtual wall, and F_0 (N) is the maximum force applied that does not move the grip part.

$$F = \begin{cases} 0 & (x < x_0) \\ k(x - x_0) + F_0 & (x \geq x_0) \end{cases} \quad (1)$$

In this experiment, seven values of k (0.3, 0.4,..., 0.9) were set, hereinafter called k_i (i = 0, 1,..., 6), and the value of F_0 was set to 0.5 N.

This experiment was performed using a constant method. The subjects included two males and one female (in their twenties, right handed). White noise was presented to both the ears of the subjects via headphones, which masked the sound of motors. The subjects were instructed to sit on a chair and hold the prototype device with their right hand. In each trial, two walls (the standard wall and the comparing wall) were presented in random order. The hardness of the standard wall was k_3 = 0.6 N/mm, and that of the comparing wall was k_i (i = 0, 1,..., 6). The subjects touched both these walls sequentially by moving their right hands along the x-axis, as shown in Fig. 7. Then, the subjects answered whether "the first wall was harder" or "the second wall was harder", according to a two-alternative forced-choice procedure. Twenty trials were performed for each condition of k; therefore, a total of one hundred and forty trials were performed by each subject.

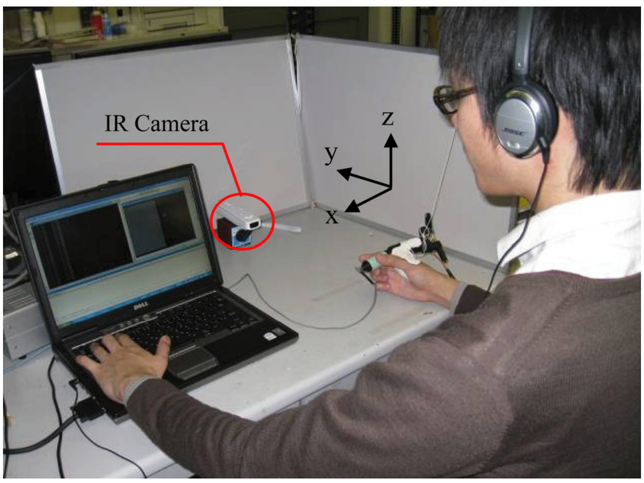

Fig. 6. Experimental setup

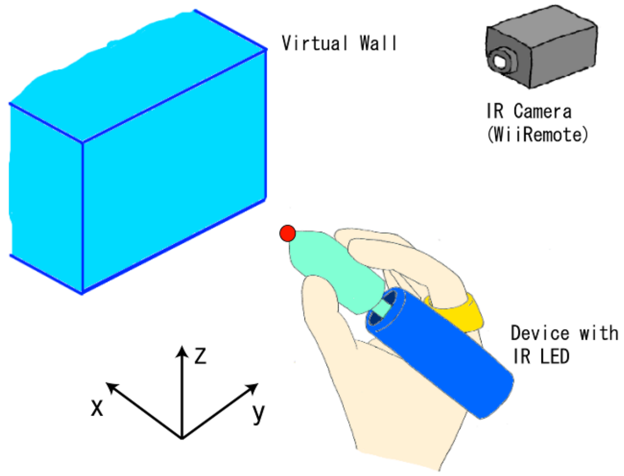

Fig. 7. Configuration of hardness detection experiment

Fig. 8 shows the rate of the responses that the comparing wall was harder than the standard wall. The curves represent the fitted lines with a cumulative normal distribution. The point of subjective equality (PSE) was 0.63 N/mm, which was nearly equal to the value of k of the standard wall (0.6 N/mm), and 75 % DL was 0.12 N/mm, which was derived from the difference between the PSE and the 75% discrimination threshold.

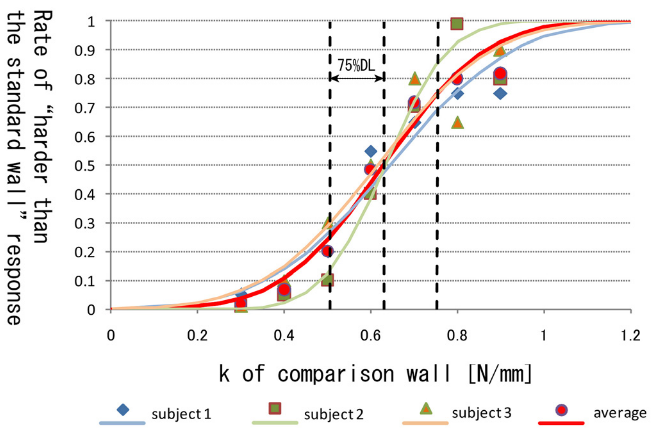

Fig. 8. Result of hardness detection experiment

B. Device Delay Experiment

We performed another experiment in order to estimate a responsivity of the prototype device. We estimated the delay of the device by measuring the movement of the tip part of the device when rectangular-wave currents were input to three motors of the device.

In this experiment, the base part was fixed so that the central axis of the pen became vertical to the ground. The tip part of the device could move parallel to the central axis of the pen by about 7 mm, and the spring constant of the spring used in the prototype device was 0.57 N/mm. Therefore, the output force we could estimate by measuring the migration of the tip part was 4.0 N at maximum. We set the maximum amplitude of the input current as the force presented by the motor was 4.0 N. The movement of the tip part was measured by capturing a marker attached to the tip of the device with an optical tracking system with multiple cameras (NaturalPoint Inc., OptiTrack FLEX: V100). Position sensing was performed at a resolution of 1 mm and a frequency of 100 Hz.

In order to stretch the strings, the minimum output force was set to 0.5 N in each trial, which was the maximum force that did not move the grip part. After 250 ms, the output force was set to 4.0 N for 500 ms. Then the output force was set to 0.5 N again for 750 ms. We performed this trial five times.

Fig. 9 shows the target force and the measured force calculated from the average migration distance of the tip of the pen at each time step. The gap between the rise of input and the time the output force reached the maximum value was about 100 ms in average.

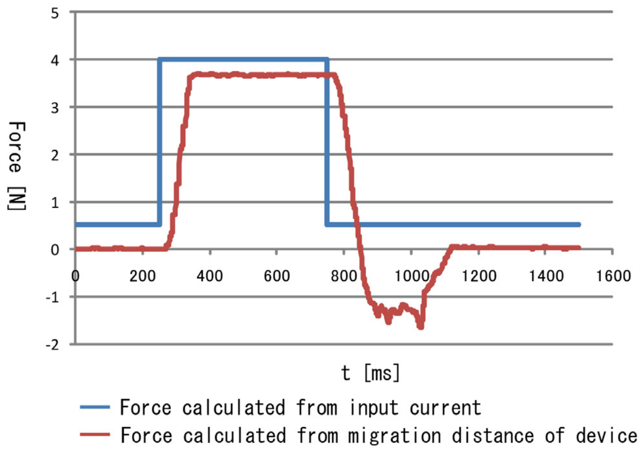

Fig. 9. Result of system delay experiment

C. Discussion

As shown in Fig. 8, it was confirmed that kinesthetic sensations were provided using our proposed method, and the subjects could identify an increase in the force by the overshoot of the tip of the pen from the edge of the virtual wall. The 75% DL for standard hardness (0.6 N/mm) was 0.12 N/mm. The maximum force applied by the prototype device was 14.7 N; when a subject touched a virtual wall and the overshoot reached a certain value, a force of 14.7 N was applied by the device. Moreover, this force remained constant even if the overshoot increased beyond a certain value. In view of these facts, the resolution of the force applied by the device can be calculated by assuming that the subjects compared the hardness of two walls on the basis of the forces provided from these walls in the same overshoot. By comparing the standard wall with the wall that had k of 0.48 N/mm, which was calculated by subtracting the 75% DL from the standard hardness, it was found that the difference between the two forces applied to these walls reached a maximum value of 2.84 N with an overshoot of 23.7 mm. By comparing the standard wall with the wall that had k of 0.72 N/mm, which was calculated by adding the 75% DL to the standard hardness, it was found that the difference between the two forces reached a maximum value of 2.4 N with an overshoot of 19.7 mm. In this experiment, since the subjects could successfully discriminate between the two walls, the maximum resolution of the force applied by the device was 2.4 N. Therefore, our prototype device is capable of applying force of at least seven levels. However, the responses of the subjects are greatly influenced by many factors (for example, how each subject touches the walls or how they arrive at a particular answer). Therefore, for a detailed verification of resolution, it is essential to perform an experiment under detailed conditions.

In the device delay experiment, an oscillating motion of the tip part around t = 900 ms occurred because of the influence of the spring. Though this movement is cranky, it would not be recognized in practical use because the tip part is grasped by fingers.

The latency of the device was about 100 ms in the device delay experiment. The device is thought to be worth practical use enough with this value of latency. As our method provide the kinesthetic sensations by moving the tip part of the device by motors, it takes some times for the output force to reach at a maximum value as motors need to roll up strings some distance (7 mm in the prototype device). However, on practical use, the tip part is grasped by the user's fingers and the tip part does not move in ideal condition. Therefore, the latency of the device will reduce when it is used in the practical system. To estimate the delay of the force presentation in the system, we will measure the force presented on fingers of the user and verify the delay of the force presentation on practical use. There was also a gap between the start of input and the start of the tip part's movement, which was about 20 ms in average. This delay is supposed to be arisen from frictions in the device. We should implement the device while taking the frictions between moving parts in the device into consideration.

V. Application

Our proposed device can provide intimate kinesthetic sensations without using mechanical linkages; therefore, a user can use the device in mid-air without any restriction on his/her movement. Because of such simplicity and usability, the device can be easily applied to various types of conventional virtual reality systems that are not haptically augmented.

We implemented a haptic augmented reality system (Fig. 10) as an example of such an application. Using this system, the user can touch a virtual cube that is drawn additionally over the image of the real world by using an ARToolKit [6]. The computer graphics cube was drawn on the ARToolKit marker, which was captured by a web camera. Kinesthetic sensations were provided by our proposed device whose tip was in contact with the cube. We attached a retroreflective marker instead of an IR LED to the tip of the pen because it is possible that the power strip for the IR LED might hide the ARToolKit marker. Furthermore, we captured the position of the tip of the device using an IR camera. Using the same approach as that used in the experiment, the applied force was calculated using equation (1). Therefore, the user could see the virtual cube augmented on the real image on the screen and also touch the cube using our proposed device.

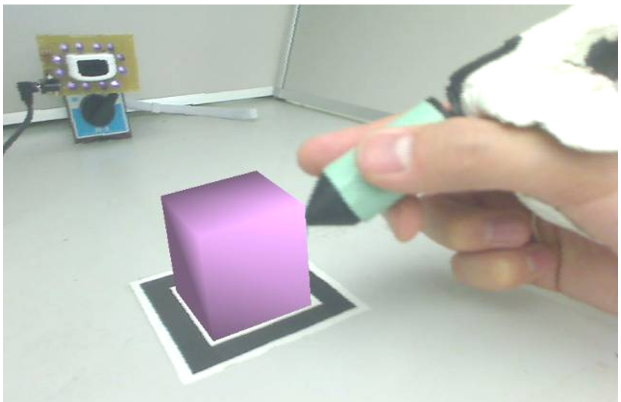

Fig. 10. Haptic augmented reality system

VI. Conclusion

In this study, we proposed a method to provide kinesthetic sensations to the fingers of a user using a portable device without the use of mechanical linkages. Using this method, we implemented a prototype pen-shaped haptic display and showed that our device can apply force of at least seven levels. We also estimated the delay of the device and confirmed that our device is worth practical use. Then, we developed an augmented reality system using which the user could see and touch a computer graphics cube in the real world.

We have tested only the force that is applied parallel to the axis of the pen. We intend to perform an experiment to test the force that is perpendicular to the axis of the pen and show the effectiveness of our device in representing realistic sensations of touching virtual objects. Taking advantage of easy accessibility and good representational ability of our proposed device, we also intend to develop more interactive applications for multiple users.

Acknowledgment

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